Mantle Convection Visualization

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Overview

The study of the Earth's core and mantle is often done using simulation of the temperature and velocity characteristics. This includes the formation and movement of geophysical phenomena known as "cold slabs" and "hot plumes". These events occur with different characteristics at different depths, and are not fully understood. Field scientists use simulation and visualization to iterate on their models. In particular, they seek insights related to

- Diameters of the plumes' thermal boundary
- Depth of seismic discontinuity
- The size of plume heads
- Study of Anomalies and their detection

Further research on the background physics can be found in M.H. Shahnas et al's two papers from 2011 [4] and 2016 [5]. For this project, we will apply multiple visualization techniques in an attempt to better understand these phenomena.

Data

This data comes from Russell Pysklywec and Hosein Shahnas at the University of Toronto. It was made available to the public as part of the SciVis 2021 Contest at [3]. It consists of about 100 GB in the NetCDF format when uncompressed. This is a time dependent dataset, and is broken into separate files with 10 timesteps each. There are 250 timesteps total, with each timestep representing 2 million years. This data is defined on a spherical 180x201x360 grid. The variables included are

- temperature (K)
- velocity in x, y, and z (m/s)
- thermal conductivity anomaly (W/m/K)

- thermal expansivity anomaly (1/K)
- temperature anomaly (K)
- spin transition-induced density anomaly (kg / m^3)

Methods and Results

Working with Large Scale Data

A major challenge in the project comes from the size of the dataset. The data is divided into 25 files in the "Network Common Data Format" (NetCDF) [2]. Each file is about 4 GB in size, and represents 10 timesteps of data. Fortunately, this format can be loaded into paraview directly, without any extra challenges. That said, we did experiment with different formats (such as .vtu) looking for more efficient interaction. We didn't see significant improvement so we continued to use NetCDF. Once the data is loaded, the mesh forms a structured curvilinear grid with 13,198,882 points. This large size makes exploring the data interactively and designing visualizations difficult due to long delays between changes. On personal machines, we experienced multiple crashes of paraview with somewhat vague error messages, likely associated with large data sizes. In addition, since the data is time dependent, it is very useful to observe changes over many timesteps in order to assess the usefulness of a given visualization. Each new timestep takes significant time to load in paraview, so this isn't really practical. When we need longer time periods, we instead set up paraview to generate an animation and wait for full completion.

Given the above challenges, we have tried a number of strategies to increase the responsiveness of visualization. First, we have utilized more powerful hardware compared to our standard desktops and laptops. We have been able to do most of our work using a remote interactive session on the CHPC's notchpeak cluster. Specifically, we used a full node on the notchpeak-gpu account/partition with 40 processes. The hardware can vary based on which specific node is assigned each session, and the list of possibilities is available at [1]. Next, we experimented with filtering the data to work with only a fraction of the full domain. One problem with this approach is that filters output an unstructured mesh, which can be inefficient when trying to do volume rendering. To compensate for this, we also used "ResampleToImage" to re-structure the filtered data. This gives a noticeable speedup at the cost of adding error to the data. One surprising observation on this subject is that "ResampleToImage" seems to be more responsive even when it has the same number of points as the original full dataset. This may have something to do with the fact that the original dataset is structured curvilinear, while the resampled dataset is structured as a uniform rectilinear grid.

Surfaces and Glyphs

Our first visualization strategy is to combine surface rendering of the temperature with arrow glyphs showing the material velocity. An example of this is shown in figure 1. One detail to note is that the dataset only includes the velocity components vx, vy, vz. They must be assembled into a full velocity vector using the calculator filter: velocity = (iHat*vx + jHat*vy + kHat*vz) * 1e9. The velocity in this case has been scaled to nm/s to avoid problems with very small numbers. This method of visualization works fairly well for identifying hot plumes and cold slabs. Their positions are clear from the temperature data, and convection movement of the mantle is visible from the glyphs. Howevever, since this is based on surface rendering, it can't really capture the 3D extent and movement of the hot plumes. In figure 2 we have attempted to extend this design by seeding the the arrows in a volume rather than on a surface. For these and later visualizations, we found the "hot and cold" and "turbo" colormaps to be most useful to highlight the features of interest.

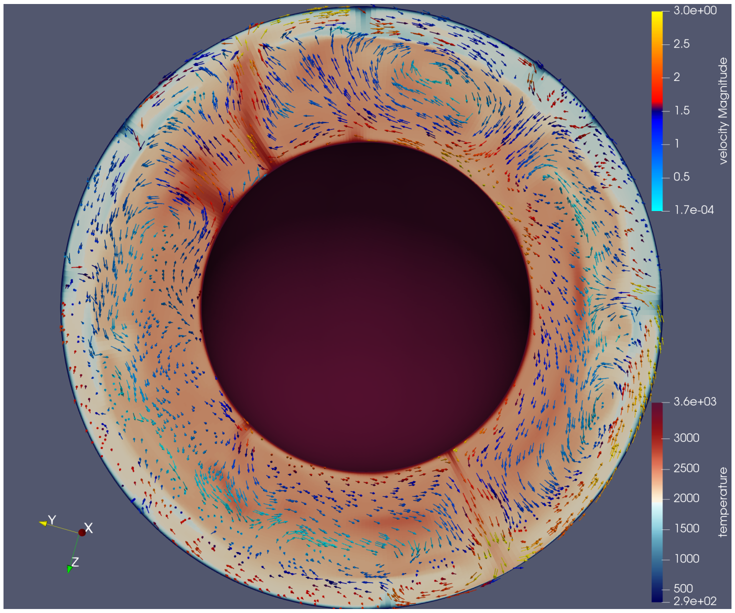

Figure 1: Temperature on a surface, with arrow glyphs showing velocity vectors. Note that high velocities correlate with high temperature changes. Glyphs colored based on velocity magnitude, showing higher speeds as the hot plumes move up towards the surface. We can also see the velocity direction changes at radial boundaries in the mantle. The velocities near those seismic discontinuities also move more slowly.

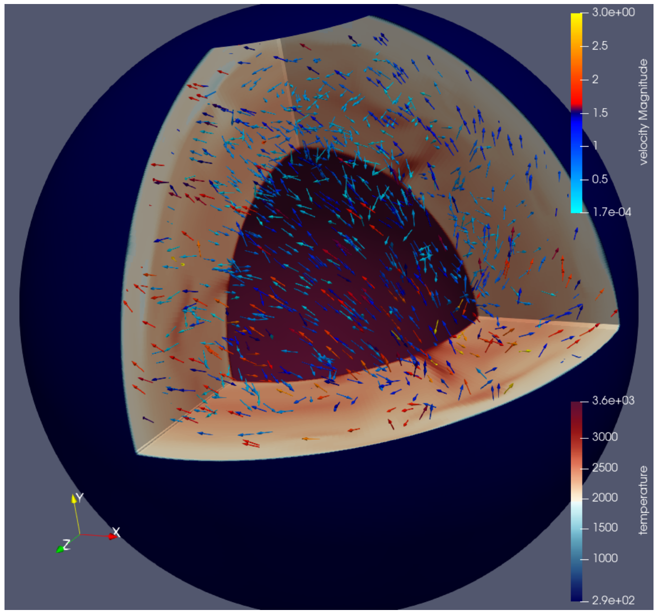

Figure 2: Cutout of surface temperatures, with velocity arrows in volume. It is difficult to make out trends in velocity movement using glyphs and tubes, although we have tried many combinations.

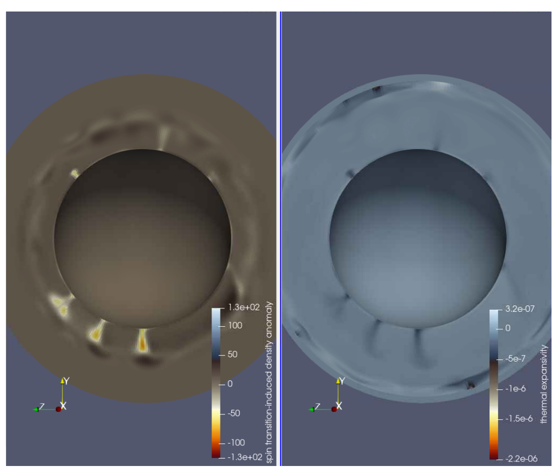

Figure 3: Spin Transition Temperature anomaly on the left, and thermal expansivity on the right. These fields correlate strongly with each other and with temperature. Therefore, when we try to superimpose them in a multi-field visualization, it creates occlusion. Because of this, most the work in this report is focused on temperature and velocity.

We attempted to extend the above by displaying temperature on multiple layered slices, with streamline tubes showing the velocity. Unfortunately, this ended up being too cluttered to give useful insight into the movement of the features. This is shown in figure 4

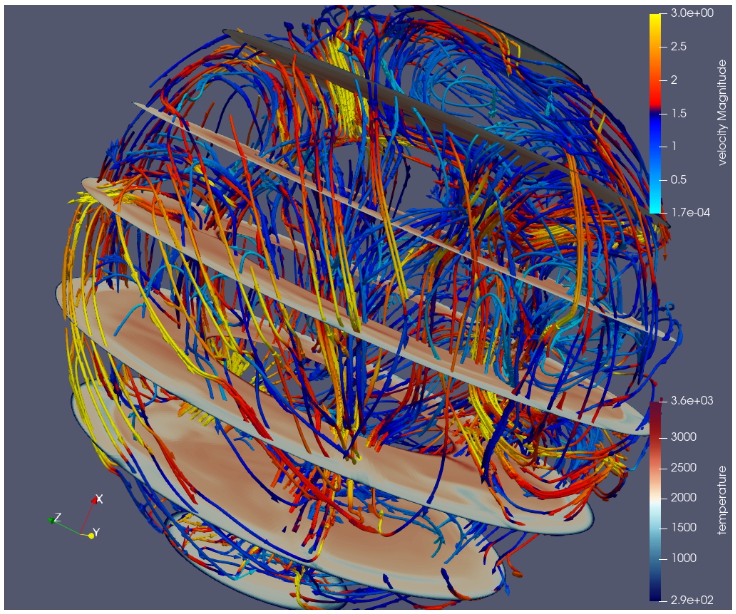

Figure 4: Temperature multiple slice layers spaced by 2000 km. Streamline tubes showing velocity between the slices. An advantage of this is to highlight areas of interest where tubes are bright and dense. Unfortunately, in many visualizations where we attempted to use streamlines, occlusion became a significant problem.

Another attempt using surfaces took advantage of the threshold filter. The filters used the temperature anomaly field, showing data at both the low and high end of the scale. This allows us to capture features, while leaving out most of the mantle data to avoid occlusion. This technique, in figures 5 and 6, does a better job of showing the 3D extent of cold slabs and hot plumes.

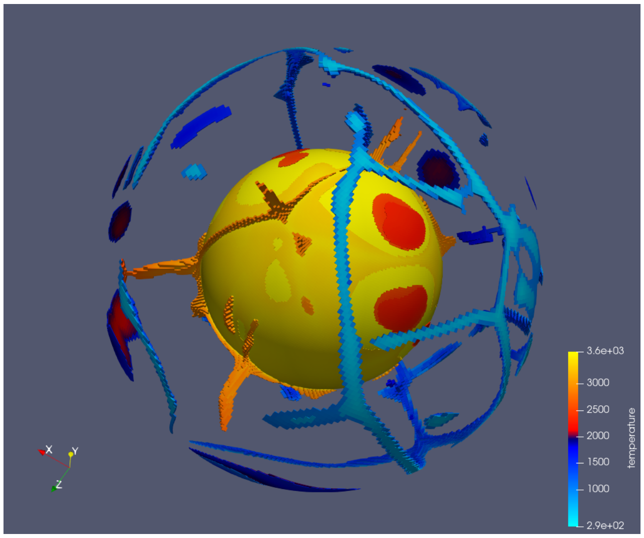

Figure 5: Two threshold filters based on the temperature anomaly field. The low filter includes data from -1102 to -410. The high filter includes data from 506 to 1131.

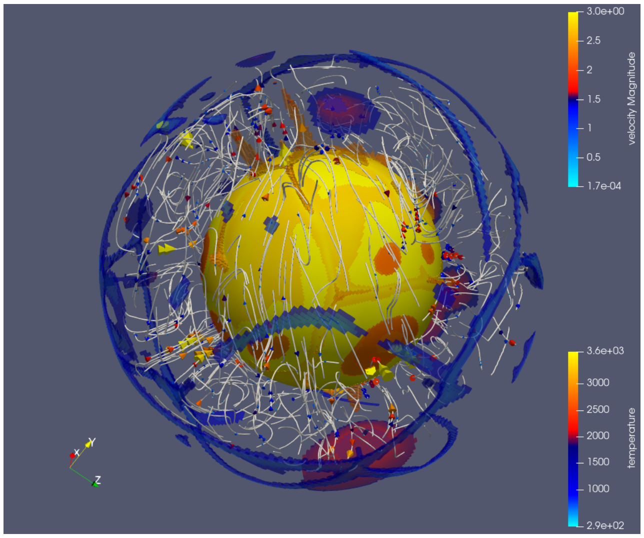

Figure 6: Reduced opacity for threshold filters, to more easily see streamline tubes for velocity. Streamlines help to show convection cells in the mantle. There is a tradeoff compared to volume rendering in that we have less occlusion to better view streamlines in this visualization, but we miss some of the details.

Volume Rendering

Volume rendering with an appropriate transfer function could be an effective way to visualize this dataset, but it is much more computationally expensive than the techniques of the previous section. Even when using a full node of the notchpeak cluster, it takes over 2 minutes to volume render the full dataset, and for every change thereafter. It is not practical to spend this time waiting while we experiment with different settings, but we do have options to make it easier. First, we experimented with a number of filters including slices, clips, extractsubset, and shrink in order to select a small segment of the domain. This produces an unstructured mesh, which is inefficient for volume rendering. Next, we use the "Resample to Image" filter which creates a new uniform rectangular grid mesh. There is some error associated with the resampling, but this makes volume rendering efficient enough to work with easily. Examples of these techniques are shown in figures 7 and 8.

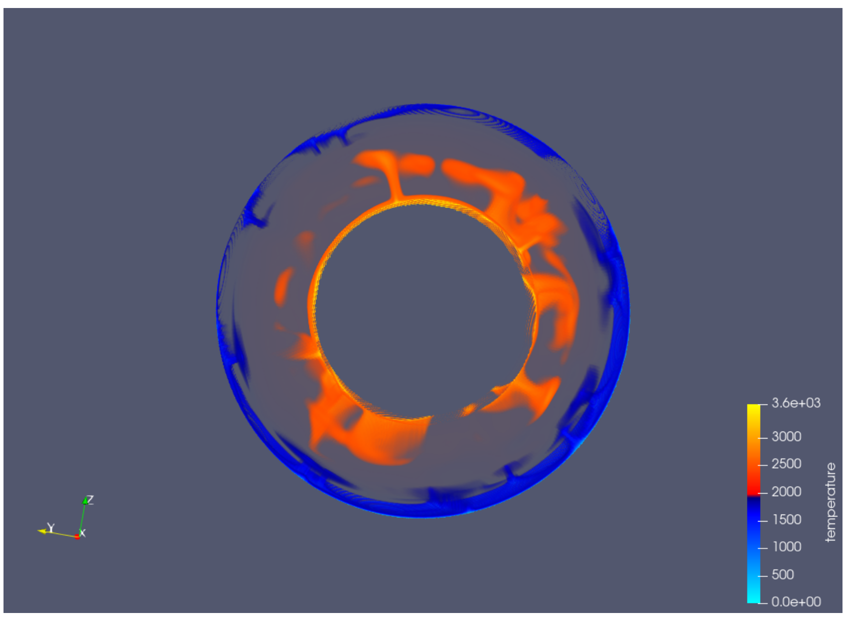

Figure 7: Filtered to a donut shape to allow unobstructed view of plumes from the side. Then resampled to a 300x300x300 rectiliniear grid to allow efficient volume rendering. Note that the total size of the resampled grid is more than double the size of the original curvilinear grid, yet it can be manipulated in paraview with minimal lag.

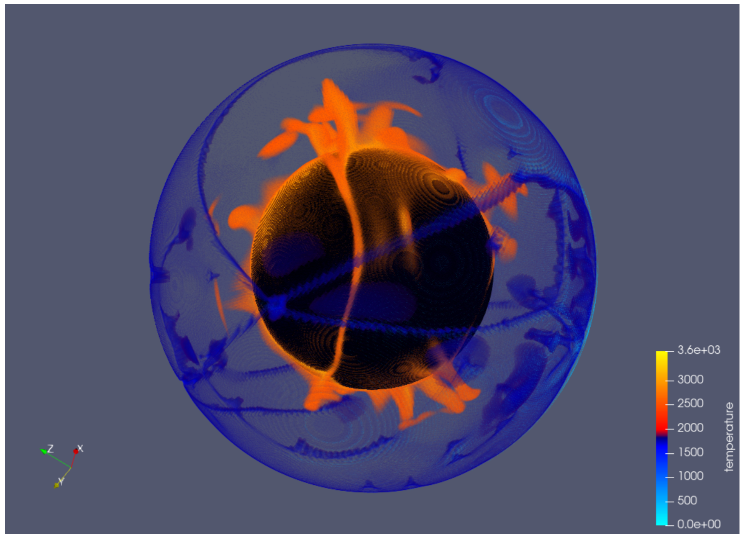

Figure 8: Volume rendering with transfer function intended to highlight hot plumes and cold slabs. This helps provide a global view of the data we are interested in like diameters of the plumes' thermal boundary.

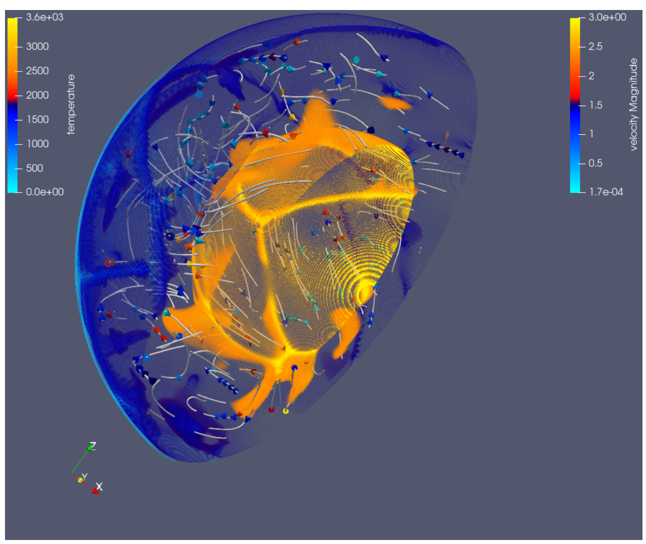

Figure 9: Multi-field visualization including volume rendering of hemisphere with tubes streamlines showing velocity. hose to cut the globe in half to gain a better view of some tubes and glyphs, as well as to reduce compute time.

A useful strategy to make use of these volume renderings is to identify global phenomena or anomalies quickly. Then we can filter around the identified features, and use surfaces and glyphs to examine properties like the size of plume heads.

Future Work

There are a number of ways this project could be expanded and improved given additional time and resources. Primarily, the usefulness of the visualization could be improved with some customized automation. as it is, we have explored the dataset by manually choosing filter settings to best highlight the features of interest: hot plumes and cold slabs. However, having read papers [4] and [5] by the domain scientists, there is an interest by these experts in specific details such as the size of the plume heads, depths that they form and reach, and the diameters of the thermal boundary. The visualizations give intuitive view of these, but it would also be useful to perform such analysis automatically. There are also relevant non-dimensional such as buoyancy number and Rayleigh number which could be computed. Taken together, these extra statistics could even be used to optimize a transfer function and improve the visualization.

An additional approach, which was used by SciVis contest winners, is to use a 3D cartographic projection instead of the 3D spherical geometry used in the dataset. A persistent challenge in this project has been occlusion of features, which is partly related to the spherical geometry. Viewing cold slabs near the surface of the sphere requires compromises to also view features beneath them. A different projection method can significantly help this problem.

Lastly, the project could be improved by reaching out to field scientists to receive design advice and expert feedback on the usefulness of the visualization.

Animations

If the reader is interested in further details, we have Paraview state which can reproduce the visualizations in this report. We can also generate animations upon request from readers.

Conclusion

In this project, we have worked to effectively visualize a large simulation dataset of convection in the Earth's mantle. We have used a variety of multi-field techniques to visualize hot plumes and cold slab features in the data. This includes surface rendering of temperatures with glyphs and streamlines for velocity, multiple threshold filters to highlight the relevant temperature features, and volume rendering. We identified useful colormaps for this dataset, including Paraview's "hot and cold" and "turbo". During this process, we learned to leverage the CHPC notchpeak supercomputer to work efficiently with large data.

References

[1] Gpus and accelerators at chpc. https://www.chpc.utah.edu/documentation/guides/gpus-accelerators.php#ngn. Accessed: 2022-04-11.

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[3] Scivis contest 2021: Earth's mantle convection. https://scivis2021.netlify.app/. Accessed: 2022-04-18.

[4] M. H. Shahnas, W. R. Peltier, Z. Wu, and R. Wentzcovitch. The high-pressure electronic spin transition in iron: Potential impacts upon mantle mixing. *Journal of Geophysical Research: Solid Earth*, 116(B8), 2011.

[5] M. H. Shahnas, R. N. Pysklywec, and D. A. Yuen. Spawning superplumes from the midmantle: The impact of spin transitions in the mantle. *Geochemistry, Geophysics, Geosystems*, 17(10):4051–4063, 2016.