Quantitative Analysis and 3D Visualization of NWP Data Using Quasi-Geostrophic Equations

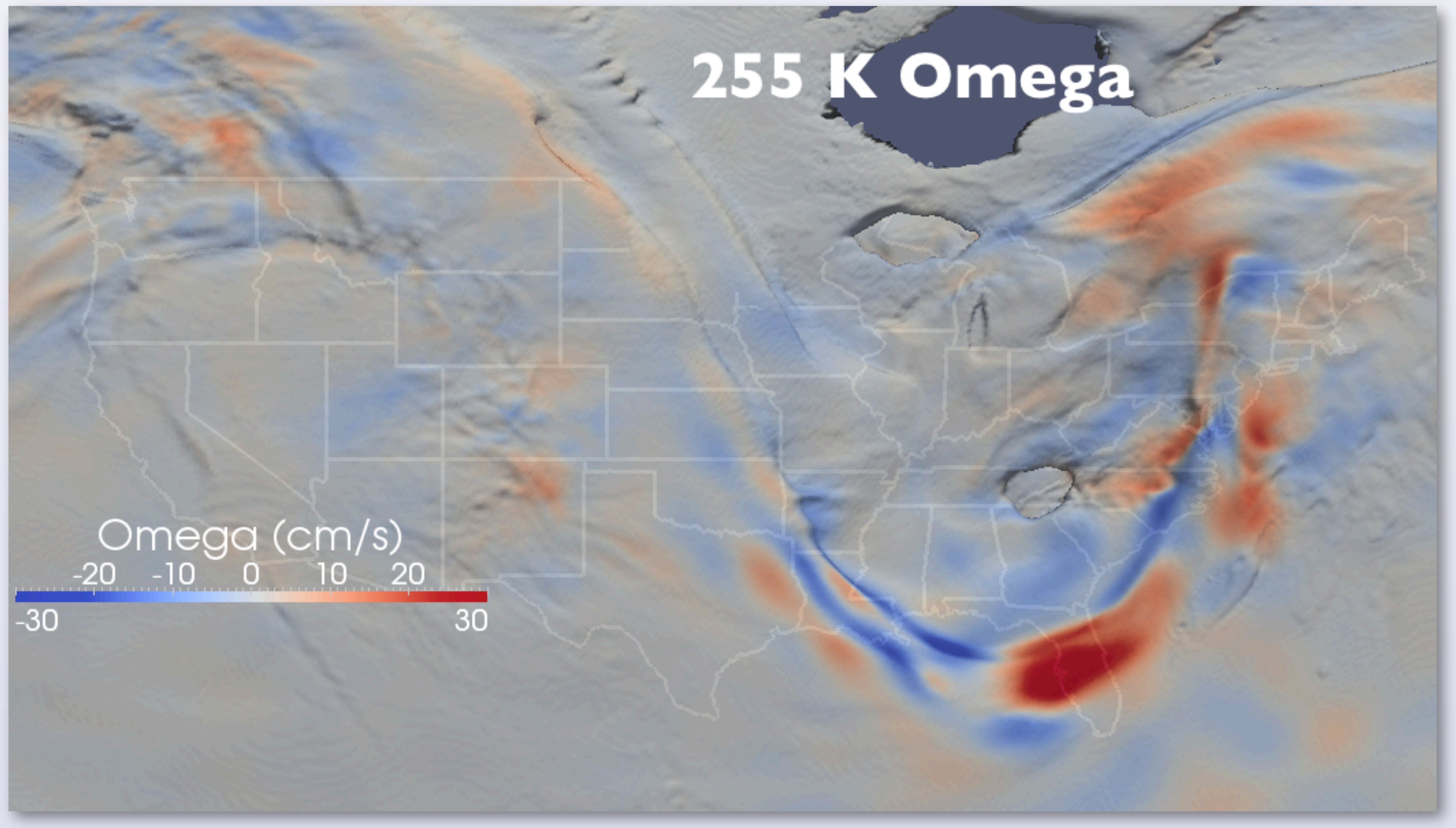
Michael Battalio, Jamie Dyer

MISSISSIPPI STATE UNIVERSITY

Department of Geosciences

Abstract

Two-dimensional analysis of atmospheric characteristics commonly utilizes predefined isobaric surfaces, effectively ignoring information between levels or relying on assumptions and approximations to define general meteorological processes. With the advent of higher graphical processing power on PCs and increasing accuracy of numerical weather prediction (NWP) models, three-dimensional (3D) visualization imposes no limits on the vertical placement or types of variables displayed on maps, reducing the time required to analyze gridded atmospheric data and removing assumptions inherent in Quasi-Geostrophic (QG) analysis. Despite the potential benefits, the adoption of 3D analysis has been slow in operational meteorology. This is partially due to a lack of links between the two-dimensional patterns of the QG diagnostic fields on the significant levels to the 3D shape of those fields in the atmospheric volume. To address this issue, a careful study of the 3D structure of each of the QG fields is required. This project begins that process by determining whether 3D visualization could aid in model verification by calculating each component of the QG omega and geopotential tendency equations. The analysis field from an event with strong synoptic forcing was chosen from the 12-km operational North American Mesoscale (NAM) model. Using a finite differencing methodology dependent on the wavelength of the synoptic waves being analyzed, vertical velocities and geopotential height perturbations were calculated at each grid point of the analysis field by employing the QG omega equation and the QG geopotential tendency equation. The open-source visualization software, Paraview, was used to visualize the 3D omega and geopotential tendency fields. It was found that although the data display considerable low-amplitude patterns, the method can identify and quantify large perturbations in the height and vertical velocity fields within the data volume. This can enhance the diagnostics of NWP-generated atmospheric data for operational forecasting purposes and can also be used to aid in verification of medium to large-scale simulated weather features.



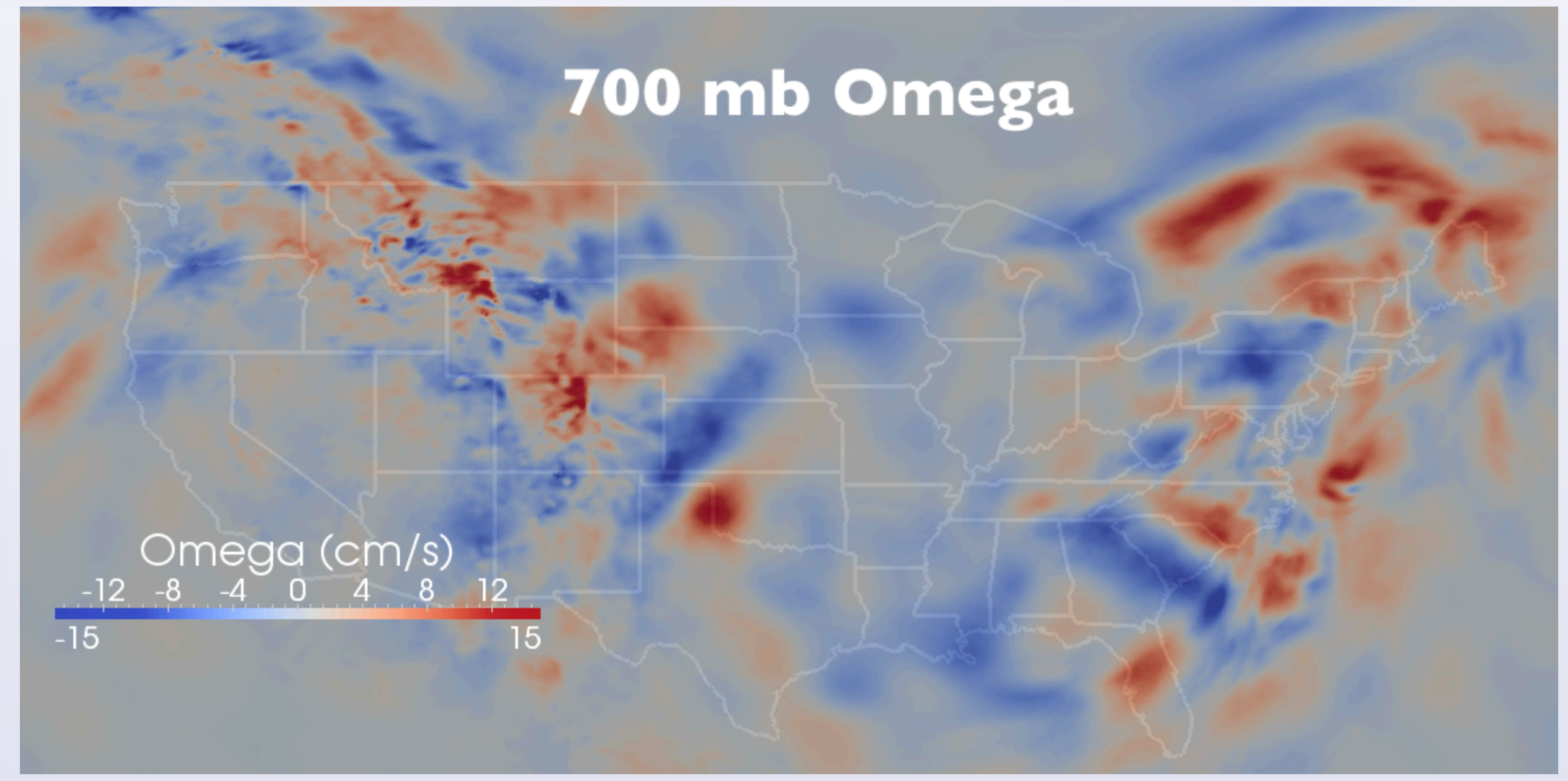
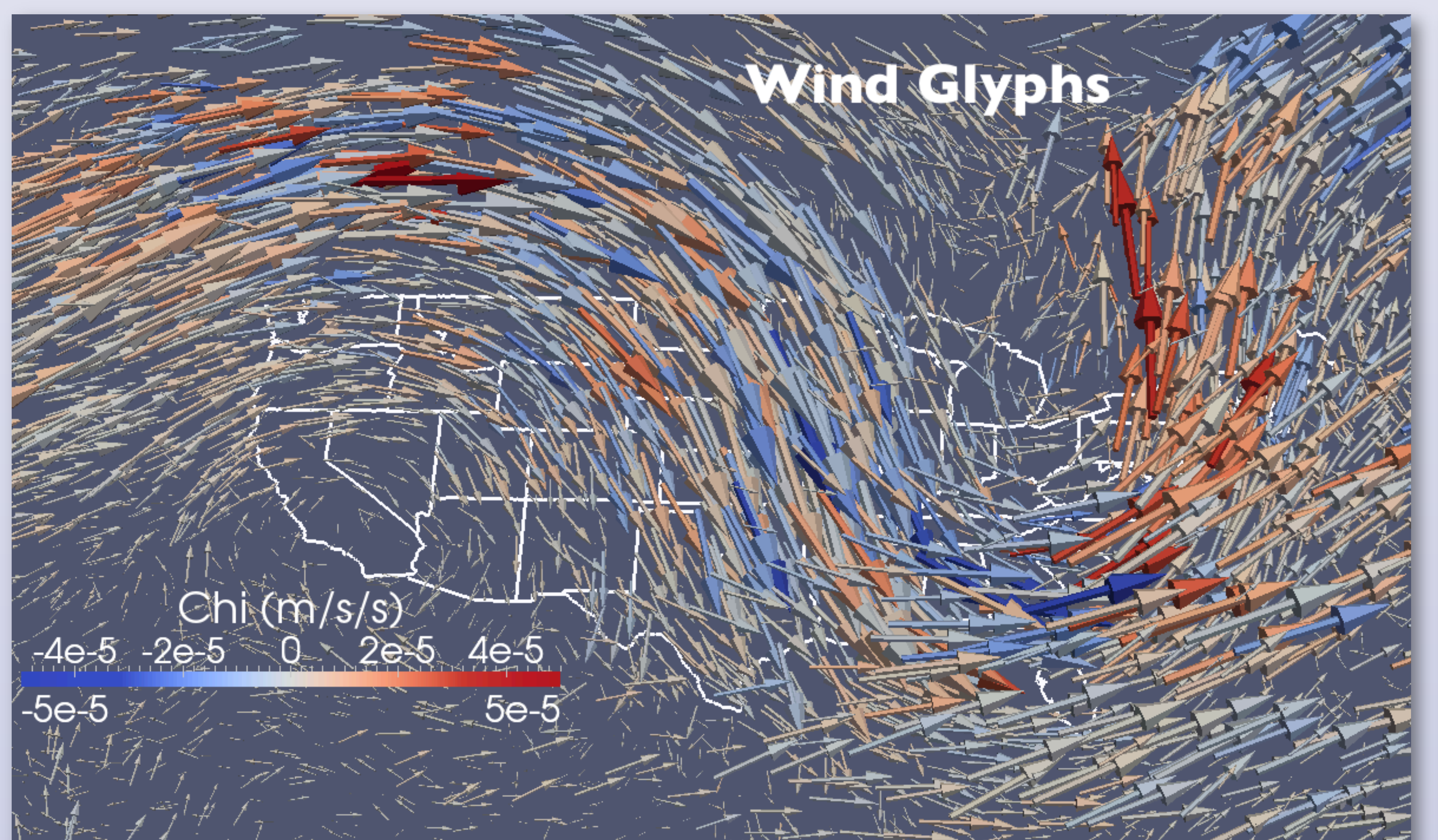
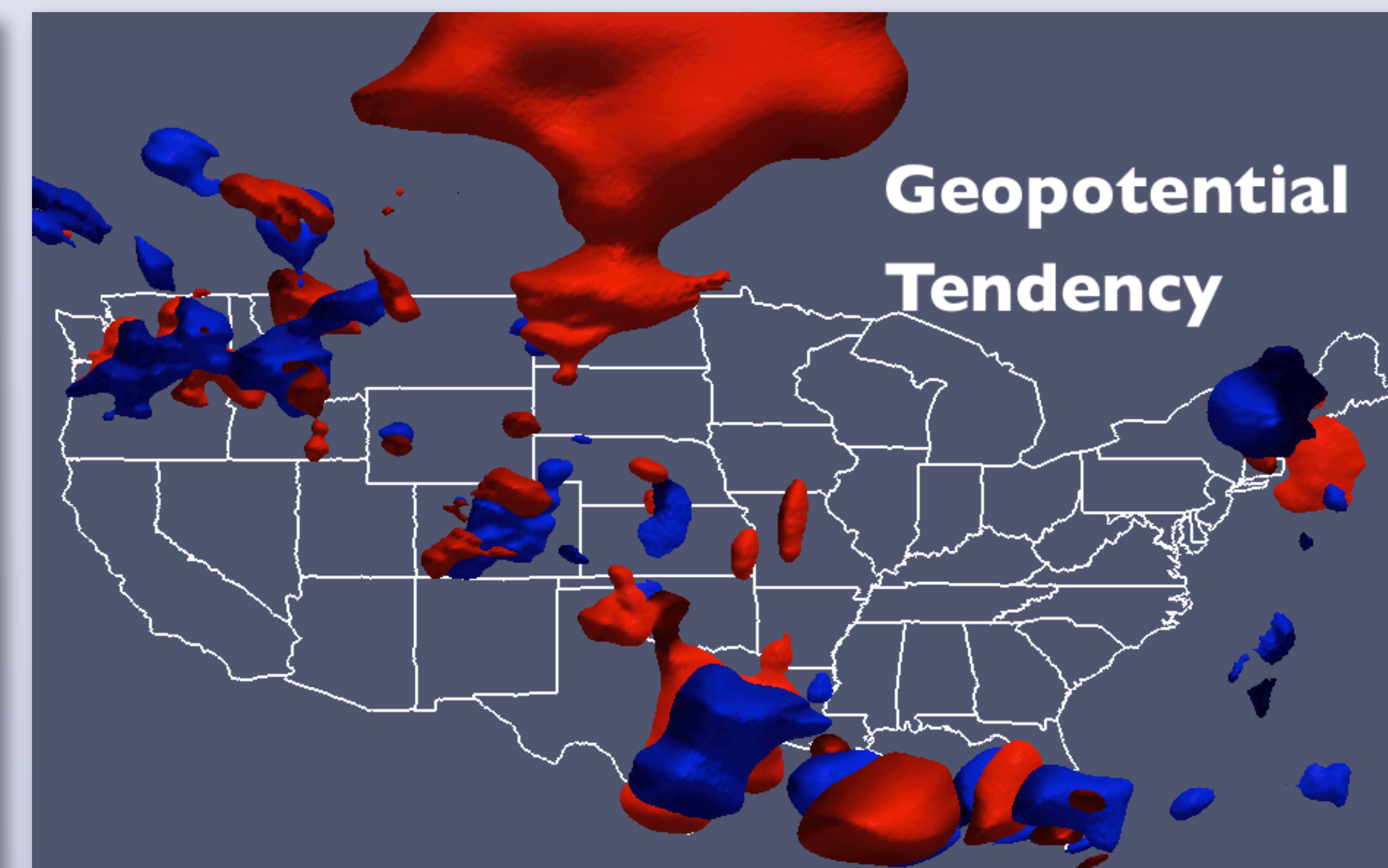


Figure 1 *left:* 255 K isotherm colored by omega (cm/s). **Figure 2** *above:* 700 mb isobar colored by omega (cm/s). **Figure 3** *below, left:* Wind glyphs colored by chi (m/s/s). **Figure 4** *below, right:* ± 2.5e-5 m/s/s chi (red-positive, blue-negative). **Figure 5** *bottom:* Calculated omega in contours of ± 23 cm/s (green-positive, purple-negative) with NAM evaluated omega in contours of ± 23 cm/s (red-positive, blue-negative)





Introduction

Quasi-geostrophic analysis has been a reliable technique to diagnose and forecast for decades. QG atmospheric analysis uses the advection of warm or cold air and vorticity to predict the vertical motion of atmospheric parcels (Sutcliffe, 1947; Trenberth, 1978).

Mathematically, quasi-geostrophic theory is a system of two equations: the geopotential tendency (chi) equation (Holton, 1992),

$$\left[\nabla^2 + \frac{\partial}{\partial p}\left(\frac{f_0^2}{\sigma}\frac{\partial}{\partial p}\right)\right]\chi = -f_0\vec{V}_g \cdot \nabla\left(\frac{1}{f_0}\nabla^2\Phi + f\right) - \frac{\partial}{\partial p}\left[-\frac{f_0^2}{\sigma}\vec{V}_g \cdot \nabla\left(-\frac{\partial\phi}{\partial p}\right)\right]$$

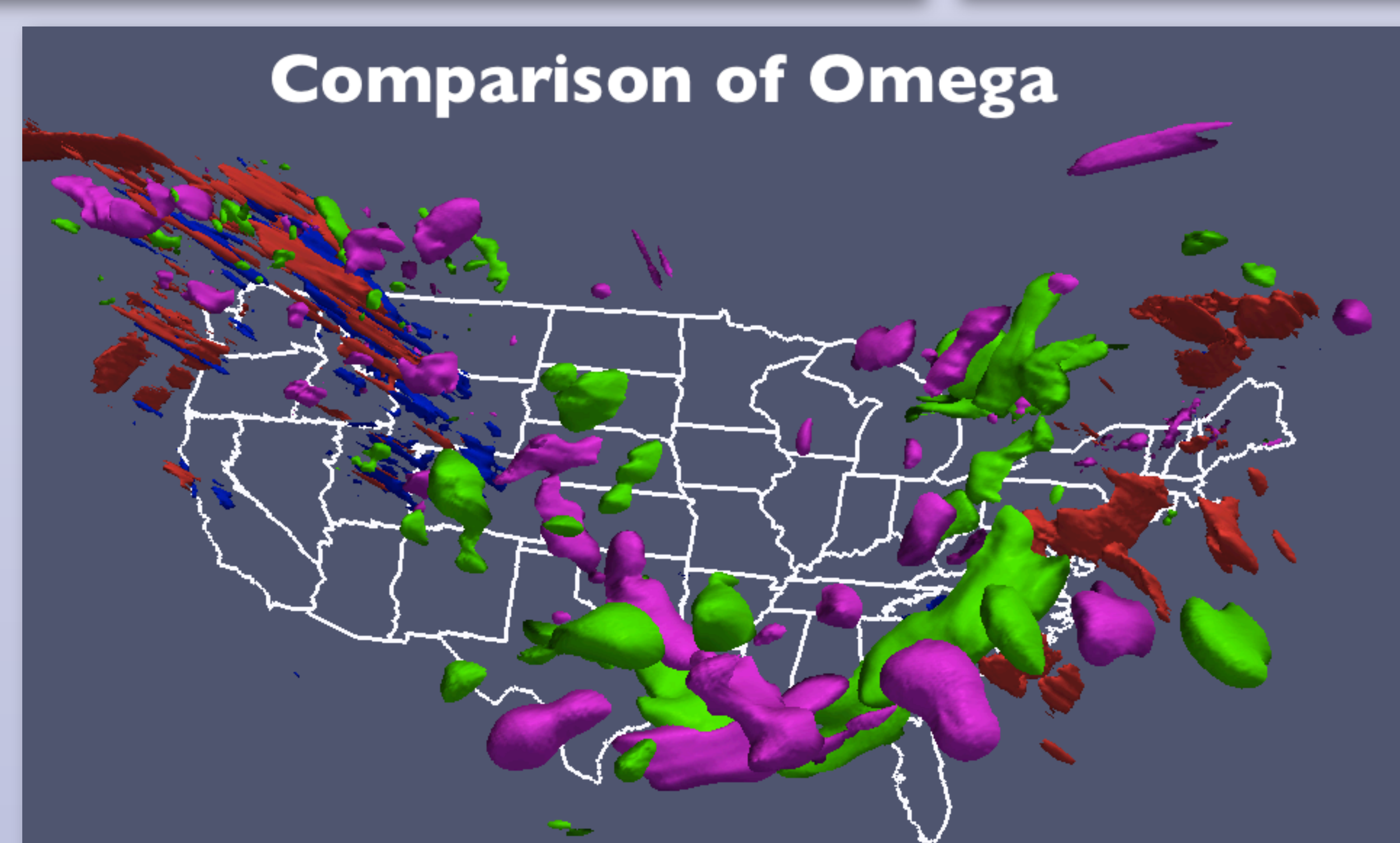
and the omega equation.

$$\left[\nabla^2 + \frac{f_0^2}{\sigma}\frac{\partial^2}{\partial p^2}\right]\omega = \frac{f_0}{\sigma}\frac{\partial}{\partial p}\left[\vec{V}_g \cdot \nabla\left(\frac{1}{f_0}\nabla^2\Phi + f\right)\right] + \frac{1}{\sigma}\nabla^2\left[\vec{V}_g \cdot \nabla\left(-\frac{\partial\Phi}{\partial p}\right)\right]$$

These two equations form the foundation of diagnosis and forecasting that occur within numerical models (Durran, 1987). However, a lack of computer processing power during the development of QG theory has limited the interpretation of the theory to a series of two-dimensional maps, necessitating the use of several assumptions that require a forecaster to unnecessarily interpolate between levels. The problem with QG analysis is the balancing act forecasters must perform when diagnosing areas of interest. Forecasters must look at two separate terms in both the omega and chi equations, that of vorticity advection and of temperature advection. The issue occurs because the two components are not independent of one another (Trenberth, 1978). Each component of the omega equation and the geopotential tendency equation must be viewed side-by-side to diagnose areas of vertical velocities and height tendencies. Three-dimensional visualization is the most effective way of achieving that goal. A first step to the adoption of 3D visualization should be viewing the QG omega and geopotential tendency equations in three dimensions.

Three-dimensional analysis allows for greater forecasting freedom in two ways. One, it allows for the expansion of forecast variables beyond QG imposed forecasting levels. The teaching of QG mandatory levels and what to look for at each level has been pervasive in forecaster education. Forecasters are trained to look for specific patterns instead of each situation individually. Three-dimensional visualization imposes no limits on the vertical placement of maps. Secondly, 3D visualization on a local machine frees the forecaster from selecting from only pre-rendered maps, allowing for independence in forecasting tools.

Hoskins (1978) affirmed that timely, reliable, and accurate methods of model verification are necessary to determine the validity of model initializations. Therefore, a careful study of the 3D structure of the QG fields is required. The objective of the study is to determine if 3D evaluation of NWP model fields using a QG system of equations can validate operational model runs.



Methods

The QG omega and geopotential tendency equations were evaluated for the zero hour diagnostic field for the day, December 12, 2010. Data from the North American Mesoscale Model (http://nomads.ncdc.noaa.gov/data.php) were used due to the close spacing of grid points, 12 km x 12 km x 40 levels. The method of finite differencing was used to calculate partial derivates where required. A stand-alone program, written in C++, calculated each term of the omega and geopotential tendency equations from the gridded data and appended the resulting values to the original data file. The data were then visualized using Paraview.

Algorithm Used: Single moment, central differences were used to calculate spatial derivatives. The laplacian of a vector field, M, was calculated by:

$$\nabla^2 M = \frac{1}{(2s\Delta)^2}\left[M_{i+s} + M_{i+s} + M_{j+s} + M_{j+s} - 4M_{i,j}\right]$$

Pressure derivatives were calculated using a single-moment, backward difference calculation.

$$\frac{\partial M}{\partial p} = \frac{1}{2\Delta P}\left[M_k - M_{k+1}\right]$$

The indices i, j, and k stand for each grid point iteration in the east-west, north-south, and vertical directions, respectively. The offset, s, is the number of grid spaces away from the center point that are used in the calculation. Delta is the distance between grid cells.

Grid Spacing: The optimum grid spacing was calculated using a scree plot. The inflection point of the curve denoted where the loss of data was balanced by the removal of noise. Grid spacings of 20 were used.

Visualization Methods: The open-source software, Paraview, was used to visualize the results. Both chi and omega were visualized using a combination of glyphs and contours.

Results

Though there are areas of low amplitude noise in the data, the finite differencing techniques performed well. Areas of positive and negative omega correspond to where areas of rising and sinking air should be using established techniques. Of special interest in the calculation of omega is that the calculated omega field can be directly compared to the vertical wind to find areas of poor model initialization. New interpretations are required for geopotential tendency as direct calculation of chi yields new quantities that are not traditionally viewed in QG analysis. Both terms in the geopotential tendency equation must be compared to other established fields. This issue is ameliorated with 3D visualization; the techniques used to visualize the omega and chi terms were successful. Comparing 2D forecasting techniques to the 3D computation and visualization of similar variables revealed the usefulness of 3D visualization.

To demonstrate 3D visualization, a case study is performed for Dec. 12, 2010. An upper-level trough is digging across the eastern third of continental US, and a strong nor-easter is developing along the Gulf Stream. Three methods have proven most successful at visualization of individual forcing terms. One technique involves the coloring of isotherms, isobars, isoheights, isentropes, or other constant surfaces by omega and chi (fig. 1 and 2). This method is particularly useful in describing the forcing along fronts, as in figure 1. Strong forcing of up to 30 cm/s occurs ahead of the front, and equally strong forcing occurs behind. For comparison, figure 2 shows UVVs on the 700 mb isobar. A second method is the coloration of stream lines or glyphs of omega or chi (fig 3). Strong negative chi occurs at the base of the trough. A third method consists of contouring strong areas of chi or omega with discrete values (fig 4 and 5). However, areas of weak forcing are difficult to interpret by method three. In figure 4, a large area of positive chi exists north of the Dakotas. This will tend to reenforce the ridge building in from the west. Figure 5 compares constant values of omega from the finite differing method to the raw model output.

Items of further study should be noted. One, the scope of this study is limited to only one event. Further research involves extending this technique to many events. Two, additional quantification of the the strength of omega and chi is needed. A possible technique is the statistical comparison of histograms between model runs and evaluated omega. A second technique is the development of a forcing index which accounts for each term of the QG equations and provides a column total of forcing.

Summary

Forecasters are no longer constrained by 2D visualization techniques. Three-dimensional visualization of omega and chi can provide for a quick diagnosis technique. The evaluation of the terms of the QG omega and geopotential tendency equations are computed by finding a finite difference between grid point neighbors of the NAM gridded data. Results were visualized using the open-source software, Paraview. Omega and chi are visualized using the glyph and contour filters.

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