Unstructured Adaptive Grid Generation for Geophysical Flow Simulations

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Abstract

This paper describes an adaptive, unstructured mesh generator, which can be used for discretizing regional and global domains for geophysical flow simulations in general, and atmospheric flow simulations in particular. The global mesh generator is a part of the Operational Multiscale Environmental model with Grid Adaptivity (OMEGA) System. For a physically complex and computationally intensive atmospheric flow simulation, such as real-time hurricane prediction, the optimization afforded by unstructured adaptive grids is demonstrated.

Introduction

Physical phenomena occurring in the atmosphere are complex and span a multitude of scales in space and time. The challenge for atmospheric modelers has been to account for this variation in spatial and temporal scales. The conventional atmospheric flow and dispersion models are based on structured grids. For simulations on the synoptic scale, atmospheric modelers face the usual computational constraints as well as difficulties due to the polar singularities. Operational models currently in use are approaching a horizontal resolution of 1° (approximately 110 km near the equator). This is true for the U. S. Navy's NOGAPS and the National Center for Environmental Prediction's MRF model. While these models are able to predict the synoptic scale flows with a good degree of accuracy, they can fail to resolve phenomena occurring at much smaller scales (*e.g.*, the development and trajectories of hurricanes). Whereas the adaptive meshing techniques have found extensive usage in aerodynamics and aerospace-related applications (*e.g.*, Löhner [1]), their use in the atmospheric sciences has been limited. On structured grids, Russell [2] has developed an adaptive and boundary conforming grid generation scheme for use in coupled, atmosphere-ocean general circulation models. The methodology looks promising in providing a high mesh resolution along the coastlines. The OMEGA model (Bacon, *et al.* [3]) is the only operational atmospheric and dispersion model, which uses unstructured adaptive grids to resolve flows on multiple scales. By using an unstructured grid methodology, variable resolution can be applied where needed in a computationally efficient manner. The grid generation process is also easy to automate, with minimal user interaction. Solution-adaptive techniques are also relatively easy to implement. For example, Ahmad, *et al.* [4] have shown considerable speed up (over 40%) and Sarma, *et al.* [5] have demonstrated marked improvement in solution accuracy by using dynamic grid adaptation for predicting chemical plume concentrations.

Grid Generation

The latest version of OMEGA has the capability of generating global grids as well as grids for regional scale simulations. The global grid generator provides the capability to generate initial static grids adapted to terrain gradients and land/water boundaries. The global grid generator can also refine or coarsen the grid dynamically to simulate the evolution of scale-spanning phenomena that occur in the atmosphere. Thus, global to local scale simulations can be accomplished by providing high grid resolution only where needed (*e.g.*, frontal activity, hurricane development, shoreline). In addition, the problem of polar singularities that is usually faced by modelers using structured meshes is also eliminated.

Initial Triangulation: In the initial triangulation, an icosahedron is created with 12 nodes, 20 cells/elements and 30 edges, using the algorithm described in Table 1 (Ammeraal [6]).

node i	x(i)	y(i)	z(i)
1	0	0	0.5×sqrt(5.0)
2, 3, 4, 5, 6	cos{(i-2)×2×π/5}	sin{(i-2)×2×π/5}	0.5
7, 8, 9, 10, 11	cos{π/5+(i-7)×2×π/5}	sin{π/5+(i-7)×2×π/5}	-0.5
12	0	0	-0.5×sqrt(5.0)

Table 1: Algorithm for generating icosahedra. For each node *i* of the icosahedra, its coordinates *x*, *y* and *z* can be calculated using the above relations.

Each face of the icosahedron is then subdivided into four triangles (see Figure 1) by inserting a node at the edge midpoint of each triangle. The midpoints are then connected to form four triangles. As the new triangles are created, all the mesh data structures are updated. These data structures include cell-based and edge- based connectivity arrays. The refinement iterations are repeated until the desired resolution for the initial mesh is achieved. Six iterations result in a mesh with 81,920 cells, with a maximum edge length of 131 km and a minimum edge length of 110 km. A mesh of this resolution is considered sufficient to resolve synoptic/global scale circulations, *e.g.*, NOGAPS model is currently running operationally with a 1° resolution.

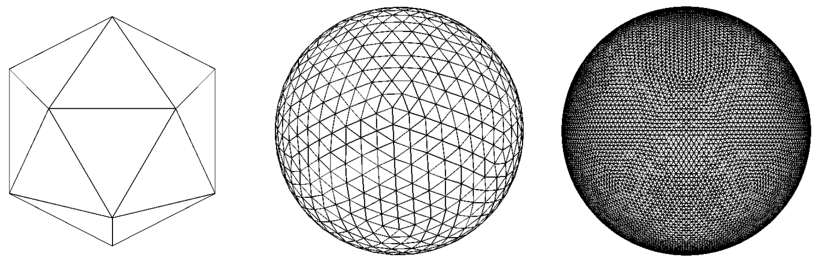

Figure 1: Initial triangulation (left), mesh after three refinement cycles (middle) and after five refinement cycles (right).

After the initial triangulation is achieved, the mesh goes through a process of adaptive refinement. Any set of criteria can be defined for refinement and coarsening cycles.

Cell/Element Trisection: A node is added in the center of the triangle resulting in two extra triangles. Trisection usually results in concave (obtuse) triangles, which need to be corrected using edge swapping. Trisection is followed by the reconnection (*i.e.*, edge swapping) process.

Edge Bisection: Edge bisection during the refinement process is mostly used on constrained boundaries. If a boundary cell is tagged for refinement then the edge on the boundary is bisected. The newly inserted node is relaxed if one of the resulting triangles has poor aspect ratio.

Node Relaxation: Relaxation is a simple smoothing process. In a loop over all nodes, surrounding nodes are stored in an array. The x, y, and z coordinates are averaged and this average is assigned to the node being relaxed. This process moves the node to the center of the polygon created by its neighboring nodes.

Reconnection/Edge Swapping: The reconnection step is carried out to eliminate any concave triangles created after trisection. The angles are calculated, and in case of obtuse/concave triangles, edges are swapped to eliminate these triangles.

Mesh Adaptation: Refinement and coarsening are based on a set of criteria, which are cast in the form of a weight function.

Refinement Criteria:

1. Cells on land/water boundary.
2. Cells in regions of steep terrain gradients.
3. If the neighboring cells are too small.

Coarsening Criteria:

1. Cells with bad aspect ratios.
2. Cells in regions of relatively flat terrain.

3. Land cells surrounded by land cells or water cells surrounded by water cells.

In addition, criteria based on physical quantities or their gradients can be specified to refine or coarsen the mesh during the simulation. Figures 2 and 3 show the mesh after completion of the adaptive refinement process. The resulting mesh has a minimum edge length of 15 km and 109,332 cells. The shoreline and the initial position of a hurricane were set as the refinement criteria in this case.

Surface Characteristics Databases: The grid generator accesses high-resolution terrain, shoreline and other surface characteristics databases during the mesh generation process. These databases are included in the OMEGA system and some are listed in Table 2.

Earth	
Terrain	5 arc minute resolution CIA and 30 arc second resolution USGS datasets
Shoreline	10 arc minute resolution CIA and 30 arc second resolution NIMA datasets
Landuse	30 arc second resolution USGS data
Vegetation	2 arc minute resolution USGS data
Soil Type	1 degree resolution GED data
Subsoil Moisture	30 arc minute resolution GED data
Mars	
Terrain	1 degree and 0.5 degree resolution MOLA datasets

Table 2: Terrain and surface characteristics datasets for Earth and Mars used by the OMEGA grid generator.

At mesh refinement iteration, the terrain and shoreline databases are accessed to assign values for the new nodes and cells. The surface characteristics datasets are used at the end of grid generation to assign values to each cell.

Vertical Grid: After the surface triangulation has been completed a structured grid in the vertical is generated (Figure 4) by extending radials through each vertex. The vertical grid has fine resolution close to the surface to resolve the atmospheric boundary layer. The user specifies the height of the first level, a stretch ratio and the total number of vertical levels. The vertical grid is terrain following near the surface but has a constant altitude (MSL) at the top of the computational domain.

The mesh generator calculations are performed in 3D on Cartesian co-ordinates. The mesh co-ordinates are converted to spherical co-ordinates (latitude-longitude space) at the time of output. The OMEGA grid generator has also been used to discretize the Martian surface (Figure 5) and the model has been

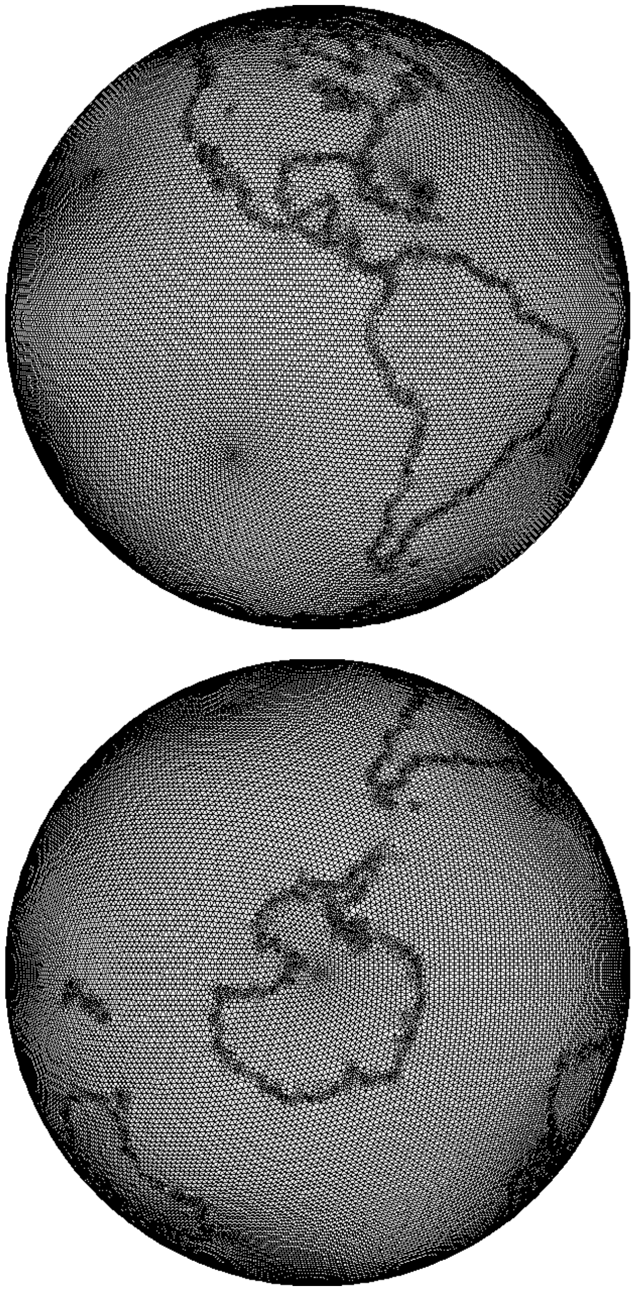

Figure 2: The Americas (top) and the Antarctica (bottom).

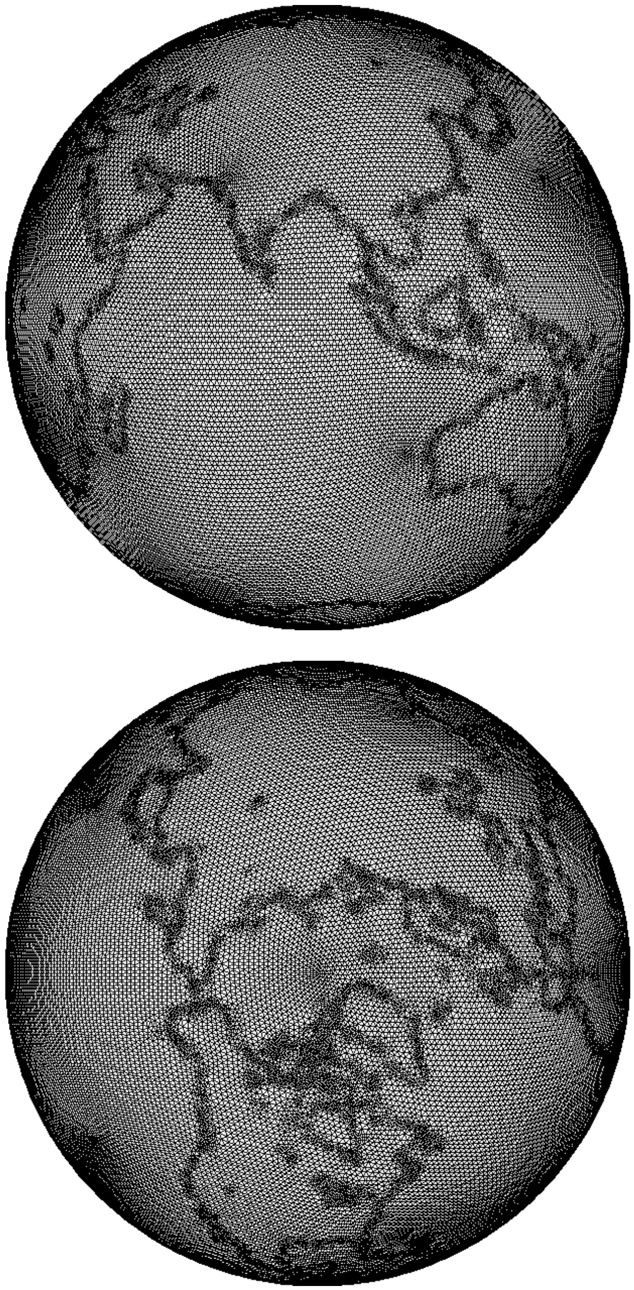

Figure 3: The Eastern Hemisphere (top) and the Arctic (bottom).

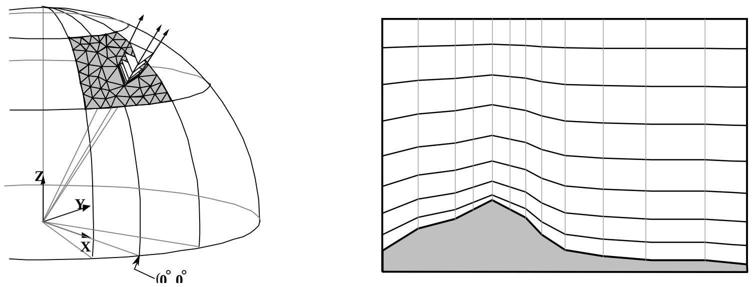

Figure 4: The vertical levels of the OMEGA grid are constructed by extending radials through each surface vertex. A set of stretchable layers follow the terrain near the surface and relax to a surface that is parallel to the reference sphere at the top of the grid.

used to study the Martian atmosphere. The Martian terrain is characterized by extremely steep gradients. For example, the volcanoes can reach an altitude of 29 km, while the canyons can extend over 5000 km long. Thus, any simulation of the Martian atmosphere or an accurate prediction of the Martian weather (*e.g.,* to support future missions to Mars) requires a detailed representation of the terrain.

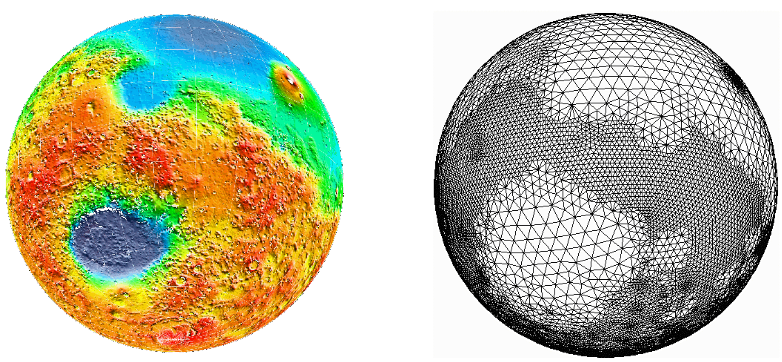

Figure 5: MOLA terrain data (left), and the OMEGA adaptive grid (right).

Prediction of Hurricane Tracks

Every year the eastern and southern seaboards of the United States are at risk of being struck by hurricanes. These hurricanes develop at low latitudes over the mid-Atlantic or the Gulf of Mexico due to the seasonal heating of the oceans and are subsequently steered by synoptic scale flows towards the eastern and southern coasts of the United States. An accurate real-time hurricane intensity and track prediction is required for emergency-response decision-making. There are many factors that can influence the accurate prediction of a hurricane by model simulation (Gopalakrishnan, *et al.* [7]), *e.g.,* initial position of the hurricane, sea surface temperature and mesh resolution in the region of hurricane. Gopalakrishnan, *et al.*, showed that a simulated hurricane could lose its intensity, and eventually dissipate if the grid is not refined to a high resolution (on the order of 10 km). The high grid resolution is required in order to maintain the structure of the hurricane core and also to predict the landfall accurately. Figure 6 shows the advantage of using adaptive grids.

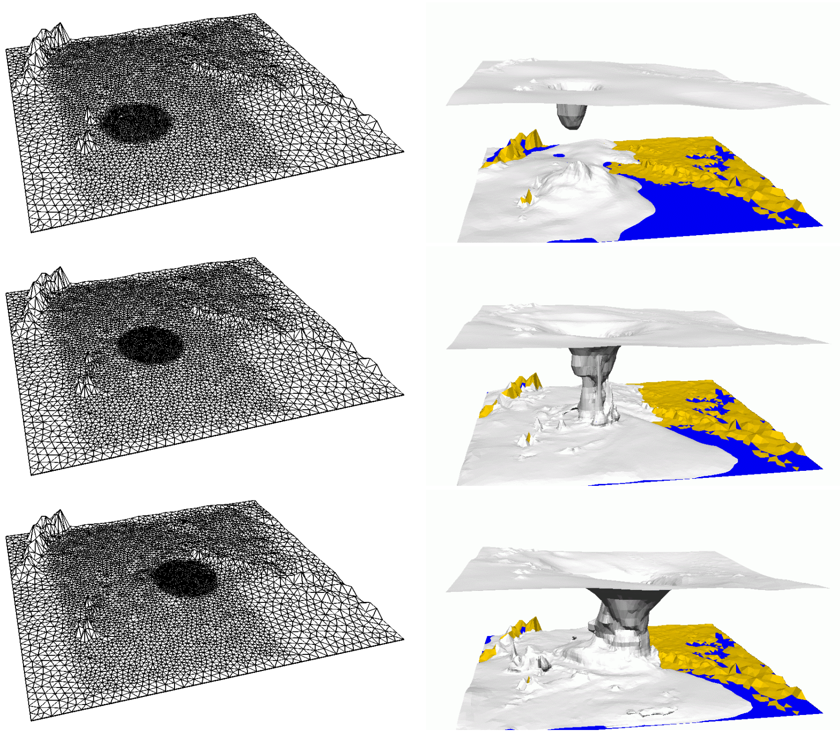

Figure 6: Dynamic grid adaptation at 0 (top), 24 (middle), and 48 (bottom) hrs into the simulation is shown in the left column and the virtual potential temperature isosurface (355K) for the corresponding times are shown in the right column. The virtual potential temperature is a good indicator of the hurricane core. In these panels, the storm is viewed from the east-southeast and from an altitude of about 15 km. The mountains in Central America can be seen at the upper left of each panel. The adaptation criteria, was set to pressure perturbation minima, i.e., to follow the eye of the hurricane.

In addition to hurricane simulations on the regional scales, OMEGA was used to simulate hurricane Floyd on the global scale. The model was initialized using the NOGAPS data for September 14, 1999, and the mesh shown in Figures 2 and 3 was used for this simulation. OMEGA was run in parallel using 16 processors on a Beowulf cluster (AMD Athlon 1.1 GHz single CPU compute nodes with 512 MB RAM running RedHat Linux 7.2). The results for 12hr and 24hr predictions are shown in Figure 7. Dynamic grid adaptation was not used in this simulation. The model was able to predict the hurricane track and landfall.

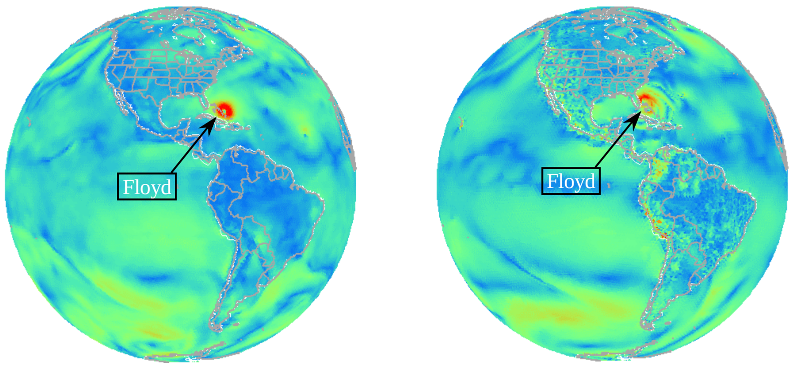

Figure 7: OMEGA track predictions at 12 hours (left) and 24 hours (right). The grid is adapted to shorelines and the initial hurricane location. Dynamic grid adaptation was not used in this simulation. Pressure perturbation fields are shown in the figure.

Conclusions

A fully automated and adaptive unstructured mesh generator for geophysical flow simulations on the global as well as regional scale has been developed and used to simulate hurricane tracks in an operational setting. The grid generator can adapt the mesh to any set of user-specified criteria, such as shoreline, terrain features or initial conditions. The adaptation is effected by a sequence of refinement, coarsening and relaxation steps, which are performed in an automatic manner. The grid generator can access multiple high-resolution terrain elevation and surface characteristics databases, which are provided in the standard OMEGA distribution. The mesh generator has been used to generate grids for atmospheric problems such as simulating the track of Hurricane Floyd (regional and global scale simulations) and for creating grids for the Martian terrain. Grids can also be generated for climate studies and ocean circulation simulations.

Acknowledgement

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