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15B.6 4-D VISUALIZATION OF STORM-SCALE FORECASTS USING VAPOR IN THE HAZARDOUS WEATHER TESTBED SPRING FORECASTING EXPERIMENT

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1 INTRODUCTION

Since 2007 the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma (OU) has produced an ensemble of numerical weather predication (NWP) forecasts at storm-allowing horizontal grid spacing (4-km and 3-km) covering the contiguous United States (CONUS) for the Spring Forecasting Experiments (SFE) in the Hazardous Weather Testbed (HWT). These forecasts are known as the CAPS Storm Scale Ensemble Forecasts (SSEF, Kong et al., 2016, Kong et al., 2015, Johnson et al., 2014). In order to gain greater understanding of the dynamics and morphology of forecasted storms and possible attendant severe weather indicated by these forecasts, we endeavored to provide three-dimensional (3D) visualization images and animations of these images to produce four-dimensional (4D) visualization of NWP output for use in the HWT daily weather briefings and for further study.

The **V**isualization and **A**nalysis **P**latform for **O**cean, Atmosphere, and Solar **R**esearchers (VAPOR, Clyne et al., 2007, Clyne et al., 2005) program from the National Center for Atmospheric Research (NCAR) is selected for this task. However, the large size of the NWP output data sets and the fact that they are produced off-site presented some logistical challenges.

This paper briefly describes the SFE, including the CAPS SSEF, the workflow that was developed to automate the transmission and processing of the data for visualization, and presents a few examples of 3D visualization images from animations produced during the HWT SFE.

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2 SPRING FORECAST EXPERIMENT

For more than a decade the NOAA Storm Prediction Center (SPC) has teamed with the National Severe Storms Laboratory, academic and research units, such as CAPS, NCAR and others, to test and evaluate new forecasting techniques each spring in the HWT Spring Forecasting Experiment (Clark et al., 2013).

A key element in the SFE has been the use of convection allowing NWP forecast ensembles. The largest ensemble, consisting of 20 or more members each year is the CAPS SSEF. In-2014 the CAPS SSEF was run with 4-km grid spacing in a domain covering the contiguous United States (CONUS). This was refined to 3-km for 2015 and 2016. The CAPS SSEF recently has consisted of WRF ARW and WRF NMM model members with initial condition, boundary condition perturbations and/or permutations to the model microphysics, boundary layer physics or land surface physics. The control member and most other members are initialized using the CAPS 3DVAR with complex cloud and precipitation analysis (Brewster et al., 2015, Hu et al., 2006, Xue et al., 2003) that includes conventional observations and data from 120 WSR-88D radars from across the country.

The large computational costs of running all the NWP members of the CAPS SSEF exceeds the local computing capacity at OU, so high performance computing resources of the National Science Foundation Extreme Science and Engineering

Discovery Environment (XSEDE) have been used to generate the real-time forecasts of the CAPS SSEF. Specifically, for 2014-2016, computers at the National Institute for Computational Sciences (NICS) at the University of Tennessee and the Texas Advanced Computing Center (TACC) at the University of Texas were used.

3 DATA PROCESSING WORKFLOW

During the SFE two-dimensional fields of popular variables at specific levels are extracted from the SSEF members and transmitted to Oklahoma from the XSEDE computing center (either NICS or TACC) over Internet2 and intrastate to OU on the OneOklahoma Friction Free Network (OFFN). Although bandwidth and realized throughput is higher on these networks than the commercial Internet, the size of all the full-volume 3D NWP output at hourly intervals is too large to send in real-time in its entirety. Also, for the purposes of studying morphology it is desirable to have NWP output at even higher temporal resolution.

Table 1 lists some of the relevant output file sizes for the models in the SSEF as configured for 2014 and 2015-2016. For the available bandwidth and the available computing for visualization, the file sizes are too large to be able to transmit, process and analyze the full NWP forecast volume for the HWT.

To address this issue, we have created scripts to extract a relevant sub-domain of 200x200 grid points from the NWP output files and transmit these extracted 3D data at sub-hourly intervals (10-min in 2014 and 6 min in 2015-2016) to OU. The location of this domain is determined manually each day, either from the previous day's forecast or an update to the domain selection made in the early morning based on examination of 2D reflectivity forecast fields. The reduced file sizes are indicated in Table 2, sizes that can be transmitted in less than 30 minutes for each ensemble member. Four or five members, including the control member and the microphysics diversity members, are subsetted and archived locally.

Once the files are received at OU, the files for the control run are copied over the local GB intranet to a laptop where they are converted to the VAPOR data format (VDF) files that are used in the rendering. The complete workflow is illustrated in Fig 1

Figures 2, 3 and 4 show the sub-domains that were processed in years 2014, 2015 and 2016, respectively. Note that the size of the subdomains were larger in 2014 because the grid spacing was 4-km in 2014 versus 3-km in subsequent years.

In addition to developing the scripts for the data handling, Python code has been added to the VAPOR program to produce diagnostic products relevant to the SFE such as updraft helicity, theta-e, horizontal wind speed, total wind speed, total liquid and frozen hydrometeors, etc. Also several custom color tables were devised that are suitable for the variables plotted in the SFE.

Table 1. File sizes for full CONUS domain data

	2014	2015-2016
Grid Spacing	4 km	3 km
Domain Size	1163x723x53	1683x1155x53
One Output Time	4.2 GB	9.7 GB
Sub-Hourly Interval	10 min	6 min
Complete Forecast Size Hourly & Sub-Hourly 18h-30h	508 GB	1639 GB
Sub-hourly 18h-30h Only	307 GB	1174 GB

Table 2. File sizes for subsetted domain.

	2014	2015-2016
Grid Spacing	4 km	3 km
Domain Size	1163x723x53	1683x1155x53
One Output Time	4.2 GB	9.7 GB
Sub-Hourly Interval	10 min	6 min
Complete Forecast Size Hourly + Sub-hourly 18h-30h	508 GB	1639 GB
Sub-hourly 18h-30h Only	307 GB	1174 GB

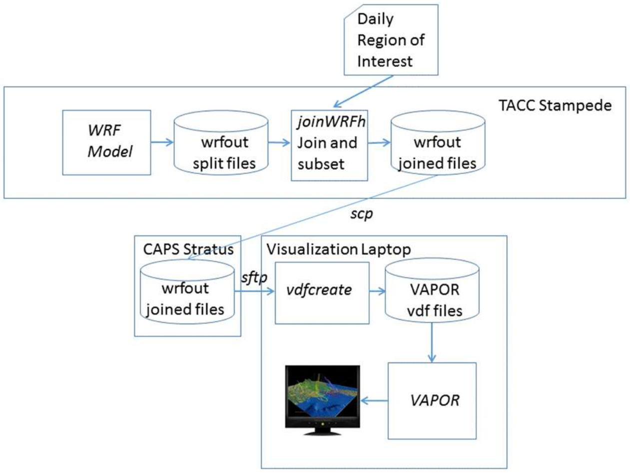

Figure 1. Workflow for 3D data subsetting, transmission and subsequent visualization processing.

4 SAMPLE PRODUCTS

In this section sample products from four different types of visualization are presented for relevant cases.

4.1 Updraft Helicity

Updraft Helicity (UH) is a variable that is commonly examined in 2D as an integrated field, often from 2 to 5 km AGL (Kain et al., 2008). The field can also be examined as a local updraft helicity at each grid point and direct volume rendered, *viz*:

$$\boldsymbol{UH(x,y,z) = w \cdot \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)}$$

Figure 5 is an example of volume rendered UH for a supercell storm case from 27 May 2015, valid at 0000 UTC 28 May 2015. This is one frame of an animation located at URL:

http://www.caps.ou.edu/~kbrews/hwt_2015/20150527_uhloc.mov

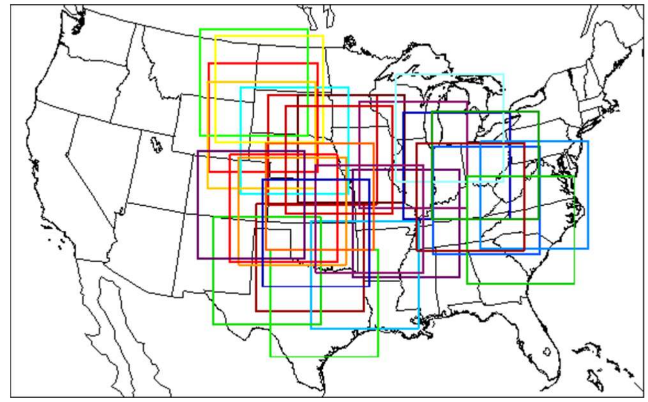

Figure 2. Locations of 3D sub-domains used in Spring 2014.

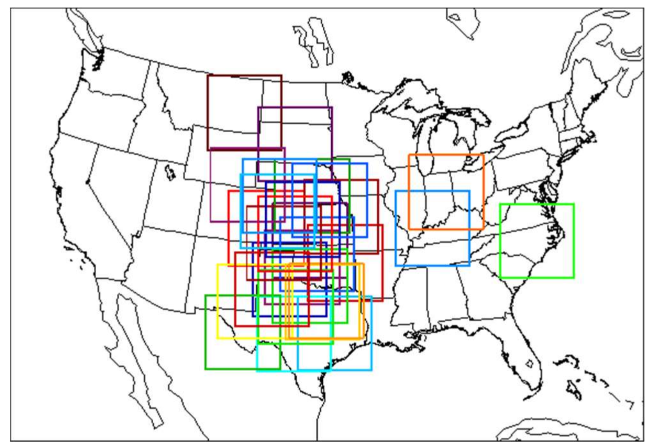

Figure 3. Locations of 3D sub-domains used in Spring 2015.

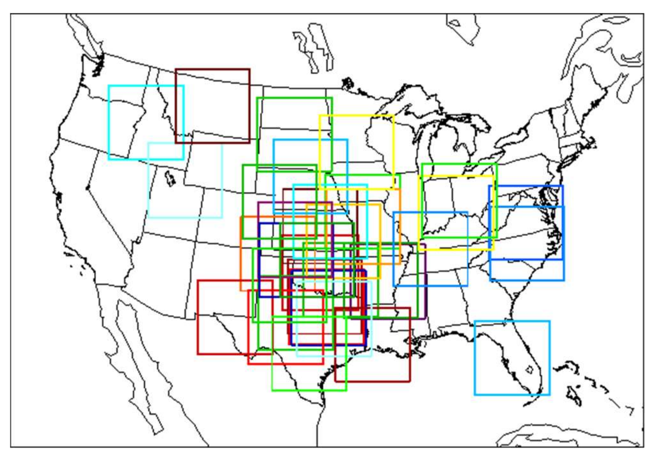

Figure 4. Locations of 3D sub-domains used in Spring 2016.

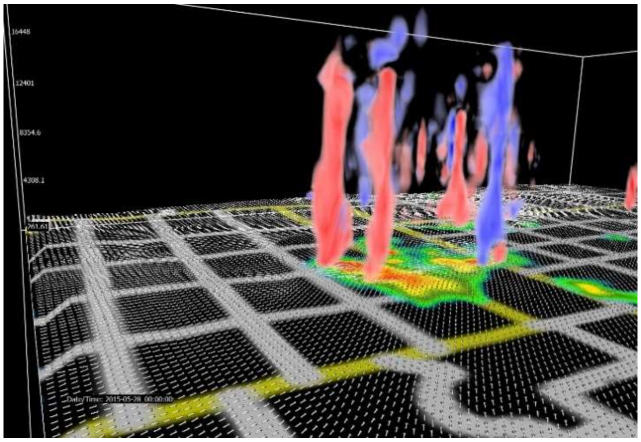

Figure 5. Visualization of CAPS 3-km control forecast valid at 0000 UTC 28-May-2015. Updraft Helicity (positive red, negative blue), low-level reflectivity and low-level wind vectors. County boundaries in white, state boundaries in yellow, looking northwest into the Texas Panhandle

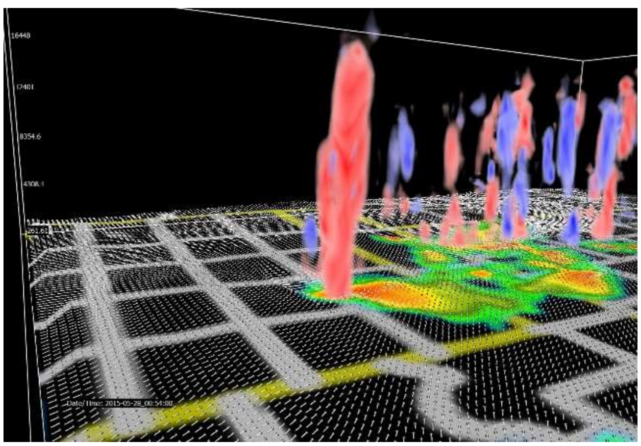

Figure 6. As in Fig. 5 for forecast valid at 0054 UTC 28-May-2015

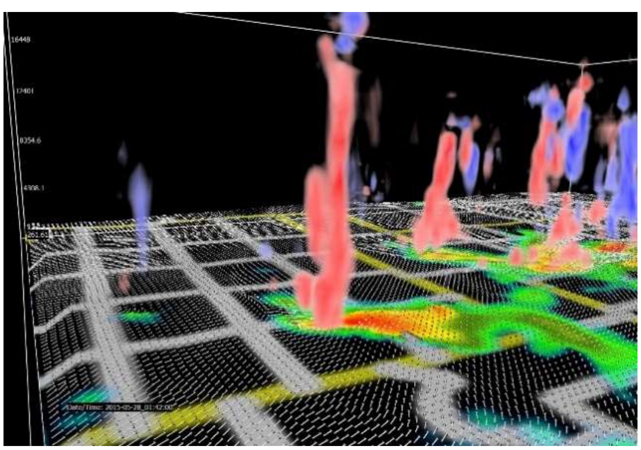

Figure 7. As in Fig. 5 for forecast valid at 0142 UTC 27-May-2015.

In this figure the positive UH (rotating updrafts) are shown in red, while negative UH is shown in blue colors. When volume rendered in this way stronger supercells appear with columns of high values of positive UH with large width and tall vertical extent. Time continuity is examined in the animations to gauge persistence of UH features.

In this case strong UH columns were present in the renderings that increased in depth and width with time (Fig 6), before narrowing again an hour later (Fig. 7). Other fields included in Figs. 5-7 are the low-level winds and simulated low-level reflectivity. The low level wind and reflectivity features confirmed supercell structure with inflow converging at the base of the UH columns in the southwest quadrant of the low-level reflectivity echo in the northeast Texas panhandle. On this day, the forecast verified with a long-lived supercell storm that produced severe hail and tornadoes in the Texas panhandle and southwest Kansas (Fig. 8) including a significant EF-2 fatal tornado near Canadian, Texas (Fig. 9), just south of where the forecast indicated the storm with the strongest UH column.

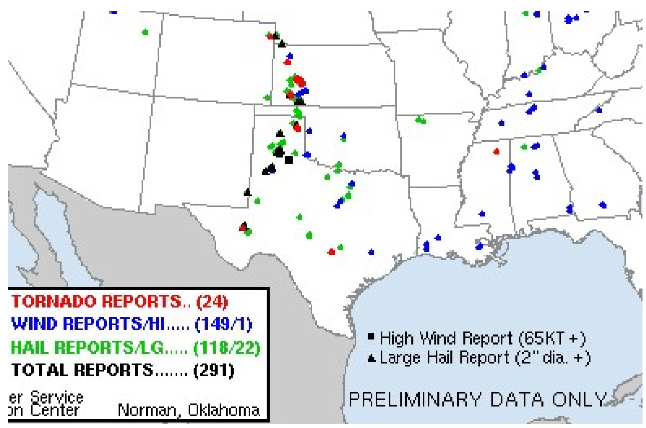

Figure 8 Preliminary Storm Reports for 1200 UTC 27 May 2015 to 1200 UTC 28 May 2015. From NOAA Storm Prediction Center.

Figure 9. Photograph of tornado in the northeast Texas panhandle near Canadian, Texas on 27 may 2015. Photo by Derek Stratman.

4.2 Horizontal Wind Speed

In some situations, the primary severe weather threat is severe wind gusts. Figure 10 shows a volume rendering of horizontal wind speed greater than 25 ms^{-1} for the afternoon 3 May 2016 for a domain centered along the South Carolina coast. Volume rendering was cut off at 10 km MSL to focus on mid- to low-level winds. Also shown in this and subsequent figures are wind vectors near the surface colored by equivalent potential temperature (θ_e). Evident in Fig. 10 are the strong winds aloft in the layer above 4 km with the depth and magnitude of the jet structure increasing toward the west.

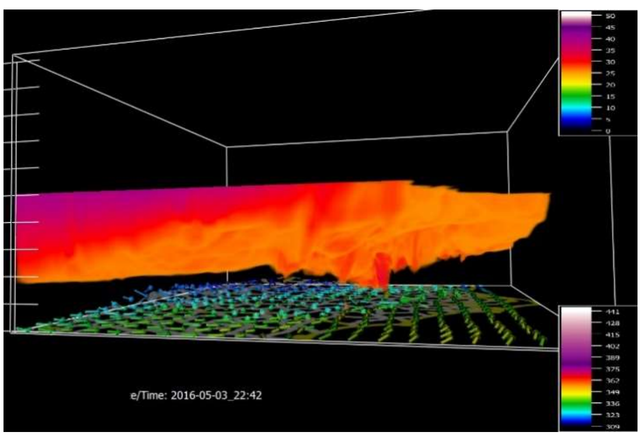

Figure 9. Visualization of CAPS 3-km control forecast valid at 2242 UTC 3-May-2016. Horizontal wind speed (colors, upper scale), low-level wind vectors (theta-e colors, lower scale). County boundaries in white, state boundaries in yellow, looking north along the east coast of the United States toward the Carolinas.

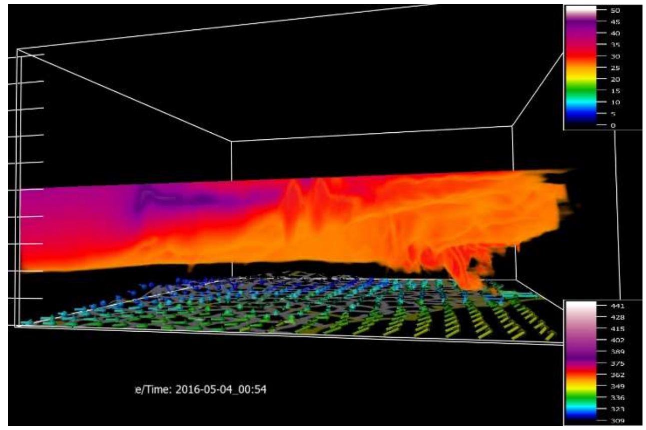

Figure 10. As in Fig. 10 but for 0054 UTC 4 May 2016.

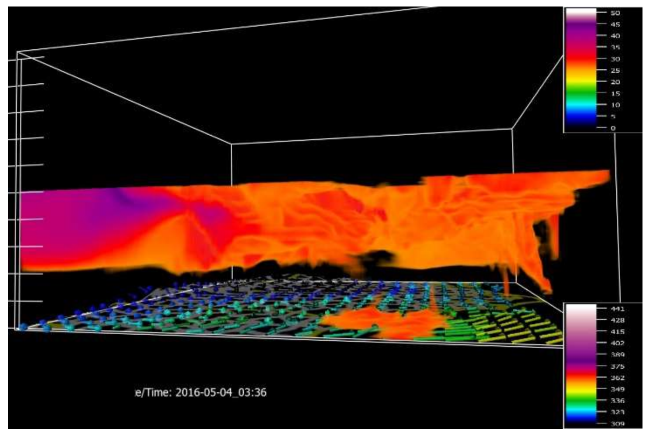

Figure 11. As in Fig. 10 but for 0336 UTC 4 May 2016.

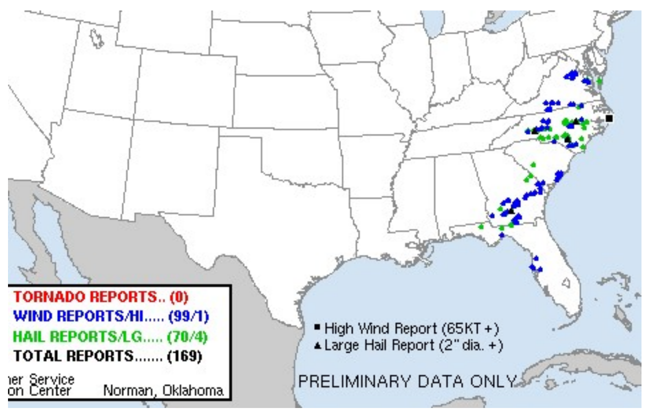

Figure 12. Map of preliminary storm reports for 1200 UTC 3 May 2016 to 1200 UTC 4 May 2016. From NOAA Storm Prediction Center.

The URL for this animation is: http:/www.caps.ou.edu/~kbrews/public_html/hwt_2016/20160503/movies/20160503_HSpeed.mp4

There is some evidence of mixing down of the higher wind speeds aloft by convection near the center of the domain. Early in the evening, (Fig. 11, 0042 UTC) mixing and acceleration down to the surface is evident near the North Carolina coast. Later in the evening (Fig 12, 0336 UTC) that area has moved offshore and a second area of strong winds appears in the model along and near the South Carolina coast. Looking at just wind speeds near the surface one may not be able to distinguish between those two areas of high winds, while in 3D, one can tell are produced by two different mechanisms. Figure 13 shows the verification preliminary storm reports for this case.

4.3 Supercell Transition

In the case of 17 May 2016 VAPOR is used to examine supercell transition to squall line with more outflow winds. Figure 14 is an image showing volume rendering of updraft helicity (positive only), low-level winds colored by θ_e and backward trajectories that end in updrafts (yellow traces). In Fig. 14 we see several UH columns and trajectories flowing in from low-levels supplying high θ_e air to what appear to be supercells in the model fields.

Later, at 0430 UTC (Fig. 15) the UH cores are lined-up and nearly merged together. Some trajectories are coming from the southeast, but in the western half of the line there are also some trajectories coming from the southwest.

Figure 16 shows a volume rendering of graupel along with surface wind vectors colored by wind speed for this same case. There are three prominent cores of graupel carried aloft evident with strong northerly surface winds along the cold front but

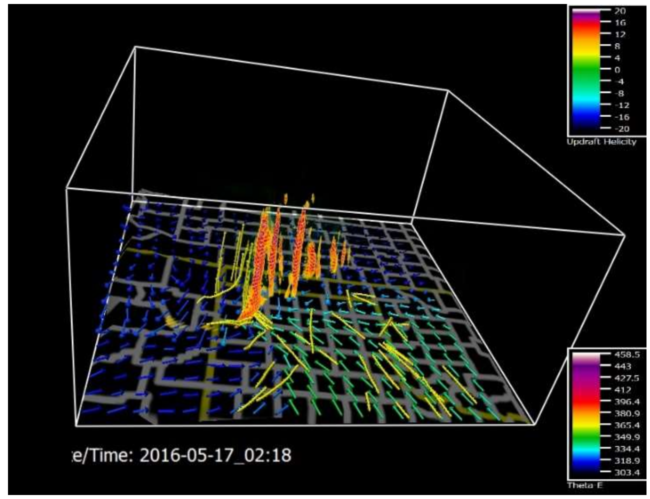

Figure 13. Visualization of 16 May 2016 CAPS control forecast valid at 0218 UTC 17 May 2016. Updraft Helicity (colors, scale at upper right), low-level wind vectors (theta-e color, scale lower right) and backward parcel tracers ending in strongest updrafts in yellow.

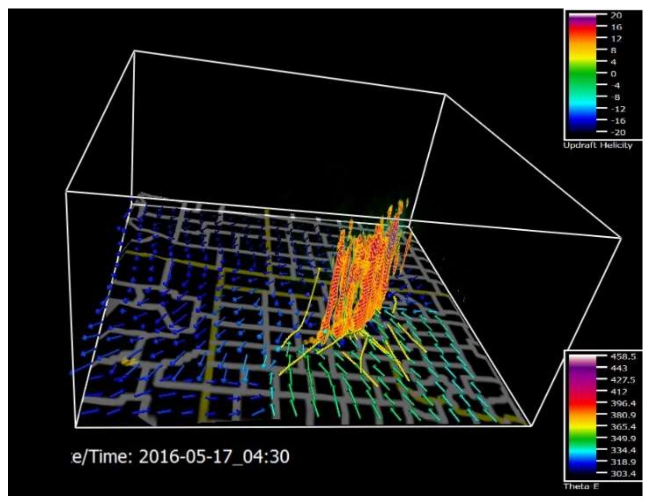

Figure 14. As in Fig. 14, but for forecast valid at 0430 UTC 17 May 2016

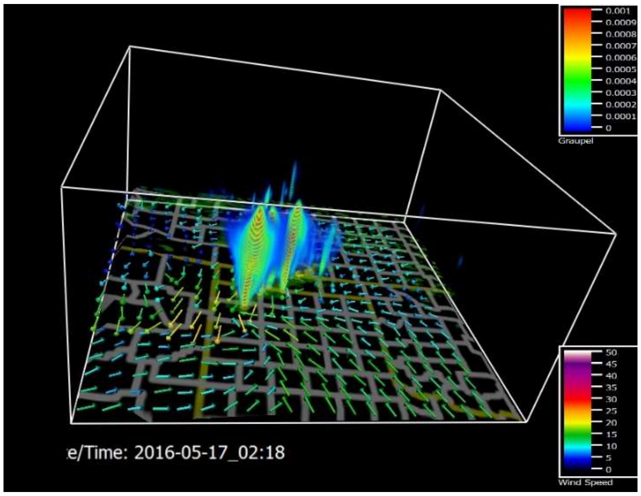

Figure 15. Visualization of 16 May 2016 CAPS control forecast valid at 0500 UTC 17 May 2016. Graupel mixing ratio (g/kg, color scale upper right) and low level wind vectors colored by horizontal wind speed (scale lower right).

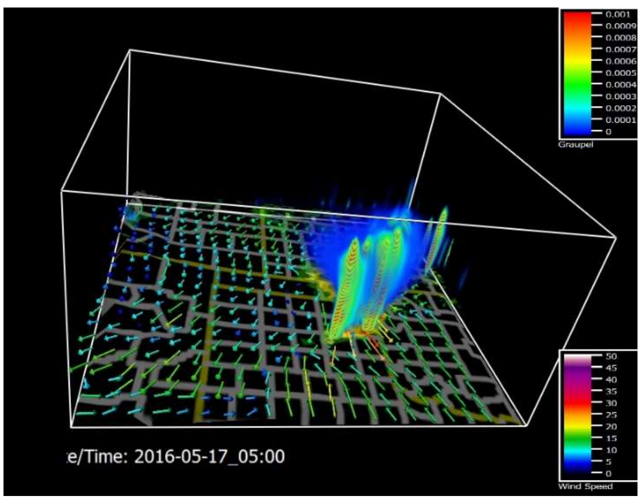

Figure 16. As in Fig. 16, except for 0500 UTC 17 May 2016.

primarily west of the graupel cores. By 0500 UTC the cores are more numerous and nearly merged into a line with strong outflow vectors evident in the near-surface wind vectors, especially along the west half of the line visible here. From the combination of visualizations and their animations, available at URL:

http://www.caps.ou.edu/~kbrews/hwt_2016/20160516/movies/

one can see visualize the upscale transition from rotating supercells to outflow-dominated squall line with hail and high wind. The storm reports (Fig 18) from this day reflect this storm mode transition.

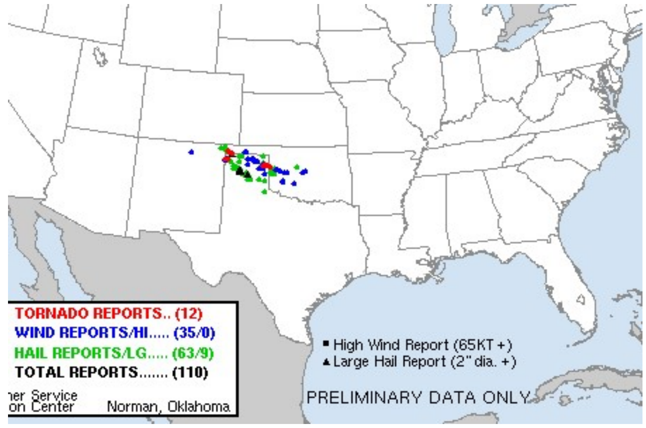

Figure 17. Map of preliminary storm reports for 1200 UTC 16 May 2016 to 1200 UTC 17 May 2016. From NOAA Storm Prediction Center.

5 CONCLUSIONS & FUTURE PLANS

For the last few years CAPS has arranged the logistics to bring full 3D subsets of convection-allowing models to the SFE in the HWT. It has been shown that 4D visualizations can be produced in real-time that may be of use to operational severe weather forecasters. A set of variables and variable combinations for 3D volume rendering and 4D animations has been developed through experience in the HWT. These seem to be useful in gaining greater understanding of the model output. For example, they can be used to diagnose supercell characteristics, detect and diagnose the source of high wind speeds at the surface and diagnose upscale transition of supercells to squall lines.

Interested readers can explore on their own other visualization from the 2016 HWT at the URL:

http://www.caps.ou.edu/~kbrews/hwt_2016/

The generation of the 4D visualizations still involves a number of manual steps. Although, with some practice, those manual steps can be carried out in a relatively short period of time, in order for such visualizations to be produced some day in an operational setting additional automation will be necessary. The VAPOR development team is current working on adding additional scripting and macro capability to the VAPOR software that may be ready for public release in the 2018 timeframe (Clyne, 2016, personal communication).

In order to guide selection of relevant rendering thresholds and contour values a more complete and quantitative study of the 3D objects and documentation of the evolution of their characteristics (height, width, magnitude) over time would be very useful. Finally, the 3D model fields for several microphysics members have been saved and are available for further study to see how the characteristics of 3D features, such as graupel or hail columns might vary for different microphysics schemes.

6 ACKNOWLEDGMENTS

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