NUMERICAL WEATHER PREDICTION FOR THE U. S. NAVY

Richard M. Hodur
Marine Meteorology Division
Naval Research Laboratory
Monterey, CA 93943-5502

1. INTRODUCTION

The Marine Meteorology Division of the Naval Research Laboratory (NRL MMD) is actively involved in the field of Numerical Weather Prediction (NWP) to provide continuous weather support to the U. S. Navy for both wartime and peacetime missions. This support extends from the surface of the earth to altitudes exceeding 10 km, and for time scales ranging from a few hours up to 7 days. The NWP products provide valuable information on tactical parameters such as wind speed and direction, temperature, precipitation, and clouds. Analyses and forecasts of these parameters are crucial for the success of many military missions.

The wide range of time and space scales of significant meteorological events necessitates the use of a dual-modeling system approach. Although computer technology continues to expand rapidly, it has yet to reach the point where only one modeling system can be used in a timely manner to capture the details of the current dual-modeling system approach. For scales of motion greater than about 1000 km, NRL MMD has developed the Navy Operational Global Atmospheric Prediction System (NOGAPS; Hogan and Rosmond 1991). For the short-term (24-48 h) prediction of smaller-scale phenomena, NRL MMD has developed the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS; Hodur 1997). NOGAPS has been proven to be useful for the prediction of large-scale trends, and phenomena such as synoptic-scale cyclones, and tropical cyclones; while COAMPS has been found to be particularly useful in the prediction of mesoscale phenomena associated with coastal regions and areas of significant topographic features. These systems are linked (nested) together in such a way that the larger-scale fields forecast by NOGAPS are used to supply the lateral boundary conditions to COAMPS. This dual-modeling system approach is useful in the prediction of multi-scale events, in that one forecast from NOGAPS can supply the boundary conditions for a fixed number of higher resolution COAMPS areas. The following sections of this paper describe the NOGAPS and COAMPS prediction systems, present applications of both, and provide an overview of the future advances planned for these systems.

2. PREDICTIVE SYSTEMS

NOGAPS and COAMPS are sophisticated data assimilation schemes, with the data assimilation scheme in each system based on four principal components. The first component is the quality control of observations, in which observational data is screened for errors, redundancy, consistency with the previous forecast, etc. (Baker 1992). The second component is the analysis, in which the irregularly-spaced, quality controlled data are interpolated to the model's regularly-spaced grid. The interpolation method used by both NOGAPS and COAMPS is based on the multivariate optimum interpolation method (MVOI; Lorenc 1986). In the third component, model initialization, the analyzed fields are adjusted to conform to one of more dynamic and/or physical constraints. Finally, the fourth component is the numerical model, which integrates the initialized fields forward in time to a specified future time, using some approximate formulation of the primitive equations. The forecast fields can then be used as the background field at the next analysis time. This process is important to maintain spatial and temporal consistency, and to allow for the history of previous observations to be maintained in future analyses. In so doing, the model is allowed to generate useful information in data-void regions, based on the interpolation of the observations from adjacent areas and in relying on the dynamics and physics of the model to project this data forward in space and time. The performance of each of the four components of the data assimilation system is critical to the overall performance of the entire system.

NOGAPS is comprised of the four components for data assimilation described above. In addition to applying quality control procedures and utilizing the standard observations in the MVOI analysis, synthetic observations are generated for all tropical cyclones with maximum winds in excess of 35 m/s. These synthetic observations describe the general wind structure of the cyclone, such as the radius of 35 and 50 knot winds, but do not attempt to describe the mesoscale structure associated with the inner eyewall. These synthetic observations are treated as valid radiosonde reports to ensure that significant tropical cyclones are included in the analyses and subsequent forecasts. The NOGAPS analysis increments are initialized using a nonlinear normal mode initialization. The NOGAPS forecast model is based on the hydrostatic approximation to the primitive equations. The equations are written in spectral form, to avoid the convergence of points at the poles associated with regularly-spaced grid point models. NOGAPS uses state of the art physical parameterizations for boundary layer processes, precipitation, and radiation. The radiation scheme includes short- and long-wave parameterizations, and each interacts with the model forecast cloud field.

COAMPS represents an atmosphere-ocean coupled system. For the purposes of this paper, only the atmospheric portion of COAMPS will be discussed. The COAMPS grid can be set to any size, within the constraints of the computer system being used, and can be located anywhere over the world. The atmospheric portion of COAMPS is also comprised of the four components of a data assimilation system as described above. With minor exceptions, the quality control and analysis components of COAMPS are the same as those used for NOGAPS. Two options are available for initialization: a hydrostatic balance of the analyzed height and temperature increments (Barker 1980), or a digital filter. The atmospheric forecast model in COAMPS uses the nonhydrostatic form of the primitive equations as described in Klemp and Wilhelmson (1978). The nonhydrostatic form of the equations is necessary for modeling systems using a horizontal resolution less than approximately 10 km. For these resolutions, the vertical acceleration may become important, such as in convective systems or flow around steep topography. The COAMPS equations are solved on a staggered C-grid, which can contain any number of nested grids. The grid spacing is reduced by a factor of 3 between each nest. In this manner, the COAMPS grid can telescope down to resolutions of less than 10 km for areas in which high resolution is a necessity. COAMPS contains an advanced moist physics parameterization (Rutledge and Hobbs 1983), which is used in lieu of convective parameterization below 10 km grid spacing. This parameterization contains explicit equations for water vapor, cloud droplets, raindrops, ice crystals, and snowflakes. In addition, COAMPS uses state of the art parameterizations for boundary layer processes and radiation.

The development of NOGAPS and COAMPS is a central component to the work performed at NRL MMD. Both systems are used in NRL MMD basic and applied research programs and both systems have been transitioned to the Fleet Numerical Meteorology and Oceanography Center (FNMOC) for operational use. Active research programs include predictability studies focussed on the development of a targeted observation strategy using singular vectors; the study of topographic and fetch-limited flows; atmosphere-ocean coupling for both the global and mesoscale systems; studies of physical processes and subsequent modification and/or development of parameterizations; aerosol retrieval, assimilation, analysis, and prediction; and the study of advanced data assimilation techniques.

3. APPLICATIONS

NOGAPS has been operational at FNMOC since 1982, at which time it had a resolution of 4° x 5°, with 6 vertical levels. Currently, NOGAPS uses a T159 spectral grid (approximately 80 km resolution) with 24 levels, and uses a 6 hour incremental data assimilation cycle. The increase in model resolution has been attained through a combination of advances in computer technology, implementation of more efficient algorithms, and improved programming practices. The NOGAPS forecast model is run to 7 days at 0000 and 1200 UTC daily using the T159 resolution, and the forecast continues to 10 days at a reduced resolution of T79 (approximately 150 km).

Since 1982, incremental upgrades have been made to NOGAPS, resulting in a steady growth in its forecast accuracy. One of the more uniformly accepted forms of validation used for global models is the 500 mb height anomaly correlation. The annual anomaly correlations for NOGAPS from 1988 through 1997 are shown in Fig. 1. In general, the scores show an increase in skill during this ten year period, with the skill at any given forecast time in 1997 comparable to the skill in 1988 for a forecast time 24 hours earlier. In other words, NOGAPS forecasts have increased in skill by 1 day over the past 10 years. This has also been noted in other measures of skill, such as the root-mean-square error of winds, heights, and temperatures (not shown).

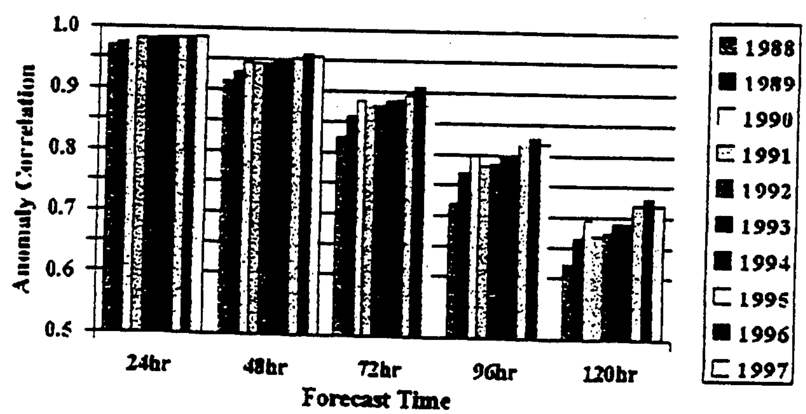

Fig. 1. Global 500 mb height anomaly correlation for NOGAPS 24, 48, 72, 96, and 120 hour forecasts for each year from 1988 through 1997. An anomaly correlation of 1.0 is considered a perfect forecast, and an anomaly correlation of below 0.6 is considered to have no skill.

Another measure of NOGAPS skill is its performance in the prediction of the tracks of tropical cyclones. NOGAPS has been found to be quite accurate for this particular forecast problem even though it uses a relatively coarse resolution compared to other models that are used exclusively for tropical cyclone track prediction. Although NOGAPS cannot resolve the inner eyewall dynamics of a tropical cyclone, it can represent the large-scale flow that plays a major role in the steering of these cyclones. In addition, since NOGAPS is a global model, it does not suffer from the requirement of lateral boundary conditions of regional/mesoscale models. This means that there are no restrictions on the interaction of the tropical cyclone with any surrounding features and there are none of the problems that are typically associated with an over-specification of boundary conditions in regional models.

An example of a NOGAPS forecast for Hurricane Bonnie, which affected the east coast of the U.S. in August 1998, is shown in Fig. 2. This figure shows the NOGAPS 10 m wind analysis at 1200 UTC 25 Aug 1998 and the NOGAPS 48 h forecast 10 m wind field generated from this analysis, valid at 1200 UTC 27 Aug 1998. During this time, Hurricane Bonnie moved generally toward the northwest, making landfall in North Carolina. The official warning position from the National Hurricane Center at 1200 UTC 27 Aug 1999 was 35.0N, 77.1W. NOGAPS 48 h forecast appears to be approximately 50 n. mi. to the southwest of this position based on the streamlines in Fig. 2.

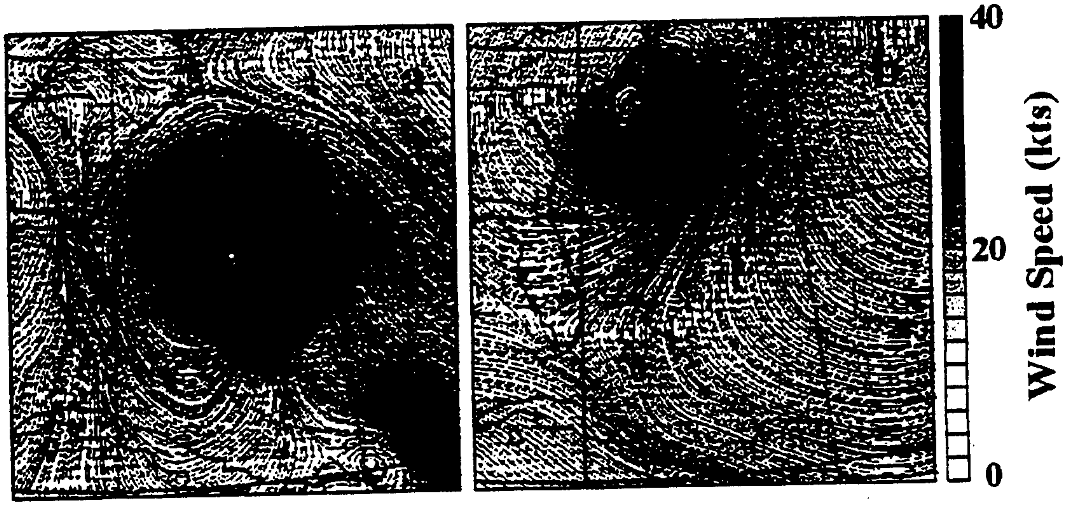

Fig. 2. NOGAPS (a) analyzed and (b) 48 h forecast 10 m winds (streamlines and gray-shaded isotachs) for Hurricane Bonnie. Analysis field is valid at 1200 UTC 25 August 1998 and the forecast field is valid at 1200 UTC 27 August 1998.

COAMPS has been operational at FNMOC since June 1998, and is currently run operationally over three areas. These areas cover the Mediterranean Sea, Southwest Asia, and the east coast of Asia (Fig 3). The Mediterranean and Southwest Asia areas utilize triply-nested grids with resolutions of 81, 27, and 9 km, while the east coast of Asia area utilizes a doubly-nested grid configuration using resolutions of 81 and 27 km. All COAMPS areas use 30 vertical levels. The length of the COAMPS forecast varies based on the area and the nest. The longest forecasts (72 h) are for the Mediterranean 81 and 27 km grids, while the shortest forecasts (all 9 km grids) extend only to 24 h.

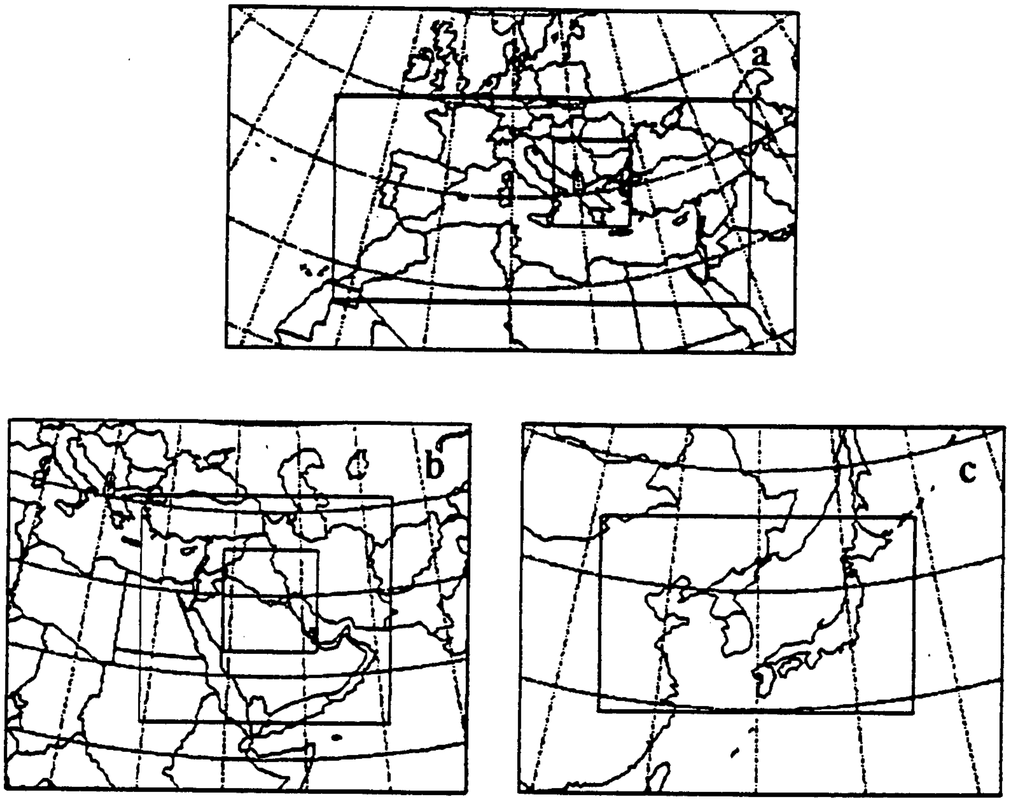

Fig. 3. COAMPS areas run operationally at FNMOC: (a) 81/27/9 km triply-nested grid for Mediterranean, (b) 81-27/9 km triply-nested grid for Southwest Asia, and (c) 81/27 km doubly-nested grid for the east coast of Asia.

The use of high-resolution grids and a detailed description of the earth's topography has been shown to be effective in the prediction of topographically forced mesoscale events. One such example is shown in Fig. 4, which represents a 36 hour COAMPS forecast of the 10 m wind field valid at 0000 UTC 13 October 1998 over the western Mediterranean. This forecast was made by the FNMOC operational Mediterranean area (27 km nest) illustrated above. In this forecast, a strong (40 knot) Mistral is present extending from the southern coast of France to the north coast of Africa. This wind is typically formed through the channeling of northerly winds between the Alps to the east and the Pyrennes to the west. Another smaller local wind maximum, often referred to as the Mestral, extends into the Mediterranean from the Ebro River valley off the northeast coast of Spain. With 27 km resolution, COAMPS is able to resolve many of the local wind patterns that develop in the Mediterranean and other parts of the world. Furthermore, COAMPS shows skill in the temporal and spatial variations of these features.

Fig. 4. COAMPS 36 h forecast of 10 m winds (streamlines and gray-shaded isotachs) valid at 0000 UTC 13 October 1998. Area in display represents only a portion of the full 27-km grid shown in Fig. 2.

The recent development of powerful workstations and high-speed communications has made it possible to utilize COAMPS at remote sites that require the use of mesoscale model output. In addition, these sites may have additional local observations that may provide important additional information for the analysis and/or prediction of the weather in the local region. To support this use, NRL MMD has developed the Tactical Atmospheric Modeling System/Real-Time (TAMS/RT). TAMS/RT combines the COAMPS data assimilation system, a powerful graphical-user-interface (GUI), tactical application programs, and additional analysis tools into a workstation-based system for an analysis/nowcast/short-term (0-36 h) forecast system for remote site users. The version of the COAMPS forecast model is identical for both the FNMOC and the TAMS/RT applications. TAMS/RT is currently undergoing demonstration projects at Navy facilities in San Diego and Bahrain. It is planned for TAMS/RT to be installed at all U. S. Navy regional centers within the next 1-2 years.

4. CONCLUSIONS AND FUTURE PLANS

NRL MMD continues to develop and extend the use of the global and mesoscale modeling systems NOGAPS and COAMPS. Both systems represent complete data assimilation systems to best define the initial conditions for their respective models using all available current data blended with their own background fields, which contain information from previous observations. NOGAPS is used to provide relatively coarse resolution (approximately 80 km) forecasts for the entire globe out to 7-10 days. Statistics demonstrate that this system is among the best global data assimilation systems in the world for 0-10 day predictions of transient weather systems, and is particularly useful for the prediction of the track of tropical cyclones.

COAMPS is used as a globally relocatable data assimilation system for the prediction of mesoscale events that require higher resolution than can currently be attained by NOGAPS. The COAMPS analyses/forecasts can be made either at FNMOC or at a remote site. In the latter case, the TAMS/RT system is used, utilizing powerful workstations. NOGAPS and COAMPS are used in a synergistic manner to yield the most timely and accurate forecasts possible for any given area of the world. The systems are intrinsically tied through the use of NOGAPS fields on the lateral boundaries of all COAMPS areas.

Significant improvements are planned for NOGAPS and COAMPS. First, a 3-dimensional variational analysis (3D VAR) is being developed. The 3D VAR will enable a more optimal fit of the data and the background field. This analysis tool will replace the current MVOI analysis in both NOGAPS and COAMPS. Both NOGAPS and COAMPS are being recoded for use on distributed memory computers. Several modifications are being developed and tested specifically for NOGAPS. These include the inclusion of semi-Lagrangian advection, to allow for more accurate prediction of moisture and a larger time step; the development of differentiable physical parameterizations, which will allow for an improved coupling of the model with the analysis; and coupling the NOGAPS model with an ice and ocean model. Other modifications are now being developed and tested for COAMPS. These include the addition of an improved surface parameters database; an improved soil model, testing the effects of coupling to a 3-dimensional ocean model; and the inclusion of aerosol analysis, initialization, and prediction components. These improvements will be included in both the FNMOC and TAMS/RT applications of COAMPS.

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