3D Weather Model Visualization

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***Abstract*—This project implements a 3d visualization of the High-Resolution Rapid Refresh (HRRR) weather model. The 3d scene can be used to observe the relationship between model parameters and how they change over time. The purpose is as a teaching tool, where the user can get a better intuition for how components of a weather system differ vertically in the atmosphere.**

***Keywords*—HRRR, 3d, visualization, teaching**

I. Introduction

Weather information is most commonly communicated in two dimensions. A horizontal slice of the atmosphere, normally along a pressure layer (a plane of constant pressure) rather than at a height above the ground, is taken and overlayed on a map of the geography below. This is an efficient way to convey information that forecasters use to inform the public about weather events. For example, to know if it will rain in a particular area, a single slice of the atmosphere is needed to show the extent of a rain cloud. Precipitation is expected with some certainty in any area under the cloud in this two-dimensional projection.

This method for displaying information, however, is unhelpful for conceptually understanding many important, vertical aspects of the formation of weather systems. This includes the vertical motion of warm air above a cold front, the formation of clouds, and the relationship between various interconnected components in the creation of complex weather systems, among other things.

This project proposes a three-dimensional visualization of the parameters from the HRRR weather model as a way to observe the interactions that are instrumental in the formation in weather, but are difficult to observe in two-dimensional representations. Specifically, in the context of the HRRR model, data can be retrieved from pressure layers at 25 hPa increments. These layers are stacked in a 3d array and visualized in the scene. More specific implementation details are in the Methods and Approach section. By interpolating between the values in these layers, vertical structures can be observed that would otherwise be hidden.

II. Related Work

Several projects and studies have been completed around the idea of visualizing atmospheric data in three-dimensions. One such project is described in the thesis paper titled “3D visualization of weather radar data” by Aron Ernvik at Linköping University from 2002. As the name suggests, the program described in the paper is used specifically for the 3d visualization of radar data, rather than a simulated weather model. The paper describes the methods used by weather radars to extract meaningful data from reflected waves at different frequencies and outlines the structure of the program they devised to visualize the data [1].

Another tool for 3d visualization is ‘Weather 3D eXplorer’ developed at the Royal Netherlands Meteorological Institute (KNMI). This tool combines data from radar, satellite imagery, and forecast models to be viewed in a 3d environment. According to the institute, the main use for the tool is for weather forecasters to study historical severe weather data [2].

III. Method and Approach

The data visualized in this project was retrieved from the NOAA High-Resolution Rapid Refresh (HRRR) model. This model simulates the atmosphere over the continental United States with some coverage of northern Mexico and southern Canada. It has a resolution of three kilometers, much higher than the similar Rapid Refresh (RAP) model with a 13 kilometer resolution. The data from HRRR is available in one hour increments and historical data can be retrieved from various online archives [3].

HRRR data is stored in the GRIB2 file format. The python library ‘Herbie’ was used to retrieve and download HRRR data [4]. Then, to extract specific model variables at different pressure layers, the library ‘pygrib’ was used [5].

The specific ordering used to create the visualizations in the Results section is as follows. First, The GRIB2 file for a specific date is downloaded using Herbie. This file contains the information for all 24 hour increments within the day. Then, the data for a specific variable (e.g. ‘Temperature’) is retrieved for all pressure layers at 25 hPa increments between 1000 hPa (close to the surface) and 400 hPa. 400 hPa is the cutoff above because the weather that is interesting to observe for the purposes of this project occurs below 400 hPa. Then, the values on each of these surfaces are combined into a 3d array. Finally, the 3d array is compressed and written to a ‘.vti’ file which can then be used in the VTK visualization. This process is repeated for each time interval in the day.

A similar process is followed to create the pressure layer component of the visualization. The data is retrieved in the same way, but, for each time step, rather than constructing a 3d array for many pressure layers, the height data of only the 1000 hPa pressure layer is retrieved. This data is then used in the visualization to create a single topographical plane. The 1000 hPa pressure layer is near to the surface of the Earth. The purpose of including it in the visualization is to show how low and high pressure regions correlate with the other visualized components.

To explain the visualization pipeline, consider an example where the data to be studied is the 24 hour increments of one day for temperature, cloud mixing ratio, and the 1000 hPa pressure layer.

For the temperature and cloud mixing ratio variables, there is a folder containing vti files for each time increment. The program iterates through each vti file, loads the 3d array, uses a vtkContourFilter to extract the isolayer corresponding to the input isovalue, then creates an actor.

For the 1000 hPa pressure layer, there is a similar folder containing vti files for each time increment. The program iterates though each vti file, loads the height information, uses a vtkWarpScalar along with a blank image to create the height-mapped topography of the pressure layer, then creates an actor.

In addition to the two variables and the pressure layer, there is a map of the continental United States placed at the bottom of the visualization for context. There are check boxes below the slider controlling the current time that allow the user to turn on or off any actor in the scene. This allows the user to better see the map by turning off the pressure layer, or let them focus on one or two specific components.

During the development of the visualization, many transfer functions were tested to replace the isosurfaces. However, all of the functions tested created artifacts in the form that made the structure difficult to discern. This was a result of the vertical resolution of the 3d arrays being much lower than the horizontal resolution.

It was decided that isosurfaces produced better visualizations than the transfer functions that were tested because the clearly defined surfaces allowed for easier comparisons of different variables, especially in the areas where the surfaces cross or are very close together. The volume rendering version made these regions, which are often the most important for studying relationships between model parameters, appear muddled and confusing.

IV. Results

The main visualization created for this project displayed three forms over a time period of two days. The forms were isosurfaces of temperature with an isovalue of 279 K, isosurfaces of the cloud mixing ratio with an isovalue of 0.0001, and the 1000 hPa pressure layer. The cloud mixing ratio is similar to water vapor mixing ratio, however, instead of measuring water vapor relative to dry air in a unit of volume, the cloud mixing ratio measures the ratio of condensed water mass to the mass of dry air in a unit of volume. Through experimentation with isovalues for this surface, it was determined that a value of 0.0001 created an isosurface that gave a good visual approximation of the presence of clouds.

Through experimentation with the isovalue for the temperature surface, 279 K was chosen. The feature desired to be observed in the temperature surface is the form and motion of cold fronts. At 279 K, a cold front makes the isosurface fold back over itself creating an 'S' shape in the cross section perpendicular to the fold. Stepping through the time increments, the major cold front present in the data can be seen moving towards the east at the same rate as the precipitation.

Fig. 1 and Fig. 2 show the entire visualization from two different angles. The red structure is the cloud mixing ratio isosurface with an isovalue of 0.0001, the blue surface is the temperature isosurface with an isovalue of 278 K, the grey surface is the 1000 hPa pressure layer, and a map of the United States is visible at the bottom.

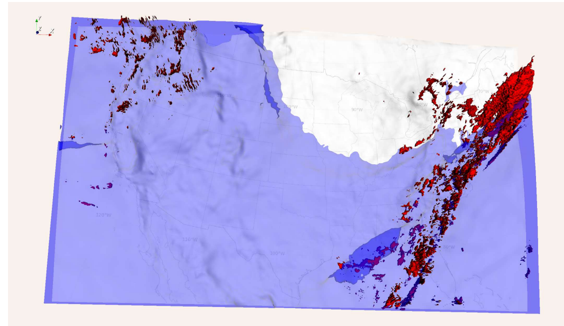

Fig. 1. Top down view of visualization: hour 2 of April 8, 2025.

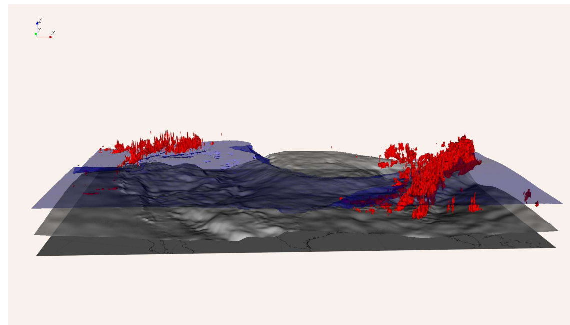

Fig. 2. Side view of visualization: hour 2 of April 8, 2025.

One specific goal for the visualization was to be able to see the relationship between cold fronts and the formation of squall lines, long lines of thunderstorms. In the northern hemisphere, cold fronts form when cold air from the north begins to circulate counter-clockwise around an area of low pressure. It can be imagened loosely like a blade of a fan rotating around its center, in this case the low pressure region. Over the continental United States, this often results in long lines of cold air moving towards the east. Cold fronts are also often associated with precipitation. Physically, this is because the cool, denser air moves like a wedge, pushing the warmer air up and making it condense into clouds. This can be seen in Fig. 1 and Fig. 2. The long red structure shows areas where a significant amount of water has condensed realtive to the dry air and rain has the potential to form. In Fig. 3, a fold in the temperature surface can be seen. This is a visual representation of the cold front wedge moving into an area of higher temperature air.

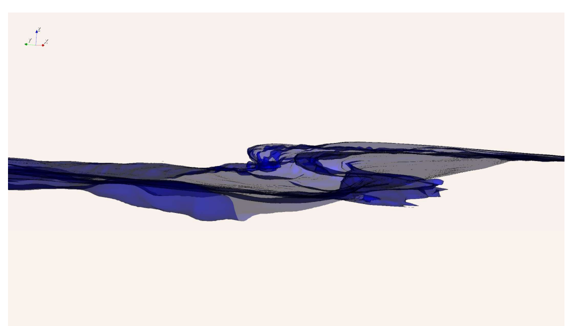

Fig. 3. View of a fold in the temperature isosurface corresponding to a cold front.

In this visualization, the relationship between the cold front and the formation of clouds can also be seen. Clouds are forming along the line of the cold front and the slanted lower portion of the red structures gives another hint at the motion of the wedge of cold air. Fig 4. shows this relationship.

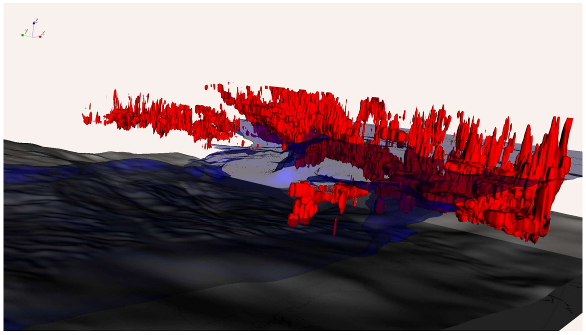

Fig. 4. View of the fold in the temperature isosurface relative to the formation of clouds.

Another interesting feature that can be observed in the visualization is the difference in height between clouds. The date observed in this data, April 8, 2025, saw the development of a large squall line. Within the system, there are both cumulus and cumulonimbus clouds. Cumulus clouds are much shorter than cumulonimbus. The cumulonimbus clouds often stretch all the way to the top of the Troposphere. This discrepancy can be seen in Fig. 5. The clouds on the left are the shorter cumulus and the right shows tall cumulonimbus.

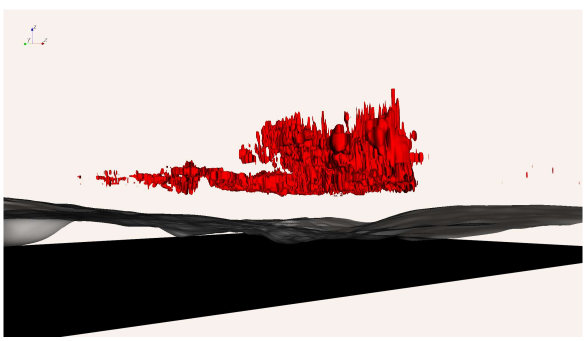

Fig. 5. View of differing cloud heights.

V. Discussion

This project provides a system for visualizing and experimenting with the relationship between the variables of the HRRR weather model. The largest benefit of visualizing these values in three dimensions is in the analysis of structures that have interesting properties vertically. As described in the results section, this includes visualizing the motion of cold fronts and the relative height of clouds.

Additionally, this report only discusses an example that explores the relationship between two variables of the HRRR model. There are many more variables that can be visualized. Some of these values include relative humidity, dew point temperature, vertical velocity, vorticity, graupel (snow pellets), among several others. These can also be downloaded and visualized in the scene.

One weakness in the visualizations generated by this project is caused by the relatively low resolution of the data vertically compared to horizontally. While it is still very useful to see the relative heights of the structures, the low vertical resolution means that any tall, thin surface appears very tubular, almost cylindrical. This is because it is interpolating linearly between surfaces that are quite far apart. It would be interesting to observe a model that calculated more intervals vertically to see if any aspects of these values are hidden by the low resolution.

During the development of the visualization, the choice was made to limit the amount of surfaces visualized at once to three. That is, two variables chosen by the user, and the 1000 hPa pressure surface corresponding to the time range chosen. This was because when visualizing more than this, even with semi-transparent surfaces, it was difficult to see the relationship between different values. This was partially fixed by including check boxes to turn on or off individual surfaces, but this only fixed the problem in the sense that a surface was removed. Further work could be done to explore other visualization techniques that meaningfully allow more than three variables to be studied at once. This could be in the form of glyphs to observe the motion of the wind, more subtle volume rendering for particular variables that would benefit from being viewed in a transparent cloud, or streamlines showing the motion of interesting structures over time.

VI. Conclusion

To conclude, this project revolved around the creation of a visualization tool using VTK for observing and comparing various variables of the High-Resolution Rapid Refresh (HRRR) weather model. It allowed for visualization over a period of time to study how weather systems change with respect to the variables of the model.

The visualizations created are not intended as a potential replacement for traditional two-dimensional weather information, but rather as a tool that can be used to learn more about the relationship between various aspects of the weather system, and how those values change vertically in the atmosphere.

References

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