

Visualization of an Above Anvil Cirrus Plume in a Supercell Thunderstorm

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ABSTRACT

We present a visual investigation of the simulation of a supercell thunderstorm. The numerical simulation and subsequent analysis was conducted on the Frontera system at the Texas Advanced Computing Center. The visualization utilized a variety of software including Paraview, OSPRay, and a collection of other post processing tools. The process involved creating a collection of data at fifty meter spatial resolution and 1/3 second temporal resolution. The temporal resolution was chosen to capture every model time step during the formation and evolution of an above anvil cirrus plume (AACP). These features are indicative of energetic storms that typically produce more violent weather and are typically observed from weather satellites. In addition to being a flag for severe weather, these structures inject water vapor and ice into the stratosphere. The presence of moisture in the characteristically dry stratosphere has been linked to ozone depletion. The visualization explores the formation and time evolution of the AACP using a collection of visualization methods. Visualization of conditions inside the storm provided insight into the mechanism that produces the cirrus plume.

INTRODUCTION

A thunderstorm forms when warm, moist air rises rapidly through the troposphere under unstable atmospheric conditions. Rising bubbles of air comprising thunderstorm updrafts remain positively buoyant so long as they remain warmer than their surrounding environment which is typical in cases of atmospheric instability. In strong thunderstorms, updrafts will grow upwards into the tropopause, the region separating the more moist and unstable troposphere from the very dry, stable stratosphere. Neutrally or negatively buoyant updraft air will often “overshoot” the tropopause owing to its momentum, extending upwards into a dome of cloud called the overshooting top. Subsequently, this air will rapidly decelerate vertically and spread horizontally, forming the thunderstorm’s anvil.

A feature called an Above Anvil Cirrus Plume (AACP) has been observed in some supercell thunderstorms by both aircraft and satellite data and has also been the subject of numerical study. The AACP is observed as an elongated elevated “tier” of ice cloud that extends downwind from the overshooting top. This feature is of great interest to atmospheric researchers and forecasters because $\frac{3}{4}$ of all supercells exhibiting AACPs were associated with severe weather (large hail and/or damaging winds/tornadoes). Understanding the specific conditions by which AACPs form in supercells is therefore of great interest, as they have the potential to serve as a useful “nowcasting” device during severe weather outbreaks. Further, the presence of water substance in the stratosphere has been linked to ozone depletion, as the injection of water into the stratosphere is considered an irreversible process. However, it has not yet been established just how much ozone destruction results from thunderstorm activity, and typical AACP-producing supercell simulations in the published literature are run at too coarse a resolution to properly study this effect.

In order to better understand the nature of AACPs and their relationship to thunderstorm severity and stratospheric moistening, eddy-resolving simulations of supercells that produce AACPs are compared to those that do not. A constant, isotropic grid spacing of 50 meters was used

throughout the entire model domain in all simulations, significantly higher than what is typically reported in the literature. Further, by utilizing a fine, isotropic mesh, the thunderstorm's top, typically occurring within a region of coarse vertical resolution owing to the use of a stretched mesh that focuses resolution near the ground in most published literature, is properly resolved and does not suffer from artifacts associated with highly anisotropic meshes.

SIMULATION

The Cloud Model 1 (CM1) developed by George Bryan, was used to simulate 1.5 hours of storm evolution on a 50 meter grid. The domain size of the computation was 243 km by 241 km by 30 km, spanning over 14 billion grid zones. In order to reduce the size of the model output, only a portion of the model domain was output. This extent ran from 11 to 21 km above the ground, centered on the thunderstorm overshooting top. The cell count of the output data in each coordinate direction was (1364, 1500, 200). This part of the grid consisted of over 400 million grid cells.

The output variables were cloud ice, cloud water, storm relative horizontal wind, vertical wind component, vorticity magnitude, and temperature. In the simulation, the x direction corresponded to east and y corresponded to north. The storm itself moved roughly southeast, and the model domain tracked with the moving storm. CM1 model output was written in HDF5 format, and a utility was used to convert to NetCDF4 files that were used for analysis herein.

As mentioned above only the domain of interest was output in order to reduce the volume of data. Lossy compression was also employed to further reduce the amount of data. The ZFP library from LLNL was used in conjunction with NetCDF4 to write the compressed files. The use of lossy compression was very effective in this instance as the precision was not needed for visualization. As an example of how much disk space was saved we calculate that the six variables stored at 409 million plus grid cells at single precision of 4 bytes per variable would amount to roughly 9.8 GB per output file. The actual size of the output files were on the order of 500 MB, a significant reduction.

VISUALIZATION

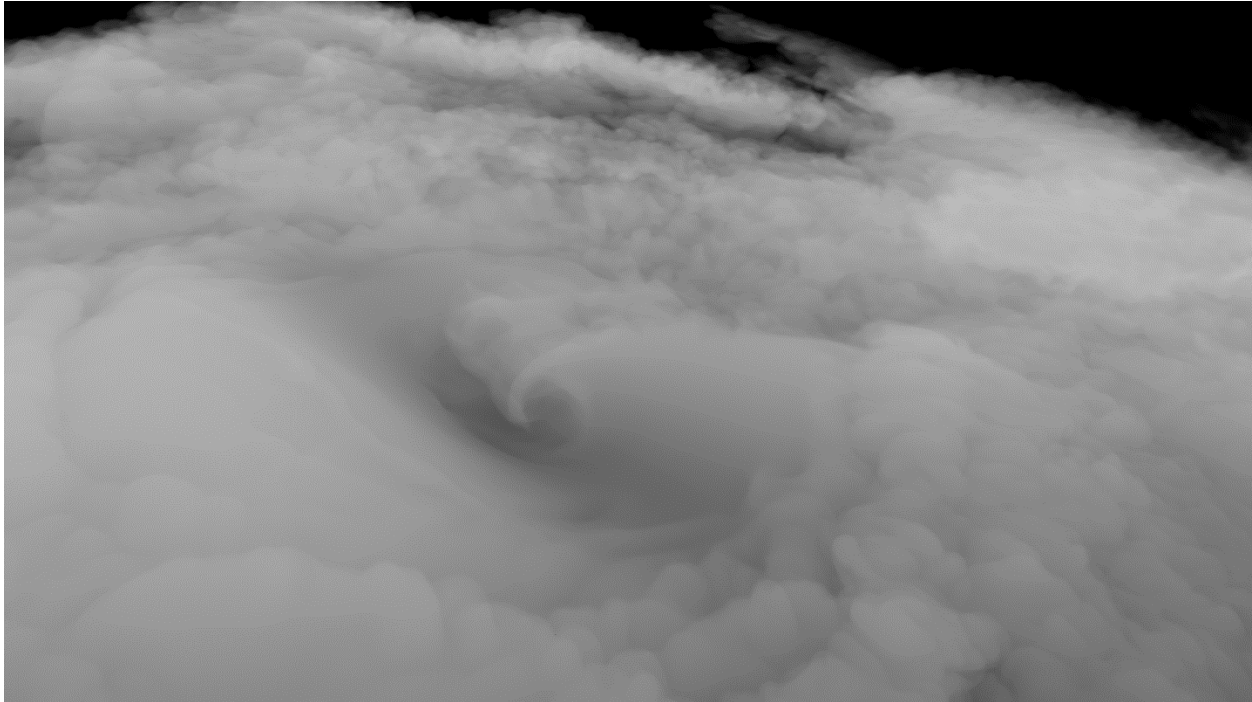
A variety of methods were used to visualize the data. Initial investigation was done on Frontera using Paraview in parallel. Eight nodes were used and the data was spread over eight mpi ranks on the nodes, one rank per node. The parallelism greatly improved IO performance as well as the performance of the visualization algorithms.

The visualization process began by using Paraview to explore the upper surface of the thunderstorm anvil for signs of development of the AACP. The expected location of development was known and so it was a matter of searching through the time series data using volume visualization to narrow down the time interval. Once the time interval of development was identified a more detailed examination of the area commenced.

Volume visualization of cloud ice revealed the development of the AACP resembled a breaking wave rather than a fountain or bubble as one might expect given the appearance of this cloud form from satellite imagery. At this point animations were created to verify the wave like dynamics. Animation of the data was instrumental in determining how the AACP developed and formed over time. This process was done on Frontera as a batch task.

The workflow for the production of each animated sequence in the analysis was basically the same. Paraview was used to create a python visualization script. The script contained Paraview

batch commands to read data, create the visualization, and save an image. This script was modified to accept a dataset name and output image name. A batch process was created that launched instances of this script cycling through the data range of interest and producing sequences of frames in parallel. Once a collection of frames was available ffmpeg was used to build the video file. While the Paraview UI supports the creation of animations we found this method to be a more efficient way to produce several animation sequences in parallel.

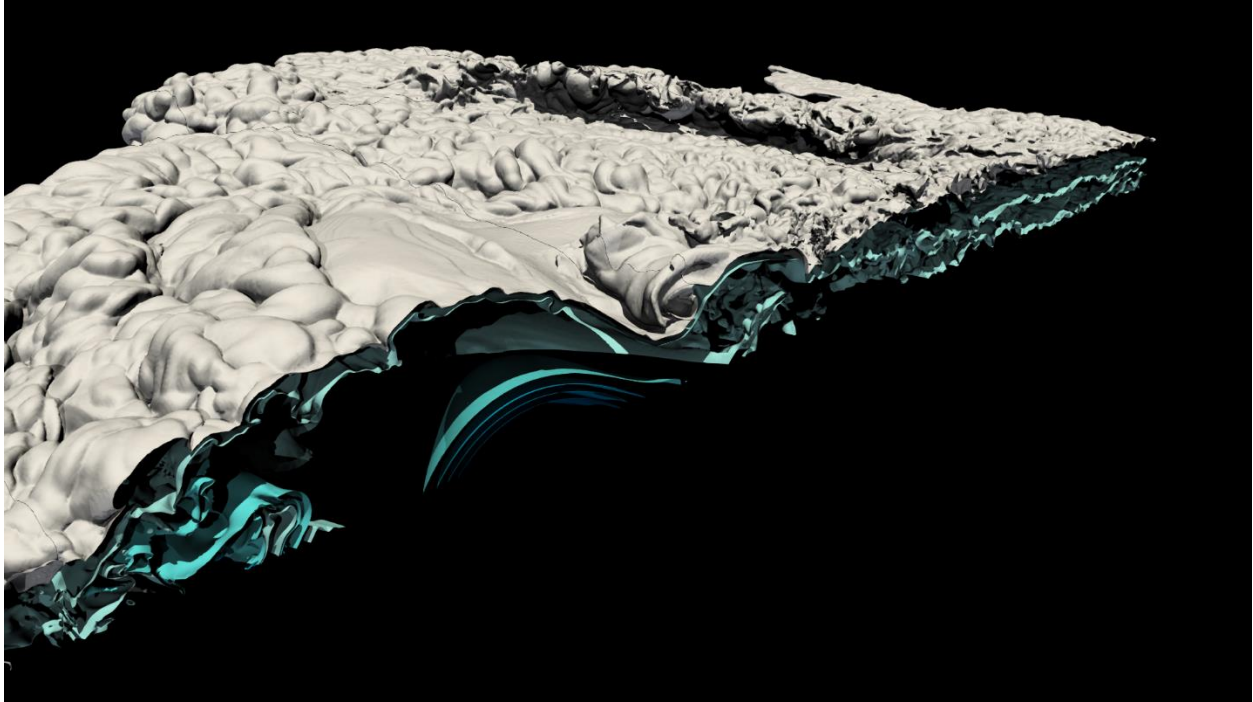


The image above shows the breaking wave that immediately precedes AACP formation. The volume render used a transfer function that mapped cloud ice concentration in the range of 0.01 – 0.1 g/kg to opacity. The choice of color transfer function was obviously white, as it's a cloud.

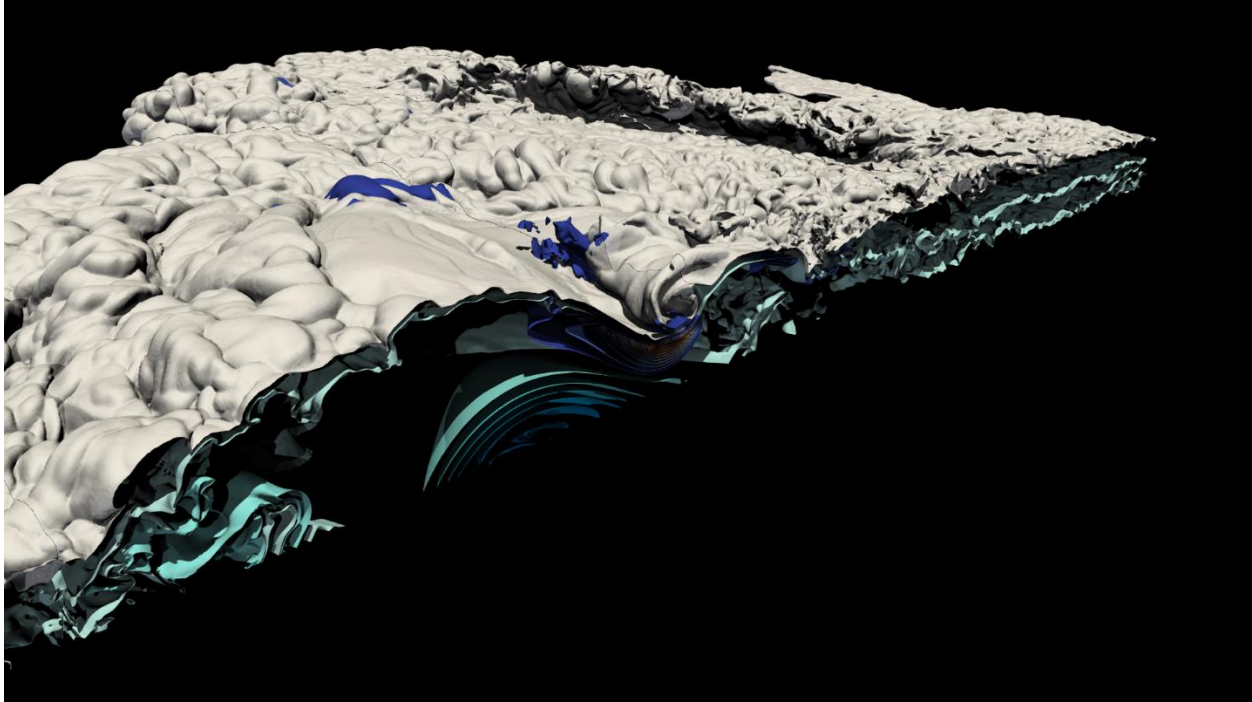
Shore waves break due to a reduction in water depth as the wave approaches shore. That mechanism is not at work here since the depth of the atmosphere does not change locally. Another possible driving mechanism for the wave formation was a hydraulic jump. The hydraulic jump forms when fluid at high velocity discharges into a region of low velocity. This phenomenon occurs in open channel flows and naturally in streams.

In order to support the idea of hydraulic jump forming this AACP in the simulation the visualization techniques shifted to the use of isosurfaces to examine the internal structure of the cloud. The search was on for the region of high speed flow. For this we examined the cross section of the cloud perpendicular to the north south direction. At a position that cut through the AACP. We visualized ten equally spaced contours of cloud ice in the range of 0.01 to 7.5 g/kg. This view was very informative in that it showed the movement of cloud ice inside the anvil, around the overshooting top, and in the AACP. Animations produced in the same manner as the volume rendering of the cloud showed the clear evolution of the breaking wave of the AACP and the resulting upwelling of cloud ice above the overshoot. Also apparent was the movement of cloud ice in the leading edge of the anvil and in the anvil downstream of the overshoot.

Evidence of the presence of high horizontal winds inside the cloud was found by examining ten equally spaced isosurfaces of horizontal storm relative wind magnitude in the range of 60 to 100 m/s. These contours were rendered along with the contours of cloud ice to show the relationship between the location of the high winds and the location of the AACP as indicated by the cloud ice contours.



The image above shows the cross section of the cloud ice rendered at the same instant in time but from a slightly different perspective than that of the previous image. Apparent are the breaking wave and the internal distribution of cloud ice.



The image above contains the isosurfaces of horizontal wind. The collection of isosurfaces can be seen to be concentrated just in front of the AACP wave and just at the edge of the cloud. This confirms the presence of relative high speed fluid moving into a region of low speed fluid and the cause of the wave being the hydraulic jump. The colormap for the wind isosurfaces was chosen to go from blue to red with blue corresponding to low speed and red to high speed flow.

Ray tracing was used in the isosurface rendering to enhance the depth information. The OSPRay ray tracer in Paraview was used for this purpose. All the images in the paper and in the animation were produced by Paraview.

Conclusion

The paper and video describe the process of visualizing a large thunderstorm simulation. The following highlights of the work are of note.

- **Scale.** Lossy compression was used to achieve very significant reduction in storage for the simulation data allowing a higher temporal resolution to be analyzed. The visualization data required over a terabyte of storage even with the lossy compression which reduced the volume by over 80 percent.
- **Vis Technique.** Use of Lossy compression produced no degradation in visual quality.
- **HPC Impact.** Both the simulation and analysis made use of one of the largest HPC resources available for open science.
- **Science Impact.** The simulation and analysis explored the formation of an important thunderstorm characteristic, the above anvil cirrus plume. The plume is a signature of severe weather and a mechanism for injection of ozone depleting moisture into the stratosphere.
- **Vis Technique.** Visual quality was enhanced by the use of ray based rendering techniques to resolve surfaces and opacity information.