An Atmospheric Visual Analysis and Exploration System

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Abstract— Meteorological research involves the analysis of multi-field, multi-scale, and multi-source data sets. In order to better understand these data sets, models and measurements at different resolutions must be analyzed. Unfortunately, traditional atmospheric visualization systems only provide tools to view a limited number of variables and small segments of the data. These tools are often restricted to two-dimensional contour or vector plots or three-dimensional iso-surfaces. The meteorologist must mentally synthesize the data from multiple plots to glean the information needed to produce a coherent picture of the weather phenomenon of interest. In order to provide better tools to meteorologists and reduce system limitations, we have designed an integrated atmospheric visual analysis and exploration system for interactive analysis of weather data sets. Our system allows for the integrated visualization of 1D, 2D, and 3D atmospheric data sets in common meteorological grid structures and utilizes a variety of rendering techniques. These tools provide meteorologists with new abilities to analyze their data and answer questions on regions of interest, ranging from physics-based atmospheric rendering to illustrative rendering containing particles and glyphs.

In this paper, we will discuss the use and performance of our visual analysis for two important meteorological applications. The first application is warm rain formation in small cumulus clouds. Here, our three-dimensional, interactive visualization of modeled drop trajectories within spatially correlated fields from a cloud simulation has provided researchers with new insight. Our second application is improving and validating severe storm models, specifically the Weather Research and Forecasting (WRF) model. This is done through correlative visualization of WRF model and experimental Doppler storm data.

Index Terms—weather visualization, grid structures, transfer function, volume rendering, volume visualization, glyph rendering, warm rain entrainment process

1 INTRODUCTION

Clouds and precipitation affect our daily lives, personal safety, commercial decisions, and future sustainability on Earth. Understanding and predicting these atmospheric phenomena is challenging due to the complexity that underlies both natural phenomena and the data produced by the computer simulations of these phenomena. This challenge is further exacerbated by the lack of highly developed atmospheric exploration tools. Current tools can visualize only a small subset of the data, creating difficulty for meteorologists attempting to analyze their data.

Motivated by acquiring the information to solve these problems, we have designed an integrated atmospheric visual analysis and exploration system for the interactive analysis of weather data sets. Our system allows the integrated visualization of 1D, 2D, and 3D atmospheric datasets in common meteorological grid structures and utilizes a variety of rendering techniques to most appropriately allow analysis and visualization of the data, ranging from physics-based atmospheric rendering to illustrative rendering with particle and glyph rendering. In this paper, we focus upon two particular atmospheric science problems: understanding mechanisms of warm rain formation and the validation and improvement of numerical weather prediction models through comparison with radar observations.

The remainder of this paper proceeds as follows. In Section 2, we provide an overview of the previous work in meteorological and weather forecasting systems. Section 3 describes the particular atmospheric problems to which our system has been applied. Section 4 provides system details and Section 5 describes the use and performance of our system as applied to warm rain formation and weather prediction models. We conclude our paper with a short summary and a discussion of future work in Section 6.

2 PREVIOUS WORK

Several visualization tools have been developed for meteorological studies and weather forecasting. The VIS-5D system [14] has been shown to be a powerful tool for analyzing meteorological data. This system is able to generate 3-dimensional graphics and provide interactive visual access to 5-dimensional data sets. The VisAD system [13, 15] is built to provide users with interactive visualizations of a shared set of numerical data and computations. These packages use scalar and vector visualization methods such as isosurfacings, vector glyphs, and volume rendering. Though various analytic capabilities are provided in these packages, all scalar renderings are still limited to univariate fields. The details and correlations among multiple fields are often neglected or undiscovered.

In order to better understand these fields, task-specific [33] and multi-resolution [34] weather visualization systems were created. These systems provide a general application framework for non-research-oriented or operational activities composed of several goals. However, most of these systems are limited to univariate fields and the visualization design and implementation is not very suitable for the interactive and flexible exploration of research data.

To enhance data exploration, volume rendering [5, 24] is often used for three-dimensional scalar data visualization. Most volume rendering systems map a single scalar value to color and opacity according to 1D transfer functions. 2D transfer functions were introduced in [24], where the second term is the data value gradient magnitude. Simulations and applications which require visualization often produce multiple values per sample point, or voxel. Further research into multivariate transfer functions is described and discussed in [5, 12], and modern graphics hardware has enabled the use of multi-dimensional transfer functions within an interactive framework [19, 20].

Other volume rendering techniques have often proved useful in visualizing atmospheric data. Texture-based volume rendering techniques have been shown to be effective at rendering atmospheric scenes [7]. Furthermore, photorealistic renderings of atmospheric
scenes [21] have enabled atmospheric scientists to gain more insight into their data, and current systems, using hardware acceleration [8, 27], are able to create photorealistic renderings with interactive performance.

Other problems that arise in visualizing meteorological data stem from the fact that such data is stored in various irregular grids. Irregular grids may be rendered through ray-casting of tetrahedral meshes [11, 36] and projected tetrahedron methods [29] allow hardware-accelerated rendering of non-uniform structured and unstructured grids. However, these methods are not well-suited for the half-angle slicing volume rendering techniques we wish to apply to our system. The approach presented in [28] introduces an efficient sampling method for advanced lighting and transfer functions on graphics hardware and is used in our rendering system.

3 MOTIVATION

3.1 Warm Rain Formation in Cumulus Clouds

Some details of precipitation formation remain a mystery after more than fifty years of intense study, yet these details are important for modeling precipitation and forecasting its development in real clouds. One of these long-standing problems concerns the speed with which rain is observed to form in small, warm (lacking ice) cumulus clouds. This so-called “warm rain process” includes the nucleation of cloud droplets upon favorable atmospheric particles, their growth by vapor diffusion (condensation), and their accelerated growth by collection of smaller cloud droplets (that fall more slowly than the larger cloud droplets), eventually reaching sizes that fall out of the cloud and to the ground as raindrops. Calculations based on traditional theory are unable to explain how droplet collection is initiated so quickly; the growth of cloud droplets by condensation alone is too slow to produce the larger cloud droplets needed to initiate such collection events [1].

One factor that is lacking in such calculations, yet is clearly present in real clouds, is turbulent cloud motions. Direct numerical simulations of cloud droplet behavior within volumes as small as 1 cm$^3$ suggest that turbulence can enhance collisions between smaller droplets by increasing their relative velocity differences, increasing their likelihood of coalescence within a given area, or increasing the number density of droplets over localized regions [10, 35].

While much effort has been spent on numerical simulations to understand the influence of turbulence at the droplet scales (below 1 cm), little has been done at larger scales (10 of meters and greater) within a cloud. The cloud properties at this scale, resulting from stronger turbulent motions within the cloud, are also important because they determine how large the drops stay within particular parts of the cloud where they are exposed to specific amount of smaller-scale turbulence. The cloud properties themselves also deserve further study to link features like the local amount of cloud water with certain turbulent scales of motion and to study the evolution of these features and their interaction as the cloud develops.

Another factor lacking in traditional calculations of warm rain formation is the effect of entrainment and mixing at the cloud edges. Entrainment is the process by which dry air outside the cloud boundary is introduced into the cloud via primary and secondary motions occurring within the cloud and at the cloud edge [2, 3]. Mixing of this dry air into the cloud alters its properties, promoting local drying and cooling. Numerous laboratory and modeling studies have suggested that limited amounts of entrainment might actually accelerate precipitation formation by locally reducing the cloud droplet number concentration, leaving fewer droplets to compete for the water vapor available for growth by condensation [22], although this remains to be suitably demonstrated in real clouds.

Studies concerning both of these, as well as other factors possibly important for warm rain formation, have been hindered, by a lack of tools with which to visualize the cloud properties in three dimensions and time, the evolving structure of correlations among the cloud properties, and the trajectories of droplets within these evolving structures.

Contouring of variable fields in a horizontal or vertical cross-section is a common form of analysis of the cloud model data and has been useful for some scientific problems, especially when it was common to perform numerical simulations of clouds in two dimensions due to computational limitations. However, three-dimensional cloud simulations are now standard, and in fact, are essential for accurately representing the behavior of turbulence in clouds [25]. When analyzing results of a three-dimensional simulation using two-dimensional plots, information into and out of the plane of the cross-section is lost and hinders efforts to understand the motions of droplets throughout the complex three-dimensional cloud structure. In addition, portions of the cloud that contain maxima of interesting cloud properties (e.g., cloud water, sub-grid scale turbulence) are unlikely to fall within a two-dimensional plane and can even be missed if the plane falls outside the realm of the maxima. Choosing the “right” cross-section is often an exercise in “trial and error” that greatly increases the time required for scientific analysis.

When studying precipitation development, particle trajectories through the cloud are very useful and have been employed widely [4, 9, 18, 22, 23, 32]. These particle trajectories are not simply computed as tracers within the wind field but are often computed externally to the primary cloud simulation using a separate droplet growth model that considers the influence of the fall velocity variation of the drop upon its trajectory. Such trajectories, when plotted in a two-dimensional framework, are either partially lost or must be projected onto a cross-section which loses some of the vital information about the parts of the cloud through which they have traveled.

3.2 The Weather Research Forecasting Model

Routine storm-scale numerical weather prediction will become operationally feasible in the near future as computing power continues to increase. Output from numerical models, such as the Weather Research and Forecasting (WRF) model [30], will be utilized by forecasters and allow for increased lead time for warnings of hazardous weather conditions. However, numerical models contain errors related to many of the critical aspects of the evolution of significant weather phenomena. For instance, there is considerable uncertainty regarding the WRF model’s capability to accurately predict the initiation of deep convective clouds, the origin and evolution of rotation in thunderstorms, and the larger-scale development of organized convective systems. Many of these issues are related to complex physical processes, such as cloud and precipitation physics, that are applied in the model by simplified parameterizations. Determining the sources of these errors will allow model developers to make significant improvements, leading to more reliable numerical predictions of hazardous weather.

A key component for discovering errors in numerical prediction models is the development of a useful tool for comparing meteorological data to numerical model output. Typically, such a comparison is performed by visual analysis of a single atmospheric variable, either via contour analysis of 2D horizontal or vertical slices, or 3D isosurfaces. A variety of statistics related to observed and predicted atmospheric variables valid at the same set of points in both time and space can also be computed. These traditional approaches can provide information related to the overall accuracy of the forecast of a specific variable. However, this sort of evaluation does not provide information regarding the relationship between predicted variables and model processes.

In order to obtain information regarding the sources of errors in the model, a physical- or process-oriented approach is required. Generally, a process-oriented model verification approach evaluates the model’s ability to capture the formation, development, propagation, and decay of specific meteorological phenomena. Such an approach requires observations of variables that affect the evolution of weather events and will be compared with corresponding forecast variables. This kind of model evaluation has been hindered in the past by a lack of tools that allow visualization of multi-dimensional atmospheric data and the evolution of the relationship between variables. For example, the production and location of condensate within a convective cloud can be estimated by radar measurements and predicted by a numerical model. There are many different kinds of hydrometeors that interact and modify the distribution of temperature, moisture and winds in the atmosphere. In order to gain understanding of the evolution of a pre-
cipitating weather system, one must have the ability to analyze the structure of this multi-dimensional dataset. With such analysis tools, one can identify characteristic and systematic errors in the prediction of specific variables and then track the processes involved to identify candidate areas of improvement within the model.

4 Atmospheric Visual Analysis and Exploration System

The development of our atmospheric visual analysis and exploration system is driven by solving the problems discussed in the previous section. The fusion of 1D, 2D, and 3D atmospheric data sets in common meteorological grid structures can be intuitively visualized by our rendering system. A variety of rendering techniques, ranging from physics-based atmospheric rendering to illustrative rendering with particles and glyphs, are integrated into our system. Correlative illustrative rendering techniques, such as applying multi-dimensional transfer functions to multi-field data and computing and visualizing derived quantities through an atmospheric calculator interface, are also combined into our visualization system.

4.1 Data Management

Meteorological research involves the analysis of multi-field, multiscale, and multi-source data sets. The data sets are usually created and stored in various grid structures based on the simulation requirements or measurement methods. In order to fuse the data from a wide range of scales and grid structures, a technique described in [28] has been developed and integrated into our system. This technique does not require the data to be uniformly sampled if it is in common meteorological grid structures. The known mappings from a physical point to a texture point for several meteorological grid structures are stored and computed, utilizing the programmability of modern graphics hardware. When a space point is being sampled, a coordinate transformation is performed so that the data stored in the appropriate grid coordinate is accessed. If exact grid vertex locations cannot be determined, our system performs a functional approximation (see [28]) to enable texture-based volume rendering. With this technique, volume data in different meteorological grid structures can be fused and visualized without losing efficiency.

In order to sample the WRF data, which is in a mass coordinate system, a set of coefficients for an 11th-order polynomial is calculated for the mapping approximation. A set of coefficients for a 5th-order polynomial is determined so that the mapping approximation for Doppler radar data, which is in the polar coordinate system, can be performed. Details can be found in our previous work [28].

Particle and glyph data are treated a little differently since they are provided as positions, not volume data. In order to correlate the geometric positions within the volume space, affine transformations are performed which only requires the origin and dimension parameters from both the glyph and volume data. The particles, glyphs, and volume data are then fused into the same space. By providing researchers with the ability to handle multi-field, multi-scale, and multi-source data and fusing them into a consistent space, we can ensure the correctness of spatial relationships among the data and enable effective visualization, comparison, and correlation studies of the data.

4.2 Physics-based Atmospheric Rendering

Our system also provides data-driven physically-based visually accurate cloud renderings. These renderings have been shown to increase volumetric understanding of both measured data and simulation models and allow for effective comparison and studies. In our previous work [27], an efficient system for graphics-hardware accelerated atmospheric rendering was developed. The volume rendering engine for this system, shown in Figure 1, incorporates a half-angle slicing scheme in order to approximate atmospheric multiple scattering properties. Based on measured particle properties, phase functions have been calculated. Thus, many complex optical phenomena can be realistically rendered from the phase functions of cloud volumes. After being optimized for graphics hardware acceleration, this system is able to perform at interactive rendering speeds.

Based on recent work [26], improved functions and optimizations have been added to this system for physically plausible cloud renderings. Phase functions for snow have been improved from the recent development of an asymptotic angular distribution solver. Improved aerial perspective, sun disk rendering, and atmospheric attenuation calculations, see Figure 1, have been added in order to better simulate the sun light scattering behavior. By incorporating these changes, our new physics-based volumetric atmospheric rendering techniques can more accurately represent the dynamic cloud and storm processes in the appropriate sky context.

4.3 Illustrative Rendering

To effectively illustrate single- or multi-field meteorological data, we use user defined transfer functions. The transfer functions in our system can be either one- or two-dimensional. One dimensional transfer functions are simpler and more intuitive as they allow quick exploration of the dataset by interactively mapping a single field value to color/opacity based on the scientist’s interest in a specific range of this field.

Two-dimensional transfer functions [20] extend the data classification domain in order to selectively map pairs of (value, gradient magnitude) to color and opacity. Applying this approach to multi-field datasets, we highlight the regions where the correlations between two fields are significant.

A special 2D transfer function has been developed to visualize the air inflow/outflow on the cloud boundary. This calculation entails a projection of the velocity direction (\(\vec{v}\)) on the cloud boundary normal (\(\vec{n}\)) and coloring the sample based on the result. The projection operation provides a scalar value \(s\) in the range from [-1, 1]. This value is then rescaled to [0, 1] and used as an argument to a 1D transfer function that sets the final color and opacity.

\[
s = (\vec{n}, \vec{v}) \cdot \vec{n} \cdot \text{sign}(\vec{n}, \vec{v})
\]

In Figures 3(b) and 4(b), a blue-red gradient color table is used to map negative-positive flow values (inward to outward).

4.4 Particle and Glyph Rendering

Along with illustrative rendering, our volume rendering engine is able to render particles and glyphs within the volume. This is useful as
In order to facilitate the use of these tools, friendly and intuitive user interfaces have been developed to integrate the data analysis and scientific discovery process into our visual analysis system, shown in Figure 2. Our system accepts a large set of parameters, which are organized into several categories, and provides users with a high degree of freedom to interact with their data.

One category is rendering quality. Here, users can adjust the number of slices, resolution and physical property parameters. Viewing these related parameters allows users to generate scenarios by adjusting light, volume and view positions. Data related parameters enable users to weigh different fields in the volume so that portions of the data can be seen.

Another category is the transfer function. Here an editable transfer function user interface has been created and a typical 1D transfer function editing window is shown on the left-bottom portion of Figure 2. For quantity accurate rendering applications, value ranges for the data sets are queried and reflected on our transfer function editing window. Thus, users are able to design and control their transfer functions based on specific numerical values. We also provide a glyph control interface. Users can control the input density of the glyph data to render a limited number of glyphs at one time. Users are also able to interactively pick glyphs that have special features and hide uninteresting ones.

5 Results

In this section, we discuss the use and performance of our visual analysis system for the two atmospheric science applications described in Section 3.

5.1 Warm Rain Formation Process

The first application is warm rain formation in small cumulus clouds. The cloud simulation generates 10-dimensional data sets in a uniform grid structure. The 10 dimensions are time, three spatial dimensions, and 6 physical variables, including water content, vapor content, TKE and three wind vector fields. The volume data has dimensions of 81 × 81 × 121 and each grid cell occupies a 50 × 50 × 50 m³ cube in physical space.

Time series data sets are generated from this simulation from time step 4200 to 5100 seconds with 3 seconds interval. Users are able to organize and visualize the data sets based on the time step parameter. For a particular time step, the 6 physical variables are stored as 6 fields in a volume. In this application, water content is stored as Field 1, vapor content is stored as Field 2, TKE is stored as Field 3 and wind vectors occupy Fields 4 to 6. An extra field is also in use for storing the result from our instantaneous atmospheric calculator.

The trajectory data contains 620 trajectories, which are described as 10-dimensional data as well, with the same data fields as the volume data and time span from 4143 to 4860 seconds. The particle geometry is transformed to the volume data coordinate system so that it is defined with respect to the same origin. Therefore, the trajectories are spatially correlated with the volume data.

The time evolution of the three-dimensional spatial correlation between the numerically simulated cloud water and sub-grid (scales below those resolved by the model) turbulent kinetic energy (TKE) fields can be easily studied with the new visual analysis system. Figure 3 highlights different values of this correlation. It is important to understand how the TKE (here, represented by the eddy dissipation rate ε) and cloud water fields evolve and their relationship to each other, and especially to what extent regions of both high TKE and cloud water exist. The influence of turbulent motions upon droplet collection would be expected to be greater when both the TKE and cloud water values are high, indicative of many cloud droplets occupying a turbulent region where their collisions with each other are enhanced.

Early in the cloud simulation, the TKE is slow to develop (this was easily judged with the photorealistic rendering capability of the system which showed a cloud with a very smooth exterior). Midway through the simulation (Figure 3(a)), however, the TKE increases to significant (and more realistic) values. As turbulent eddies develop (these are the small rotating motions in the cloud that are responsible for the “cauliflower-like” appearance of cumulus clouds), it is interesting to...
clouds outwards from cloud to clear air, blue, velocities directed inward from clear air to cloud.

These spatial correlations, however, must be investigated further with precipitation brought to the ground. The realism of the evolution of water below as they fall through the cloud, maximizing the amount of large drops formed at cloud top are able to collect much of the cloud water and TKE values may be applicable at higher altitudes and later stages of the cloud lifetime. Such enhanced collection among the droplets would have the greatest impact at this time. If this breakdown is realistic, this result suggests that enhanced droplet collisions predicted by DNS results for potential enhancement of droplet collection by turbulence at these later times.

Further insight into the possible influence of cloud turbulence upon droplet collection is gained by investigating the paths of individual drops through areas of high TKE. The particle trajectories have been calculated apart from the main cloud simulation, using a condensation growth model based upon the simulated cloud values, and includes the changing fall velocities of the droplets as they grow. The ability to interactively choose the trajectories for viewing greatly simplifies the analysis. Instead of contriving some complicated lookup procedure for selecting trajectories with desired characteristics, such as those containing loops as a result of being caught up in eddies at the cloud edge or those traveling through high TKE regions, one can simply select these visually for further inspection.

An investigation of trajectories that ascend through the core of the cloud (Figure 5, a and b) corroborates the conclusion derived from the analysis of the spatial correlation of TKE and cloud water. The trajectories are colored according to the amount of cloud water present when the droplet was in that region (providing a visual history of the cloud water experienced by that droplet) and the sphere (showing the present location of the droplet) color indicates the value of TKE in the vicinity of the current drop location. The droplet trajectories demonstrate that those droplets occupying the center of the cloud within the main thermal circulation experience the highest cloud water regions, but some of the lowest TKE regions. At later times, however, when the primary thermal circulation has broken down into smaller eddies, these same trajectories now occupy a region of high TKE, and still reasonably high cloud water regions, although the amount of cloud water is less than it was earlier, as entrainment and mixing dry out this upper region of the cloud. Clearly, though, these trajectories are favorable for potential enhancement of droplet collection by turbulence at these later times.

An additional investigation of droplet trajectories caught in eddies at the cloud edge (Figure 5, c and d) also provides some new information. These droplets experience high TKE values earlier (note bright orange color of the sphere as it is caught in a turbulent eddy at the cloud base but occur within regions of low cloud water. This region is in the wake of the primary thermal circulation (Figure 3(b)), where the large toroidal circulation (indicated by the outward-directed velocities at cloud top and the inward-directed velocities immediately beneath) has already mixed an abundant amount of dry environmental air into the cloud. Within this primary thermal circulation near the cloud top, a nearly undiluted core of cloud water exists (green), but the flow is more laminar and thus the TKE values are low. If these patterns are representative of real cumulus clouds, the increase in droplet collection suggested by the direct numerical simulation (DNS) results within regions of high cloud water and TKE are not applicable earlier in the cloud lifetime. Several minutes later in the simulated cloud lifetime (Figure 4(a)), however, these spatial correlations patterns have changed drastically near the top of the cloud. Suddenly numerous regions of collocated high TKE and cloud water appear, as the primary thermal circulation breaks down into many smaller eddies, as indicated in the velocity field (Figure 4(b)). If this breakdown is realistic, this result suggests that enhanced droplet collisions predicted by DNS results using high cloud water and TKE values may be applicable at higher altitudes and later stages of the cloud lifetime. Such enhanced collection among the droplets would have the greatest impact at this time. Large drops formed at cloud top are able to collect much of the cloud water below as they fall through the cloud, maximizing the amount of precipitation brought to the ground. The realism of the evolution of these spatial correlations, however, must be investigated further with studies of the entrainment itself, and by comparison to in situ observations collected by instrumented aircraft flying through warm cumulus clouds.
cloud edge) than those ascending straight up the core of the cloud. Within the turbulent eddies, entrainment depletes the cloud water significantly (note the sudden change in the trajectory color to dark blue, indicating minimal cloud water). Thus, the regions of the turbulent eddies themselves are not as promising for accelerated raindrop formation because little cloud water (few drops) occupy those regions. However, further scrutiny of the droplet trajectories indicates that a related scenario might be important. If the few drops surviving entrainment events collide and join together as a result of the high TKE in those regions and then are transported by the cloud motions into regions of greater cloud water directly afterward, they would potentially scavenge much of that cloud water, and be responsible for the first few raindrops formed in the cloud. This hypothesized sequence of events can occur as shown in Figure 5(d), where it is simple to evaluate visually with the new analysis system. As drops caught up in the eddies experience values of high TKE as indicated by the color of their spheres, the trajectory color in the time steps immediately following the high TKE event can be scrutinized to discern if these droplets are then entering high cloud water regions. This scenario has occurred in the trajectories shown in Figure 5(d), where immediately after the loops in the trajectories, the trajectory color becomes warmer indicating regions of higher cloud water are being encountered by the drops. If only 0.1% of the droplets experience greatly accelerated growth by this sequence of events, however, this number would be sufficient to explain the formation of the first raindrops in warm cumulus clouds. Further study is required to quantify the frequency of this sequence of events in the droplet trajectories, and to understand the generality of this result with respect to other cloud simulations and by comparison with real observations.

It is interesting to note that this signature of potential accelerated growth of droplets due to high TKE followed by entry into a high cloud water region has a similar appearance to the other mechanism described in Section 3.1, the influence of entrainment and mixing at the cloud edge. In that proposed mechanism, the droplet collection process is not enhanced by the introduction of dry air into the cloud, but instead droplet growth by condensation is enhanced by reduced competition for the water vapor available for growth. As demonstrated by [22], the introduction of these growth-enhanced droplets into high supersaturation (the amount of relative humidity exceeding 100%) in the core of the cloud is capable of producing large drops quickly. The analysis performed here has not contradicted such results but has indicated that enhanced collection growth could be occurring as well. Future study is required to determine which mechanism is dominant. The visual analysis system presented here can include additional fields such as supersaturation, cloud droplet number concentrations, etc., and will prove helpful in this endeavor.

5.2 Model Validation and Improvement in Severe Storm Forecasting

Recently, computing power has advanced to the point where large-domain, convection-allowing numerical model forecasts can be executed quickly enough to be used in real-time forecasting environments. Specifically, the past two Storm Prediction Center/National Severe Storms Laboratory (SPC/NSSL) Spring Programs [17] have obtained output from experimental runs of the WRF model to evaluate the utility of such models in realistic severe weather forecasting situations. During the 2005 Spring Program, forecasters and researchers examined the performance of WRF model forecasts of equivalent radar reflectivity and storm rotation by visually comparing 2D fields of reflectivity values and diagnostic measures of storm rotation in the model output and radar measurements. We will first examine the type of information that can be obtained by such traditional comparisons, and contrast this with the information that we are able to obtain using the atmospheric visual analysis and exploration system described in section 4.

In a traditional validation analysis, for example, Figure 6(a) shows a typical display of predicted reflectivity from the Advanced Research WRF (WRF-ARW) core, using the mass-coordinate dynamics package running at 4 km horizontal grid spacing with 34 vertical levels. The domain size was 970 x 740 x 34, which covered the eastern 2/3 of the contiguous 48 states, and forecasts were run out to 30 h, beginning at 0000 UTC each day. The model forecast was compared to a similar display of observed radar data, such as that shown in Figure 7. In this instance, one can see that the forecast was generally too far north with the convective rainfall, while the basic morphological characteristics of the predicted rainfall pattern (orientation, structure, intermittency) generally match that of the observed pattern.

To validate the WRF model’s prediction of storm rotation during the 2005 Spring Program, several diagnostic fields were computed based upon various measures of swirl and turning of the wind with height. For example, a supercell detection index (SDI) was computed to help the forecasters identify supercell thunderstorms within the WRF model output. This index was based on previous work [6, 16] that identified regions of high correlation between a storm’s updraft velocity and vertical vorticity as deep, long-lived, rotating circulations. In practice, if the SDI value exceeded a specified threshold, that region would be highlighted using a color-filled 2D plot. In the WRF forecast shown in Figure 6(a), the supercell index (not shown) did not exceed the threshold, indicating to forecasters that no deep, long-lived rotation was found. Observations of storm rotation were obtained from a mesoscale detection algorithm applied to Doppler radar wind measurements [31].

The traditional methods for validating the numerical model have shown the forecast to be too far north with convective rainfall, and perhaps under-predicting the intensity of the rotation of the circulation associated with the predicted updrafts. It is difficult to determine from this information whether the model actually predicted rotating circulations that were just below the threshold for the supercell detection index, or if the full 3D structure of the predicted storms showed any resemblance to what was observed. To obtain more information along these lines, the atmospheric visual analysis and exploration system was used to compare the three-dimensional structure of multiple atmospheric variables in the WRF model and radar observations.

Figure 6(b) displays physics-based atmospheric rendering of hydrometeor variables (cloud, rain, snow, ice, graupel) from the WRF model, using our multi-scattering, multi-field photorealistic rendering system. Comparing this to the observed radar data, also using physics-based rendering (Figure 7(b)), one can determine that the basic 3D structure of the precipitation system predicted by the WRF model is basically correct. We can also combine information on the rotation of the winds with the hydrometeor information (Figure 8). In this figure, the WRF forecast vertical vorticity has been computed using the atmospheric visual analysis and exploration system described in section 4, and illustratively rendered using a 1D transfer function within a semi-transparent rendering of the hydrometeor information. This 1D transfer function maps value range [-445, -270] to blue and value range [270, 445] to red. By examining the multivariate information in this fashion, we can see that the WRF model did, in fact, predict rotating winds along the south and west flank of the convective system, similar (but further north) to the observed locations of the mesocyclones relative to the observed convective system.
Compared to previous work, our system is more suitable for atmospheric visual analysis and exploration. Photorealistic rendering of clouds from our system allows meteorologists to visually compare their data with observed events. Applications of 1D and 2D transfer functions eliminate the limitations of univariate field visualization of many previous systems.

While our system has proven to be quite adaptable to different meteorological visualizations, we intend to add more visualization and rendering enhancements to provide users with the highest possible degree of flexibility, particularly in cases where event locations, topography, and map projections are concerned. Future plans include creating advanced transfer functions for better feature extraction and system validation through user studies. Future applications for this system include a visual analysis of Doppler radar data and integration with other meteorological radar tools, such as the Warning Decision Support System - Integrated Information (WDSS-II). We hope these future enhancements and applications will eventually provide scientists with a more comprehensive meteorological visualization software tool.

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