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

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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 is becoming a necessity. These techniques allow for independent selection of variables and types of surfaces 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 and the 3D shape of those fields in the atmosphere. To address this issue, a careful study of the 3D structure of each of the QG fields is required. This project begins the process of determining 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 North American MesoAnalysis Mesoscale (NAM) model. Using a finite differencing methodology dependent on the wavelength of the significant waves being analyzed, vertical velocities and geopotential height tendencies were calculated at each grid point of the analysis field by employing the QG omega and geopotential tendency equations. 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 velocities fields within the data volume. This can enhance the diagnostics of the gridded atmospheric data for operational forecasters for purposes and can also be used to aid in verification of large-scale simulated weather features.

Introduction

Two-dimensional 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 (Tribbet, 1947). Mathematically, quasi-geostrophic theory is a system of two equations: the omega tendency equation (Holton, 1992),

\[ \omega = \frac{\nabla \cdot (u \times \nabla) V}{\beta} \]

and the omega equation,

\[ \frac{\partial \omega}{\partial t} = \frac{\nabla^2 \omega}{\nabla^2 - \beta k} - \frac{\nabla \cdot (u \times \nabla) V}{\beta} \]

These two equations form the foundation of diagnosis and forecasting that occur within numerical models (Dorr, 1987). However, a lack of computer processing power during the development of the theory limited its applicability 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 the QG theory is that 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 temperature advection. The issue occurs because the two components are not independent of one another (Tribbet, 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 geopotential heights. 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 visualization allows for greater freedom in the way the data are represented in the field. One, it allows for the expansion of forecast variables beyond QG omega and temperature levels. The teaching of QG theory mandates that for each level, a forecast for each level has been presented in forecast education. Therefore, forecasters are trained to look for specific patterns instead of each situation individually. Three-dimensional visualization removes these 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 independent selection in forecasting tools. Hoskins (1978) affirmed that timely, reliable, and accurate methods of model verification are necessary to highlight the potential for operational use of QG fields. Hoskins (1978) also revealed that 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 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 derivatives as required. A stand-alone program, written in C++, calculated each term in the QG 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 scalar field $M$, was calculated by

\[ \nabla^2 M = \frac{M_{i-1} - 2M_i + M_{i+1}}{\Delta x^2} \]

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

\[ \frac{\partial M}{\partial y} = \frac{M_{i+1} - M_{i-1}}{2\Delta y} \]

The indices, $i$, 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. $D$ is the distance between grid cells.

Figure 3: $\omega$ visualization on a local machine frees the forecaster from selecting from only pre-rendered maps, allowing for independent selection in forecasting tools. These two equations form the foundation of diagnosis and forecasting for decades. QG atmospheric analysis uses the advection of warm or cold air and vorticity to predict the vertical motion of atmospheric parcels (Tribbet, 1947). Mathematically, quasi-geostrophic theory is a system of two equations: the omega tendency equation (Holton, 1992),

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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 warm and cold advection, respectively, and should be used to determine areas to be used in QG analysis. These two equations form the foundation of diagnosis and forecasting that occur within numerical models (Dorr, 1987). However, a lack of computer processing power during the development of the theory limited its applicability 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 the QG theory is that 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 temperature advection. The issue occurs because the two components are not independent of one another (Tribbet, 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 geopotential heights. 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.

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