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Aviation Forecasting using Adaptive Unstructured Grids

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1. INTRODUCTION

Weather affects virtually every aspect of aviation operations. The ambient temperature affects the engine performance and lift on departure, the ceiling and visibility impact the number of terminal operations that can be conducted, and the enroute weather impacts flight routing, which in turn affects safety and efficiency. Weather can be exploited for advantage or it can be a safety hazard. Therefore, the accurate prediction of adverse weather such as icing, severe thunderstorms, tornadoes, turbulence, fog, hail, heavy rain and snow, gust fronts, and low ceiling and visibility (C&V) is very important for aircraft safety.

Weather has an obvious impact on aviation safety in the terminal environment (e.g., on August 2, 1985 an L-1011 (DL 191) encountered a microburst on landing at DFW resulting in a crash and 135 deaths; on June 2, 1999 an MD-80 (AA 1420) landed at LIT in a Level 6 storm, running off the runway resulting in 9 deaths). Indeed, the worst accident in civilian aviation history did not occur during flight but rather on the ground when two B-747 aircraft collided in fog on the runway at Tenerife resulting in 583 fatalities. The weather factors that affect both enroute and terminal operations are often of limited extent - horizontally and vertically - and duration (as in the AA1420 accident), which makes the forecasting of these features extremely difficult. To forecast these features, it is necessary to construct computational tools that can automatically provide high resolution where required by the small-scale physical processes that impact on flight operations and safety.

2. OMEGA

The Operational Multiscale Environment model with Grid Adaptivity (OMEGA) is an atmospheric simulation system that links the latest methods in computational fluid dynamics and high resolution gridding technologies with numerical weather prediction. OMEGA is a complete, operational, atmospheric simulation system (Bacon, 2000) built upon an unstructured triangular grid (*c.f.*, Figure 1), which can adapt to a variety of static user-defined fields as well as dynamically during the simulation (*c.f.*, Figure 2). While it was designed to forecast the dispersion of hazardous aerosols and gases (Boybeyi *et al.*, 2001), OMEGA has proven useful for a variety of strictly meteorological missions including site-specific, point weather forecasting and hurricane track forecasting (Gopalakrishnan *et al*., 2002).

OMEGA is designed with both static and dynamic adaptation. Static adaptation (Figure 1) automatically provides high resolution in regions of complex terrain and along land/water boundaries; this provides a benefit

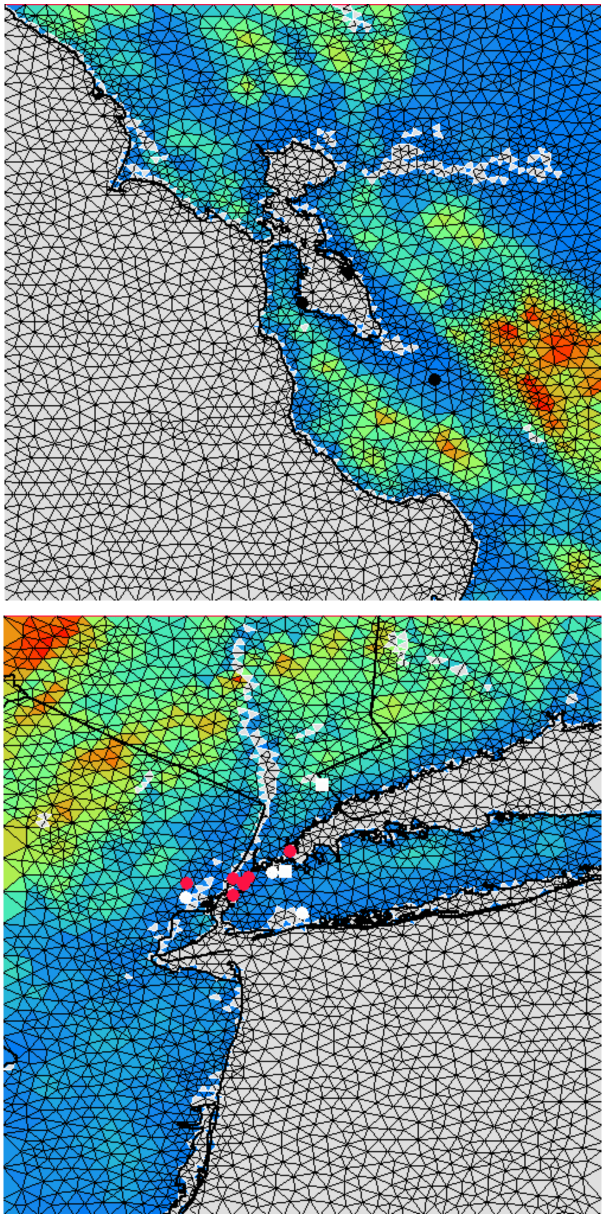

Figure 1. The OMEGA grid increases the grid resolution wherever necessary to meet the mission needs. Shown are OMEGA grids for the San Francisco / Oakland / San Jose terminal area (left) and the John F. Kennedy / La Guardia / Newark terminal area (right). In both cases, the resolution is roughly 2-10 km and the three primary airports are shown as white dots. In the New York case, also shown are Flushing and Westchester County (white squares) and the heliport and seaport bases (gray dots).

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to forecasting in terminal operations where these surface features are often critical to the formation of fog or low clouds. Dynamic adaptation (Figure 2) automatically provides high resolution in regions that meet criteria specified by the user (*e.g.*, a surface temperature or pressure gradient, gradients in the moisture field, or the eye of a hurricane). In addition, the user can specify a set of points or regions with higher (or lower) resolution. This is useful for forcing extra resolution around aerodromes. Figure 3 shows an example in which a grid with higher resolution around the 25 busiest airports in the US was created.

To demonstrate the utility of OMEGA for aviation forecasting, two different test problems were conducted. The first examined the forecasting of ceiling and visibility in the San Francisco Bay area; the second looked at the problem of oceanic forecasting. These test problems are the subject of the following sections.

3. CEILING AND VISIBILITY FORECASTING

Ceiling and visibility both depend on the presence of three factors: moisture, condensation (or freezing) nuclei, and some method of causing super-saturation. For the purpose of creating cloud cover, the most common source of super-saturation is convection caused by surface heating, orographic lifting caused by rising terrain, or low-level convergence. For the purpose of creating surface fog or haze, the most common source is advection of moisture over a cool surface, radiative cooling of the surface, or orographic lifting. All but one of these processes that dominate the creation of clouds and surface fog (haze) are strongly influenced by the surface terrain features – elevation, land/water fraction, albedo, vegetation, and soil texture.

The calculation of ceiling using an NWP model requires the ability to resolve the vertical and horizontal structure of the clouds. Since the horizontal resolution of most operational NWP models is in the range of 20-30 km, knowledge of the sub-grid cloud cover is typically missing making it hard to identify broken cloud cover and hence limiting the quality of ceiling predictions in broken conditions.

In calculating visibility, consider an illuminated object that is at a distance x_{obs} from an observer. If the intervening medium absorbs light, then the ratio of the intensity at the observer to that emitted is given by:

$$\alpha = \frac{I\left(x_{obs}\right)}{I_o} = \exp\left\{ -\int_0^{x_{obs}} \beta\left(x\right)\ dx \right\} \qquad (1)$$

where I_o is the luminance of the object, $I(x_{obs})$ is the intensity at the observer, and β is extinction coefficient of the intervening medium. It is often assumed that an intensity ratio of 0.02 represents the point at which the contrast between an object and its background makes the object effectively invisible. For aviation applications where low visibility is the area of concern, it is appropriate to consider the extinction coefficient to be constant along the path leading to:

$$x_{vis} \equiv \frac{-\ln(0.02)}{\beta} = \frac{3.91}{\beta} \qquad (2)$$

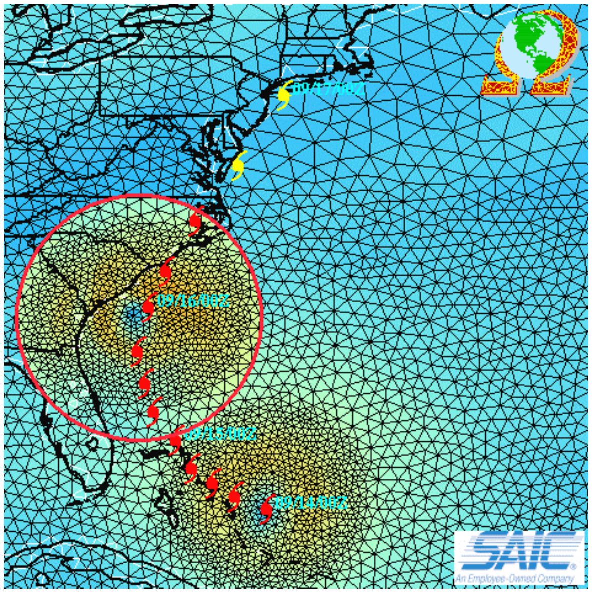

Figure 2. Dynamic adaptation allows OMEGA to automatically maintain resolution in regions of meteorological interest. Seen are the hurricane Floyd grid and wind speed (gray scale) initially and (inset) at 48 hours into the forecast. The hurricane symbols show the observed storm track.

The extinction coefficient can be linearly partitioned according to different extinguishing factors such as cloud droplets, cloud ice, rain, and snow. In OMEGA, the following extinction coefficients derived by Kunkel (1984) are used:

$$\begin{array}{ll} \text{For cloud droplets:} & \beta_c = 144.7\,C^{0.88} \\ \text{For cloud ice:} & \beta_i = 327.8\,C \\ \text{For rain:} & \beta_r = 2.24\,C^{0.75} \\ \text{For snow:} & \beta_s = 10.36\,C^{0.776} \end{array} \qquad (3)$$

where β is in km^{-1}, and C is the mass concentration of the various hydometeors in g/m^3. The overall extinction coefficient is the sum of the components:

$$\beta_c = \beta_c + \beta_i + \beta_r + \beta_s \qquad (4)$$

Finally, the visibility (km) is calculated using (2) above. (Light rain in OMEGA is treated as cloud droplets rather

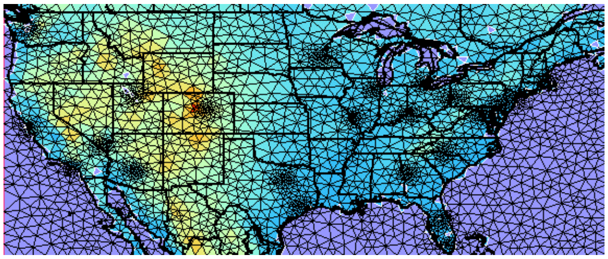

Figure 3. An OMEGA grid with 60-120 km resolution over the continental US, with higher resolution (20 km) around the 25 busiest airports in the United States. This grid could be used for forecasting mesoscale weather over the continental US for flow control.

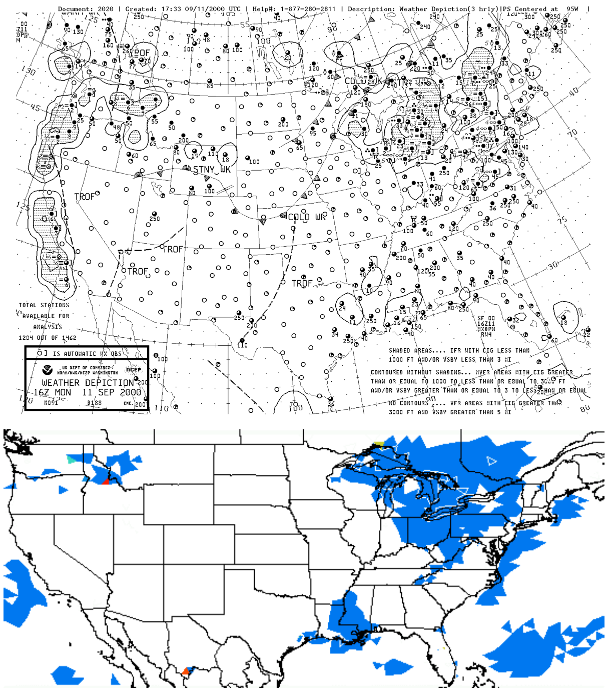

Figure 4. The observed and (16 hour) forecasted cloud ceiling and visibility at 1600 UTC 11 September 2000. Shaded areas on the top indicate IFR regions (ceiling less than 1000 ft and/or visibility less 3 miles) and contoured areas indicate MVFR (ceiling between 1000 and 3000 ft and/or visibility between 3 and 5 miles). Clear areas are VFR with ceiling and visibility greater than 3000 ft and 5 miles. On the bottom is shown the OMEGA simulated visibility field with the blue areas indicating a visibility of 5 km (roughly 3 miles) or less.

than rain drops for visibility purposes.)

To demonstrate the potential to forecast visibility with OMEGA, a test using the grid shown in Figure 3 was conducted. OMEGA was initialized from the Medium Range Forecast (MRF) global model analysis at 0000Z on September 11, 2000. The lateral boundary conditions were derived from the MRF forecast. One modification was made to the OMEGA model for visibility forecasting: the cloud microphysics was modified to produce cloud droplets / ice crystals when the relative humidity exceeded a threshold of 87.5% for the entire computational cell rather than requiring saturated conditions to recognize the stochastic nature of clouds in large grid volumes.

Figure 4 shows the cloud ceiling and visibility observations 16 hours after initialization. This figure indicates three primary regions of weather requiring operations under instrument flight rules (IFR): the California coast and Pacific Northwest extending from the coast to the mountains of Idaho, the Upper Midwest and the Great Lakes extending down to Pennsylvania, and, to a lesser extent, the Mexican Gulf Coast. While some areas show reasonable agreement between the observations and the OMEGA forecast, others indicate a need for improvement. One such area is the coast of California where the OMEGA simulated visibility is IFR over the water (where there are no observations) but VFR over the coastal landmass. This discrepancy is possibly due to a lack of inclusion of information on atmospheric aerosols and their role in visibility. These aerosols can be either natural or anthropogenic (*e.g.* sea spray or vehicle exhaust particulates, respectively).

Another ceiling and visibility demonstration was performed using a regional simulation to compare with visibility observations taken at San Francisco International (SFO), Oakland (OAK), and San Jose (SJC) airports in the San Francisco Bay area. This simulation used a grid with resolution ranging from roughly 5 to 20 km with higher resolution in the complex terrain of the Rocky Mountains and along the coast. The model was initialized at 0000Z on August 31, 2000 and ran for 72 hours using the MRF model for initial and lateral boundary conditions.

Figure 5 compares the 24-48 hour forecasted terminal flight conditions with the observations at the three primary airports in the San Francisco Bay area. The primary cause of the transition from VFR to IFR in this case is the arrival of a band of precipitation that lowers the ceiling below minimums, though the visibility is also lowered.

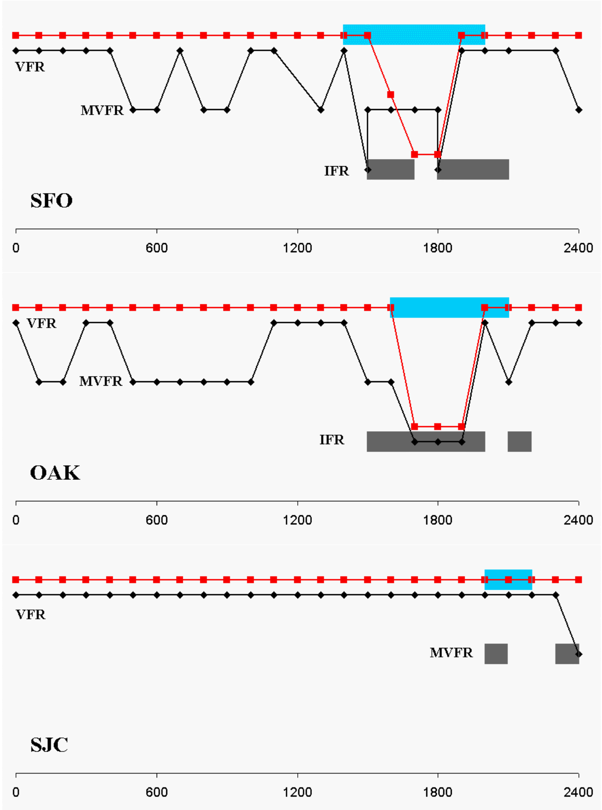

Figure 5. OMEGA forecasted (gray) terminal flight conditions (VFR, MVFR, or IFR) compared with observations at SFO (top), OAK (middle), and SJC (bottom) from 0000Z on September 1 to 0000Z September 2, 2000. Also shown are the OMEGA forecasted (light shading) and observed (dark) periods of light rain. The forecast started at 0000Z August 31.

4. OCEANIC CONVECTION FORECASTING

Three ingredients are required for convective initiation: moisture, instability, and a triggering mechanism. Also for organized convective systems, a fourth necessary ingredient is wind shear. Quite often these ingredients exist over large spatial domains over oceans and cause the development of oceanic convective systems. The timely knowledge of these hazardous weather elements is important to the controller, the airline dispatcher, and the pilot.

Oceanic convection is a very difficult problem for forecasters for a number of reasons. First, there is very little *in-situ* meteorological data that is collected over these regions. Second, the lack of data contributes to significant uncertainty in weather forecasts over oceanic regions. Third, the large-scale uniformity of the ocean surface does not provide a clear break in symmetry making it difficult to determine those regions that will be convectively active and those regions that will not.

As a demonstration of the potential of OMEGA to provide oceanic convection forecasts, a retrospective forecast of a case from the Genesis of Atlantic Lows Experiment (GALE) was performed. In particular, we simulated the cold air outbreak during the GALE IOP-2 (January 26-28,1986). The computational domain is shown in Figure 6. A horizontal grid resolution ranging from 20 km to 60 km was used, resulting in about 14,000 horizontal grid cells. OMEGA used 31 vertical grid levels with a vertical resolution ranging from 15 m near the ground to 1 km at the top of the domain. The top of the simulation domain was set to 12 km above the ground. OMEGA was initialized on January 26, 1986 at 0000Z using Medium Range Forecast (MRF) model gridded data. The model was run for 48 hours. Lateral boundary conditions for the simulation were also derived from the same gridded data field at 12-hour intervals.

The left panel of Figure 6 shows a horizontal view of the 24 hour predicted fields for the 500 mb level moisture field and cumulus heating contours. In this situation, very cold air with below freezing near-surface temperatures was advected over the warmer ocean. This caused significant convection along the East Coast of the United States. As a result, strong vertical velocities and high moisture content caused development of deep cloud bands along the convection line formed along the east of the US.

The right panel of Figure 6 compares the lightning data from the GALE experiment with the OMEGA predicted deep cumulus cloud cover after 24 hours of simulation. The results show fairly good agreement with the observed data.

5. CONCLUDING REMARKS

A new atmospheric forecasting system based on a dynamically adaptive unstructured grid shows promise for aviation applications. The dynamically adapting grid can ensure that the critical regions of microphysical activity that determine ceiling, visibility, and convective activity are resolved sufficiently to permit accurate forecasting. While this study is preliminary, a host of future research directions is readily foreseeable.

Further information on OMEGA is available at the OMEGA web site: http://vortex.atgteam.com.

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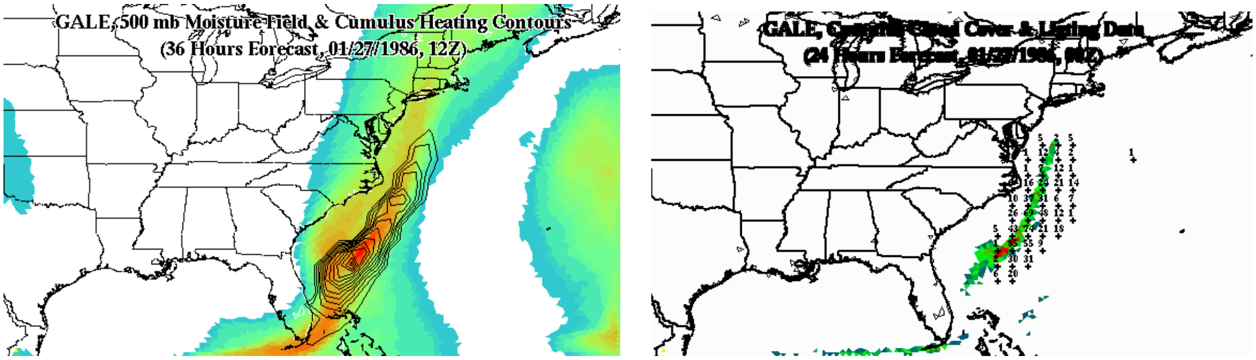

Figure 6. (Left) OMEGA forecasted 500 mb moisture field (background field) and cumulus heating field (superimposed contours) at 24 hours into the GALE-IOP2 study. (Right) A comparison of the GALE lightning data (numbers) with the OMEGA forecasted cumulus cloud cover at the same time.