Global to Local Weather Forecasting Using an Adaptive Unstructured Grid Model

(*NOAA Grant #NA04OAR4310102*)

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1. Introduction

Weather is the result of air motion and physical processes involving a variety of scales from the global to the local. The atmospheric system starts with the weak (0.001 mb/km), but persistent forcing caused by the heating differential between the polar and equatorial regions, and by the day and night time regions of the Earth. The mesoscale forcing caused by the differential heating due to differences in surface properties (*e.g.* albedo, heat capacity, thermal conductivity) lead to the meso-α (0.01 mb/km), meso-β (0.10 mb/km) and meso-γ (1.0 mb/km) forcing. Orographic forcing is important in complex terrain and can equal the meso-γ forcing (1.0 mb/km); the thermal forcing due to a sea-land boundary can be similar in scale. These forcings have a direct impact on the weather. For example, orography plays an important part in shaping the weather in a region (Smith, 1979; Barros and Kuligowski, 1998). It is well known that mountain ranges increase precipitation on the upwind side by mechanically lifting moist air (Bonacina, 1945), while the downwind regions receive much lower precipitation. Mountains and other significant terrain features also divert low-level winds and produce thermally driven circulations such as density currents (Scorer, 1949) and hence affect the distribution of water vapor and precipitation over the region (Banta, 1990). Major mountain ranges have direct influence on the large-scale weather systems with obvious impacts on the precipitation patterns (Seluchi *et al.*, 1998).

The simulation or forecasting of the atmospheric system must therefore be able to span a set of spatial and temporal scales that ranges over three orders of magnitude (1000 to 1 km; 100 to 0.1 hr). The current paradigm of using either flat spectral models or nested grid point models is not geared to considering the myriad of up and down scale interactions in a self-consistent manner. To move from 3-5 day forecasts with skill to 14 days will require a change in the operational paradigm. One commonly proposed change is the use of ensemble or probabilistic forecasting to attempt to quantify the uncertainty in the forecasted state (Sivillo *et al.*, 1997). This, however, ignores the fact that some physical forcings – especially those that are linked to the terrain – are fixed and knowable. A complementary approach is to incorporate as much of the fixed surface information as possible into our forecasting systems. The span of scales involved, however, makes this approach impossible unless a different paradigm is used for the numerical mesh. This is the approach used in the Operational Multiscale Environment model with Grid Adaptivity (OMEGA) (Bacon *et al.*, 2000).

OMEGA represents a different approach to atmospheric simulation – the use of an adaptive unstructured grid forecast system. This system has three primary advantages. The first is that the unstructured triangular grid can simulate coastlines and orographic features without the “stair-step” geometry required of nested rectilinear grid models and its resultant impact on dynamics (*cf.*, Zhang *et al.*, 1999). Second, the unstructured grid permits a range of scales to be modeled with full scale-interaction over the domain and without the wave-reflecting internal boundaries of traditional nested grid models. Third, adding dynamic adaptation allows the system to maintain high resolution over regions of interest automatically, providing computational efficiency and leading to potentially better forecasts. This project is intended to demonstration the benefit of using a global to local scale adaptive unstructured grid NWP model as a different and complementary paradigm to ensemble forecasting to increase *high impact weather forecast* accuracy, which is a fundamental goal of the THORPEX program (Shapiro and Thorpe, 2004).

2. Two Paradigms

The official goal of the THORPEX program is to *improve high impact weather* (Shapiro and Thorpe, 2004); before we can meet this goal, however, we have to decide on the meaning of "high impact". In many cases, the key factor is precipitation, which can weaken the soil leading to landslides, or overcome the ability of a watershed to direct the runoff to the sea leading to flooding. Alternatively, severe wind storms may play a significant role in some areas leading to the destruction of structures and/or infrastructure. Tropical and/or extra-tropical cyclones represent one of the worst *high impact* features since they combine elements of both precipitation and wind loading.

The current paradigm of using either spectral models or nested grid point models is not geared to considering the myriad of up and down scale interactions in a self-consistent manner. In addition, to move from 3-5 day forecasts with skill to 14 days will require a change in the operational paradigm. One commonly proposed change is the use of ensemble or probabilistic forecasting to attempt to quantify the uncertainty in the forecasted state (Sivillo *et al.*, 1997). This, however, ignores the fact that many physical forcings are linked to the terrain, which is known and immovable. The use of coarse resolution ensemble forecasts in cases where the local terrain forcing is important is therefore inappropriate.

NWP is basically a set of partial differential equations (PDEs) whose solution is dependent on the terms of the equations (physics), the initial conditions (analysis), and the boundary conditions (lateral forecasts, if applicable, and the surface properties). While grid resolution is an important part of the solution of the PDEs, recognition of the importance of the initial conditions on the forecasts led to the development of *ensemble prediction systems* such as the NCEP Ensemble Forecast System (EFS) (Sivillo *et al*., 1997). The rationale for ensemble forecasting was expressed by Leith (1974) – "*If the initial state were [sic] known exactly and if the model exactly simulated the atmosphere, then the computed phase path would provide an exact forecast. But neither assumption is valid.*" Ensemble systems perturb the initial conditions of the model to explore the potential range of variability in the final forecast given the known (and unknown) uncertainty in the initial state of the atmosphere. However, the "*ensemble strategy will work only if the models are good enough that model-related errors do not dominate the final error fields*" (Toth, *et al.,* 1997). While this is often the case in forecasting large-scale weather patterns, the scale interactions discussed above lead to many features having a strong small-scale forcing, which means that the Toth criterion is violated.

The problem with missing physics in operational ensemble forecasting is due to the need to work within a timeline. In order to generate many ensemble elements during one forecast cycle, the resolution of each element of the ensemble must be degraded. This means that the PDEs are solved using a lower resolution grid, which in turns limits the physical processes that can be treated in a self-consistent and accurate manner. Normally this is at least heuristically recognized by having the full-resolution deterministic run included in the ensemble. If a critical factor in the forecast is not resolved in the deterministic run, however, then there is ***no*** element of the ensemble to provide guidance. This is often the case in terrain-forced situations. (As an aside, the prevalence for *multi-model ensembles* would seem to *a priori* violate the Toth criteria as it indicates that the *physics* is uncertain and hence that model-related errors *do dominate* the final forecast error fields.)

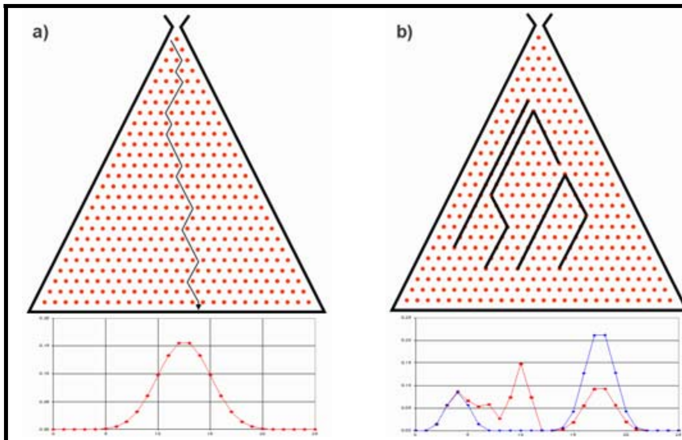

Figure 1. A Pachinko machine can serve as an ansatz for ensemble forecasting. The path of the ball is subject to the small variability in the input conditions. In the ideal case, however, (a) the probability distribution of balls after many trials is the Poisson distribution shown (red curve). On the other hand, if the Pachinko machine has internal baffles, then (b) the probability distribution (red curve) will be influenced by the "complex terrain" of the baffles. If the resolution of the underlying terrain is reduced by half, however, the predicted distribution (blue curve) cannot recapture the correct distribution no matter how many trials occur.

An ansatz for this situation can be constructed using a Pachinko machine (Figure 1). These games involve dropping a large number of balls (ensemble elements) through a maze of pins (decision points). In the ideal case, the result is a binomial distribution of balls. An ensemble forecast of this situation *with sufficient resolution* will reproduce this distribution (Figure 1a). In the case of "complex terrain" or the introduction of interior baffles (Figure 1b), however, the situation is different. In this case, if the ensemble elements do not have sufficient resolution to resolve the critical terrain forcing (the "valley" flow), then an incorrect distribution of solutions is computed. It is important to note that in this case, *an increase in the number of ensemble members will **not** increase the accuracy of the solution*. The limiting factor in this case is the fact that ***each*** of the ensemble members is missing critical physics – a direct violation of the Toth criteria.

A complementary approach is to incorporate as much of the fixed surface information as possible into our forecasting systems. The span of scales involved, however, makes this approach impossible unless a different paradigm is used for the numerical mesh, such as the adaptive unstructured mesh used in OMEGA. This approach, used in OMEGA, optimizes the resolution of critical terrain forced features that are **known** to influence high impact weather situations. This approach has three primary advantages. The first is that the unstructured triangular grid can simulate coastlines and orographic features without the "stair-step" geometry required of nested rectilinear grid models and its resultant impact on dynamics (*cf.*, Zhang *et al.*, 1999). Second, the unstructured grid permits a range of scales to be modeled with full scale-interaction over the domain and without the wave-reflecting internal boundaries of traditional nested grid models. Third, adding dynamic adaptation allows the system to maintain high resolution over regions of interest automatically, providing computational efficiency and leading to potentially better forecasts.

3. Progress

Administrative issues prevented this award from being completed until the end of September / the beginning of October, 2004. The three (3) questions being considered in this first funding period are:

(1) Does an unstructured grid provide a better representation of complex terrain and complex land-water boundaries by virtue of the fact that the grid elements are not aligned North-South and East-West?

(2) Does the irregular grid create issues such as the wave reflection common in nested grid models?

(3) Is the unstructured grid more efficient in the computational sense than nested or multi-grid methods?

Our first task was to identify the period(s) of interest for the numerical experiments. The First THORPEX International Science Symposium in December, 2004 was a good step towards finalizing this important decision. Several papers were presented documenting the spectrum of *high impact* weather phenomena. We are currently in the process of collecting data from the various periods of interest and will make the final determination once we have an assessment of the data available.

Our plan remains to perform a series of numerical experiments each lasing one-month. First two (2) baseline simulations will be performed, one for each 15-day half of the 1-month period. These simulations will use a grid with uniform resolution (~100 km edge lengths yielding an effective square-equivalent resolution of 70 km). A new set of grids will then be generated using the OMEGA grid generator to adapt to high-resolution terrain data. The minimum edge lengths will be reduced from 100 to 60, and then to 40 km. The first demonstration of this concept is shown in Figure 2, in which the results from a global simulation using OMEGA are compared with satellite observations. These results (24-hour forecast) show that OMEGA was able to correctly capture all of the major weather systems as indicated by the cloud distribution.

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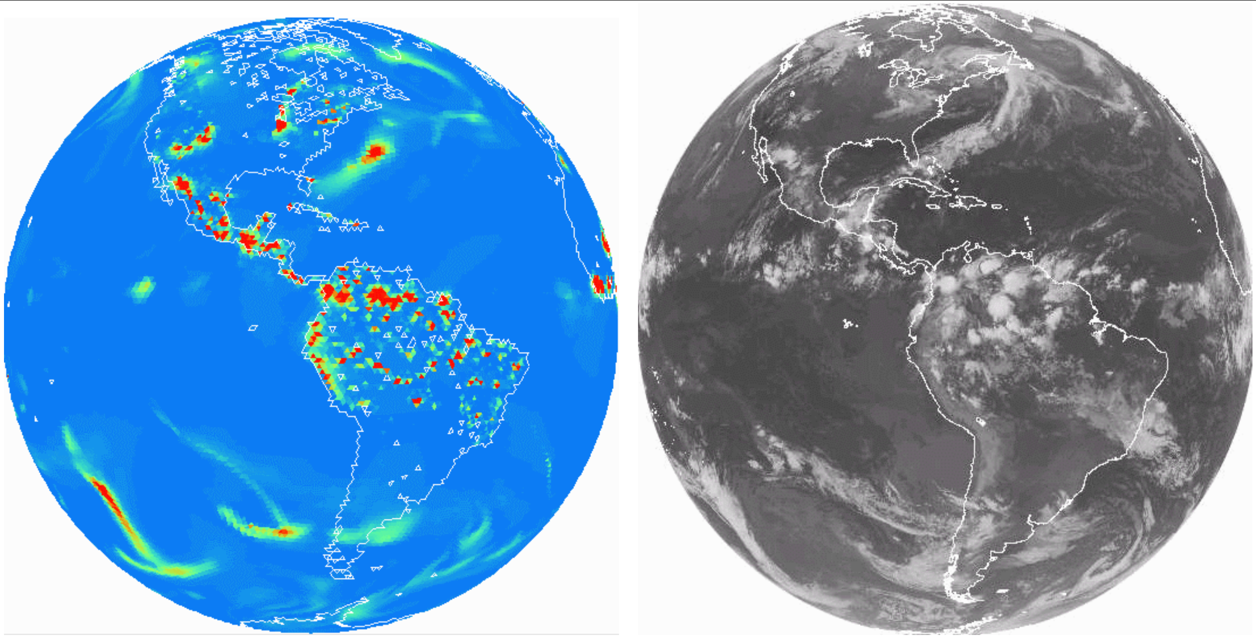

Figure 2. A global 24-hour demonstration forecast run with OMEGA. This simulation used a relatively uniform roughly 100km grid. The simulation is on the left with the verification satellite image on the right.

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