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Review of Operational Multi-Scale Environment Model with Grid Adaptivity

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A new numerical weather prediction and dispersion model, the Operational Multi-scale Environment model with Grid Adaptivity (OMEGA) including an embedded Atmospheric Dispersion Model (ADM), is introduced as a next generation atmospheric simulation system for real-time hazard predictions, such as severe weather or the transport of hazardous releases. OMEGA is based on an unstructured grid that can facilitate a continuously varying horizontal grid resolution ranging from 100 km down to 1 km and a vertical resolution from 20 - 30 meters in the boundary layer to 1 km in the free atmosphere. OMEGA is also naturally scale spanning because its unstructured grid permits the addition of grid elements at any point in space and time. In particular, the unstructured grid cells in the horizontal dimension can increase the local resolution to better capture the topography or important physical features of the atmospheric circulation and cloud dynamics. This means that OMEGA can readily adapt its grid to a stationary surface, terrain features, or dynamic features in an evolving weather pattern. While adaptive numerical techniques have yet to be extensively applied in atmospheric models, the OMEGA model is the first to exploit the adaptive nature of an unstructured gridding technique for atmospheric simulation and real-time hazard prediction. The purpose of this paper is to provide a detailed description of the OMEGA model, the OMEGA *system*, and an detailed comparison of OMEGA forecast results with observed data.

Key words : numerical weather model, atmospheric dispersion, grid adaptivity

1. Introduction

Over the past forty years, numerical weather prediction has undergone tremendous advances. The 1960s saw the initial success of the barotropic model, whereas the 1970s included the introduction of the baroclinic model, the university-developed Regional Atmospheric Modeling System, RAMS[1], and the Penn State/NCAR Mesoscale Model now in its fifth version, MM5[2]. The increased computational power of the 1980s enabled the introduction of more elaborate model physics, whereas the mesoscale models of the 1990s pushed toward finer and finer resolutions, mostly through the use of nested grids[3] or variable horizontal resolution[4]. At the same time meteorology has benefited from this research and technology boom, for example, researchers in the field of computational fluid dynamics(CFD) created new innovative numerical techniques designed to model fluid flows around complex boundaries. Thereafter, in the 1970s and early 1980s, models developed for use in aerospace engineering and plasma physics were surprisingly similar to those developed in the field of atmospheric science. The grids were composed of regular, rectangular cells extending from no-slip or free-slip surfaces. Meanwhile, with the availability of more computational power and the inclusion of more physics in atmospheric models, CFD researchers have since focused on refining complex gridding techniques around irregular surfaces.

Current operational atmospheric simulation systems (Hoke, et al., 1989; Janjic, 1990; Mesinger, et al., 1988) use fixed grid spacing or rely on nesting to achieve a cascade of scales[5~7]. The secret to using these models in a forecasting mode is to place the nest over all areas of concern and to do so within economical and computational limits. However, even with recent advances in computational power[8)], the architecture and physics of today's generation of atmospheric models still cannot fully simulate the scale interaction of the atmosphere. Although several groups have developed non-hydrostatic, nested (multiply nested in some cases) atmospheric models[9,10)], these represent an incremental evolutionary path in atmospheric simulation; as long as the same basic physics is solved, with roughly the same order of accuracy and same grid resolution, the computational performance of different simulation systems must be roughly the same.

For the reasons given above, it is impossible to change the basic performance of an atmospheric simulation system without changing the basic paradigms utilized. In contrast, OMEGA advances the current capability of numerical weather prediction(NWP) through the application of advanced numerical methods, including a dynamically adapting triangular prism computational mesh. In addition, it advances dispersion modeling by embedding a dispersion calculation within the NWP model, thereby providing access to the full resolution of the atmospheric simulation at every timestep.

2. What is OMEGA?.

OMEGA is a multiscale, non-hydrostatic atmospheric simulation model with an adaptive grid that permits spatial resolution ranging from roughly 100 km to less than 1 km without the need for nested grids.

The Operational Multiscale Environmental Model with Grid Adaptivity(OMEGA) was originally developed to link the new gridding technologies of computational fluid dynamics with state-of-the-art numerical weather prediction. OMEGA has been running in an operational mode at several sites for the past three years, plus it has also performed well in field experiments. OMEGA was designed as a multiscale simulation tool that can simulate fine scale flows without the need for multiple nested grids. It was also built to address atmospheric transport and diffusion applications. Therefore, to improve the accuracy of hazardous dispersion models, it is essential that the meteorological forecast itself be improved. This is because the modeling of atmospheric dispersion involves virtually all scales of atmospheric motion from microscale turbulence to planetary scale waves.

3. Structure of OMEGA System

The OMEGA modeling system(see Fig.1) is an operational real-time meteorological forecasting and atmospheric dispersion system. The OMEGA system consists of ; 1) Routines to maintain and manage real-time weather data feeds from the National Oceanic and Atmospheric Administration (NOAA), National Centers for Environmental Prediction(NCEP), and/or the US Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC) ; 2) World-wide datasets for surface elevation, land/water, vegetation coverage, soil-type, land use, deep soil temperature, deep soil moisture, and sea surface temperature at varying resolutions ; 3) An integrated Graphical User Interface(XOMEGA) that provides a user-friendly method for rapid model re-configuration ; 4) The OMEGA Grid Generator that can access the surface datasets and create OMEGA grid and terrain files ; 5) A meteorological data pre-processor that can ingest gridded terrain, gridded meteorological analyses and forecasts, and raw observations and perform a detailed Quality Control of the ingested data, followed by an Optimum Interpolation data

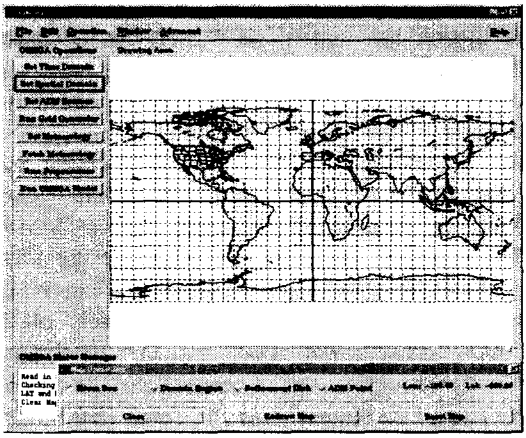

Fig. 1. XOMEGA, the OMEGA GUI.

assimilation to produce initial and boundary conditions for OMEGA ; 6) The OMEGA atmospheric simulation model and its embedded Atmospheric Dispersion Model(ADM) ; 7) The OMEGA graphical post-processing tool(XGRID) that enables the user to display the OMEGA output as two-dimensional slices(horizontal slices overlaid on mapping information from a Digital Chart of the World or vertical slices), skewT-logP profiles for any location, and animations ; 8) Additional post-processors to provide for data extraction and re-formatting for external applications.

OMEGA is a fully non-hydrostatic, three-dimensional prognostic model. It is based on an adaptive, unstructured triangular prism grid that is referenced to a rotating Cartesian coordinate system. The model uses a finite-volume flux-based numerical advection algorithm derived from Smolarkiewicz(1984). OMEGA also includes a detailed physical model for the planetary boundary layer(PBL) with a 2.5 level Mellor and Yamada (1974) closure scheme. OMEGA uses a modified Kuo scheme to parameterize cumulus effects(Kuo, 1965; Anthes, 1977), and an extensive bulk-water microphysics package derived from Lin et al. (1983). OMEGA models shortwave absorption by water vapor and longwave emissivities of water vapor and carbon dioxide using the computationally efficient technique of Sasamori(1972). OMEGA uses an Optimum Interpolation analysis scheme (Daley, 1991) to create initial and boundary conditions and supports piecewise four-dimensional data assimilation using a previous forecast as the first guess for a new analysis. Finally, OMEGA contains both Eulerian(grid based) and Lagrangian (grid free) dispersion models embedded into the model.

4. Evaluation of OMEGA using Orographic Precipitation and Tornado

Fig. 2 shows the results of a case study of an orographically driven snowstorm in the Black Hills of South Dakota using OMEGA. The OMEGA simulation accurately predicted both the synoptic conditions and the fine scale terrain driven snowfall. Figs. 2a and 2b show an intercomparison between OMEGA and the observed precipitation, respectively. Six sites(H1, H2, H3, H4, H5, and H6) were selected for the intercomparison in Fig. 2b. The simulated precipitation corresponding to the 6 sites was 25.3, 20.1, 12.5, 12.2, 9.9, and 13.5 mm, respectively. The observed precipitation at the six sites was 24.41, 13.97, 14.78, 11.0, 22.7, and 10.97 mm, respectively. Accordingly, there was a good agreement as regards the precipitation predicted by OMEGA and the observed values.

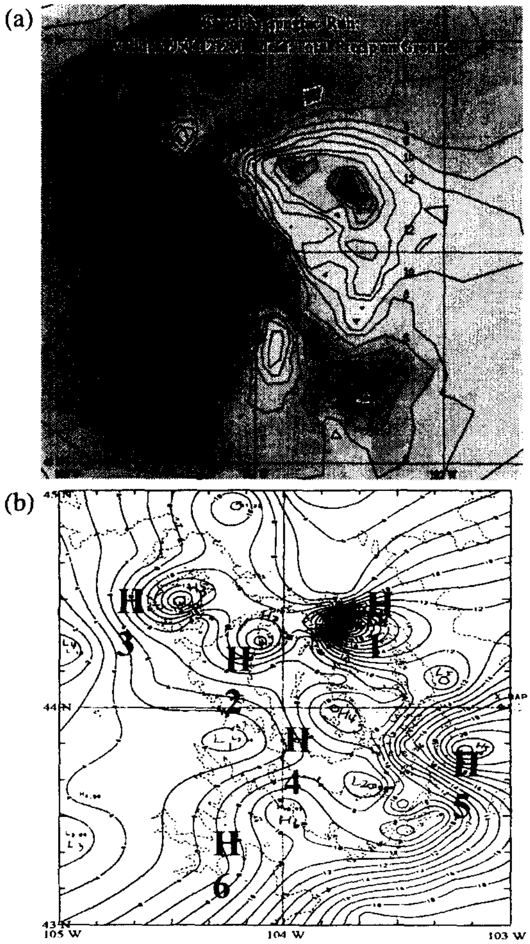

Fig. 2. Evaluation of precipitation predicted by OMEGA. (a) and (b) show the OMEGA result and observational data, respectively. Both are in good agreement with each other.

Fig. 3 shows the track forecast of typhoon Xangsane, which passed Taiwan island on Nov. 1st, 2000, using OMEGA. The OMEGA straight forecast exhibited an excellent agreement with observations obtained after the event. The root-mean-square error in the OMEGA forecasted track was 54 km after 24 hours, 64 km after 48 hours, and 71 km after 72 hours. However, after 62 hours, the OMEGA forecasted track took a marked turn to the East, away from the observed track. The root-mean-square error in the GFDL(Geographical Fluid Dynamic Laboratory) forecasted track after 24 hours, 48 hours, and 72 hours was 130 km, 220km, and 330km, respectively. Considering the track errors, OMEGA produced a better track-forecasting performance.

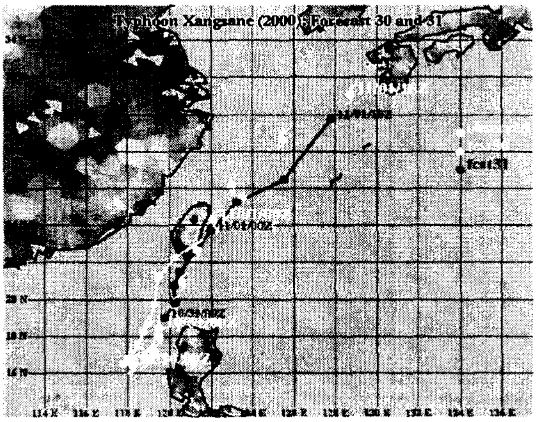

Fig. 3. Track of typhoon Xangsane forecasted by OMEGA. The yellow and red tracks are the forecasted tracks for 42 hours starting from Nov. 30 and 31, respectively. The track predicted by OMEGA was the best track of the typhoon.

5. Applications of OMEGA in Korean Peninsula

The meteorology of Korea is extremely complex especially given the terrain in the Eastern part of the country plus the interaction of the large scale synoptic forced by the sea-land breeze from the East, West, and South Seas in relation to the complicated topography. As a result, forecasting weather and the dispersion of effluents causing air pollution and smog or hazardous airborne material is extremely difficult.

Fig. 4 shows the dispersion of two plumes over a period of 48 hours - one from Seoul(yellow color) and the other from Pusan(red color). The wind vectors are displayed on the surface. Note that the wind directions were sensitive to elevated terrain around mountain areas.

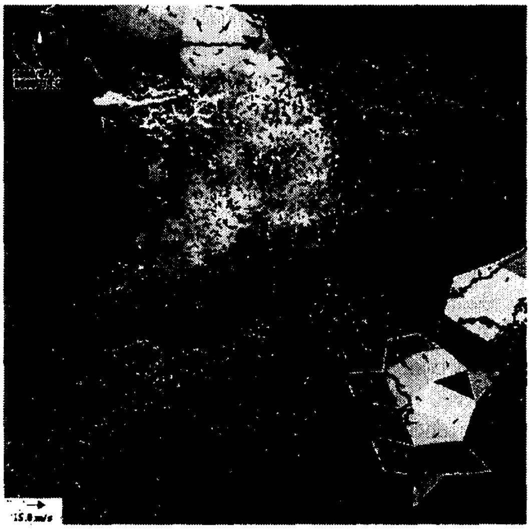

Fig. 4. Simulation of dispersion around Korean peninsula using OMEGA. The yellow and red colored particles were released from Seoul and Pusan 24 hours previously, respectively. The arrow indicates the surface wind field simulated by OMEGA.

Figs. 5a and 5b show an example of a downscale run in a domain without nesting, as in the case of MM5. In contrast, OMEGA does not have an extra internal boundary problem because of its multi scale grid structure. Fig. 5a shows the structure of the grid around the Pusan area as an example of downscaling, whereas Fig 5b shows the simulated wind field on the grid structure of Fig.5. Note that the Nakdong river can also be configured in the simulation.

6. Summary

The OMEGA modeling system represents a significant departure from the traditional methods used in numerical weather prediction and real-time hazard prediction. For the first time in recent years, advanced numerical and grid generation methods developed by researchers in the field of computational fluid dynamics have been successfully applied to the problem of atmospheric simulation. Accordingly, this has permitted the development of an extremely high resolution and flexible operational atmospheric simulation system.

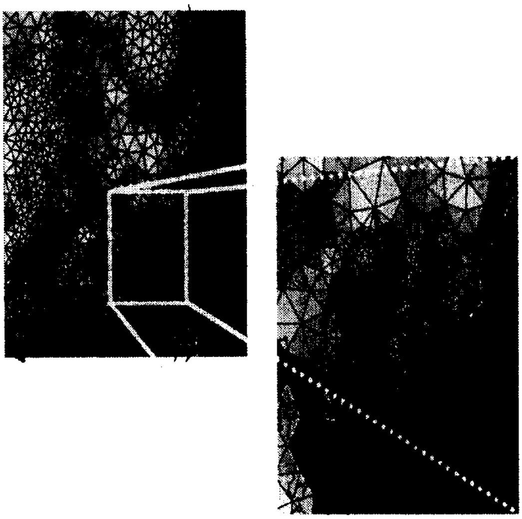

Fig. 5a. Structure of grid around Pusan region as example of downscaling. OMEGA can ingest a fine mesh into a coarse domain without nesting. OMEGA can also configure the Nakdong river, as show in the amplified figure (right side).

Fig. 5b. Simulated surface wind field on grid structure of Fig. 5a. The yellow region indicates a mountain area with an altitude of about 500m. Note that the surface wind field around the Nakdong river, mountain region, and coastal region shows a variety of flows.

The current article presented a variety of case studies using OMEGA to provide additional validation of the model as well as demonstrate in more depth the flexibility and power of unstructured static and dynamically adapting grids.

At this point, the OMEGA model and its Atmospheric Dispersion Model(ADM) would appear to be the only operational atmospheric flow system based on an unstructured grid technique, which can fully exploit the advantages and flexibility of unstructured grids. It can adapt its grid both statically and dynamically to different criteria, such as fronts, clouds, hurricanes, and plumes, etc. For real-time flow predictions, given the constraints of CPU, the capability of grid adaptivity is very important. This capability is also crucial in responding to emergency scenarios, such as the release of hazardous materials. OMEGA with its grid adaptation capability has a unique advantage over other atmospheric flow models as it can provide accurate solutions quickly in an operational setting.

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