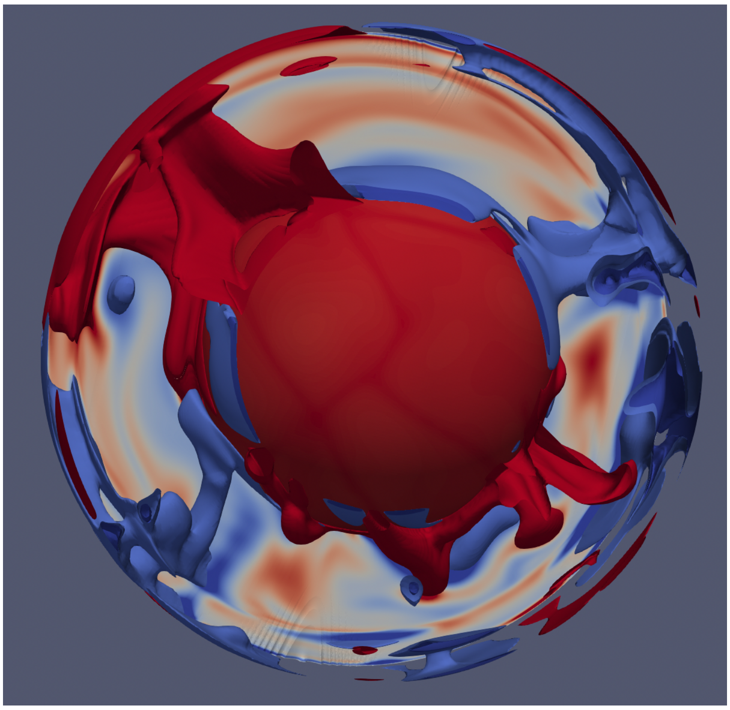
PROJECT FINAL REPORT

SciVis Contest 2021: Earth's Mantle Convection



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1. Overview and Goals

Every year, the SciVis IEEE hosts visualization contests that allow participants to showcase their advanced visualization skills and innovative techniques. The aim of these contests is to assist domain scientists in gaining a deeper understanding of a specific topic within their field by presenting new approaches to visualizing data. These contests allow participants to demonstrate their state-of-the-art visualization techniques and explore novel ways of representing complex data sets.

The topic in the 2021 Contest was Earth's Mantle Convection. We aim to use the 3D Scalar field data present at the contest site in order to better showcase the phenomena that happen inside Earth's mantle. Our main goal is to use visualization tools like Paraview and Python to visualize the dataset given in the contest. At a high level, we plan to study the various anomalies present in the Earth's mantle. In order to achieve our goal we plan to implement some or all of the tasks mentioned in the contest with the tools that we have.

To go into the details of the Visualization we first need to understand what the topic and the domain represent.

2. Background and Related Work

The Science Behind the Process:
The Earth's radius is approximately 6400km, with the core extending from the center to a radius of around 3485km. The lower mantle occupies the region between the core and approximately 4800km from the center, while the mid and upper mantle span from this point to approximately 5700km from the center. When rocks in the Earth's mantle get hot, they rise toward the surface. This creates a circular flow of material called convection, which helps to distribute heat and materials within the mantle. However, sometimes this flow of material gets slowed down or even stopped by high-velocity anomalies, particularly in the lower mantle. Scientists have found this may be due to a transition in the iron atoms found in two of the most abundant minerals in the lower mantle - ferropericlase and perovskite. This transition in the iron atoms affects the density, thermal conductivity, and compressibility of the minerals, which in turn affects the buoyancy of the rocks. This can cause descending cold slabs and rising hot plumes to slow down or stop at a depth of about 1600 km, leading to stagnation. If these stagnant materials eventually gain negative buoyancy, they can cause sudden mid-mantle avalanches or merge together to form superplumes.

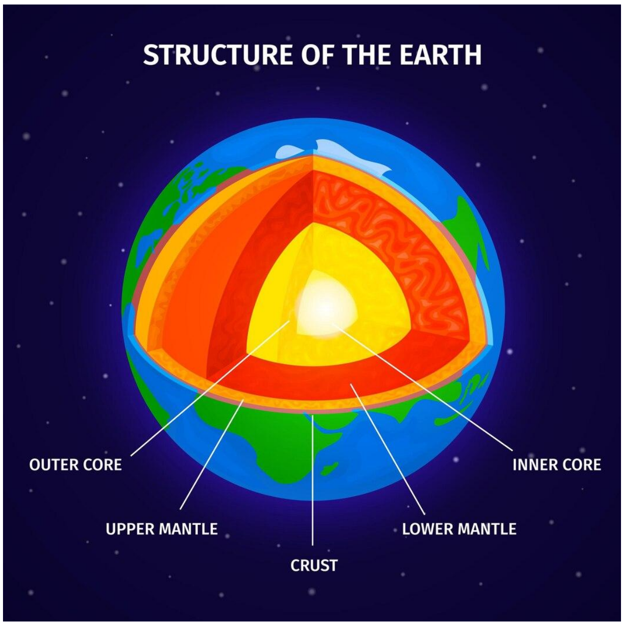

Fig 1. Structure of the earth

The process mentioned above has many effects that are quite fascinating, including the formation of new crust at mid-ocean ridges, the movement of continents over time, and the distribution of heat and materials within the mantle. It is also believed to play a key role in other geologic processes, such as volcanic activity and earthquakes. A visualization explaining the above phenomenon can help scientists to reach better conclusions.

There is a lot of related work in this domain. To better understand the science and the various terminologies mentioned throughout the paper we took help from the following papers (Source: Contest info) :

a. M. H. Shahnas, W. R. Peltier, Z. Wu, R. Wentzcovitch (2011): The high pressure electronic spin transition in iron: potential impacts upon mantle mixing. J. Geophys. Res. 116, B08205
b. M. H. Shahnas, R. N. Pysklywec, and D. A. Yuen (2016): Spawning superplumes from the mid mantle: The impact of spin transitions in the mantle. Geochemistry, Geophysics, Geosystems 17, 4051-4063
c. M. H. Shahnas, D. A. Yuen, R.N. Pysklywec (2017): Mid-mantle heterogeneities and iron spin transition in the lower mantle: Implications for mid-mantle slab stagnation. Earth and Planetary Science Letters 458, 293–304

We also went through a lot of Wikipedia pages to understand the core and mantle of Earth.

3. Project Description

Our project involves visualizing a 3D scalar field dataset and vector field (velocity) to better understand anomalies underneath the earth's surface. Specifically, we focus on the upper mantle, mid mantle, and core-mantle boundary. The dataset is a time series with 251 steps of 3D scalar fields covering 500 million years, with each step containing information about temperature, velocity components, thermal conductivity and expansivity anomalies, temperature anomaly, and density anomaly. Due to resource limitations, we used the first 100 steps of the dataset, covering 200 million years. Our modified dataset is approximately 42 GB in size. Each file in the dataset is a NetCDF Climate and Forecast (CF) convention format, with each 3D scalar field being a function of latitude [degrees north], longitude [degrees east], and radius [km].
Various Scalars:

1. Temperature [Kelvin]
2. Cartesian Velocity Components [m/s]
3. Thermal Conductivity Anomaly [Watt/m/K]
4. Thermal Expansivity Anomaly[1/K]
5. Temperature Anomaly [Kelvin]

6. Spin transition-induced density anomaly [kg/m^3]

We plan to visualize the dataset by completing several tasks provided by the contest. These tasks are:

a. Visualize stagnated or diverted cold slabs (descending mantle material) at ~660 km (upper and lower mantle boundary) depth.
b. Visualize stagnated or diverted cold slabs at ~1600 km (mid-mantle) depth.
c. Visualize stagnated or diverted hot plumes (rising hot mantle material) at ~1600 km depth and their rise to the upper regions of the lower mantle.
d. Visualize stagnated or diverted hot plumes at ~660 km depth.
e. Visualize correlations between the variables and the flow patterns described below.

By completing these tasks, we hope to gain a deeper understanding of the relationships between various scalars in the dataset. During the implementation process, we encountered several visualizations that raised questions about the behavior of the scalar fields at different depths, which we will discuss in the implementation section.

4. Implementation

To complete the project, we utilized Paraview (version 5.11) as our primary tool. Given the large size of the dataset, we required additional computation resources and therefore worked on the CHPC servers provided by the School of Computing.

To effectively analyze the dataset and identify anomalies and patterns within the Earth, we split the five tasks mentioned earlier between the three team members. In the following sections, we will provide a detailed overview of our implementation process for each task.

Task 1: Visualize stagnated or diverted cold slabs (descending mantle material) at ~660 km (upper and lower mantle boundary) depth.

Task Overview: In this task, We need to visualize the convection flow of cold slabs at a depth of ~660 km from the earth's surface and observe the various trends within this flow.

Implementation: We loaded the 100 timesteps of the data (200 myrs) in Paraview. The initial representation is an outline representation. We changed the representation to surface to properly visualize the data (latitude, longitude, and radius).

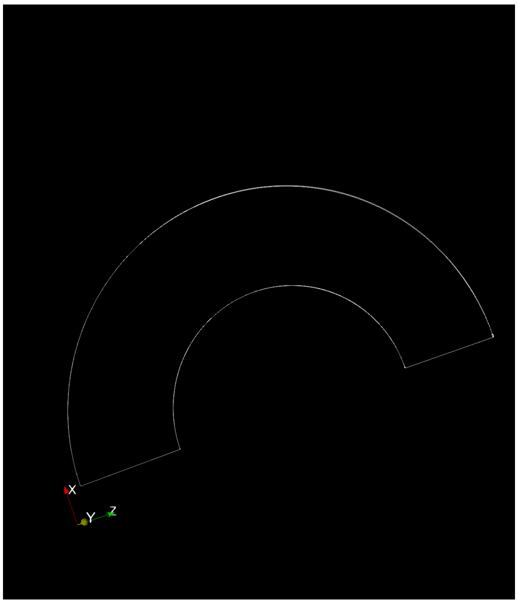

Figure 2: Outline Representation

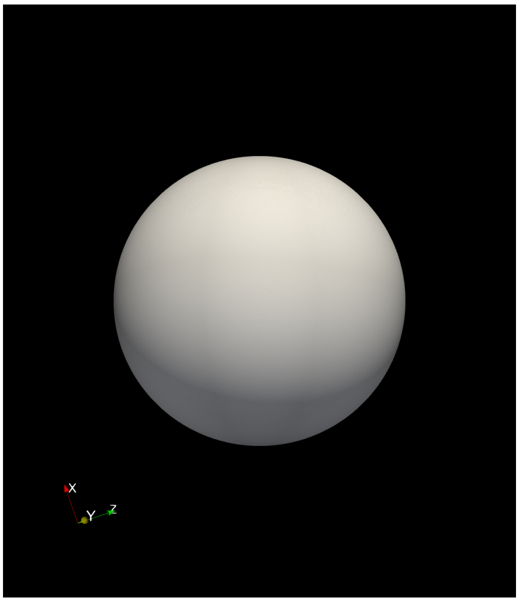

Figure 3: Surface Representation

Since our data contained cell points and in order to apply most of the filters in Paraview we needed point data. We first converted our data using the CellDataToPointData filter in Paraview. We then applied four clip filters as follows to better visualize the trends.
Clip1 (Plane): Here we clipped across the X normal plane, keeping the origin point as the center of the earth.
Clip2 (Plane): Here we clipped across the Y normal plane, keeping the origin point as the center of the earth.
Clip3 (Sphere): Here we clipped a sphere with a radius of 3485 km, keeping the origin point as the center of the earth.
Clip4 (Sphere): Here we clipped a sphere with a radius of 5700 km (660 km from the surface), keeping the origin point as the center of the earth. We also reduced the opacity of this clip to show a border at the 660km line to visualize the data trends in a better way.

The best way to track the physical processes under the earth's surface mainly the cold slab movement is to visualize the scalar - Temperature anomaly. Hence, we changed the colormap settings to visualize this scalar instead of solid color. We also changed the colors to vividly describe the trends.

Now to visualize the convection movement we used iso surface representation using the contour filter as this is one of the best ways to visualize the scalar data. We applied the contour filter on the fourth clip to see the trends around 660km.

Contour: Contour by - Temperature anomaly. The total temperature range is from -1100 to 1100 K. Since we only need to examine the cold slabs in this task, We specified the Isosurface value ranges from -1100 to -200 K, with uniform distribution and 10 values. We also adjusted the specular power, diffusivity, opacity, tone mapping, etc to have a pleasing effect.

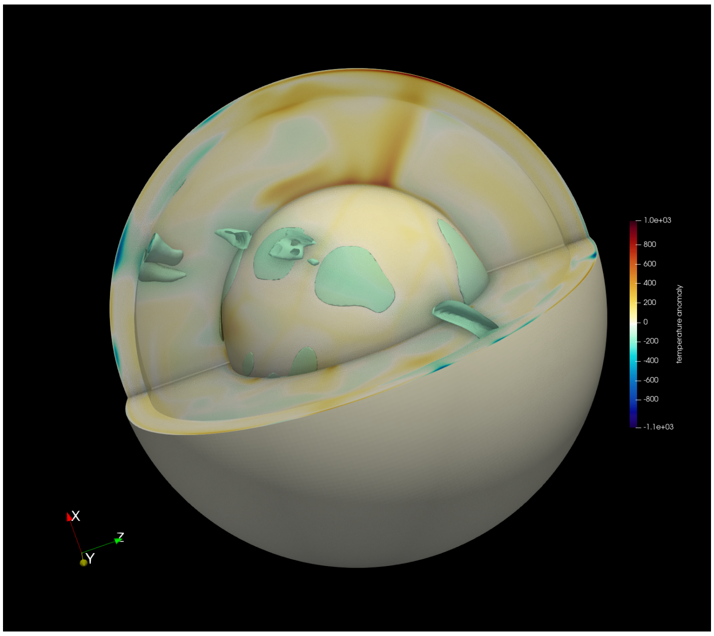

Figure 4: Final view at time step 0

Additionally, to also understand the temperature anomaly direction trends on the entire dataset, we created a new view under the same layout. Since to visualize any stream, we need a vector first. We applied the calculator filter in order to create a new vector data - temperature_vector = (iHat*"temperature anomaly" + jHat*"temperature anomaly" + kHat*"temperature anomaly"). After getting the vector, We applied stream tracer, tube, and arrow glyph filters to showcase the directionality and movement. Also changed the representation to Wireframe for clarity.

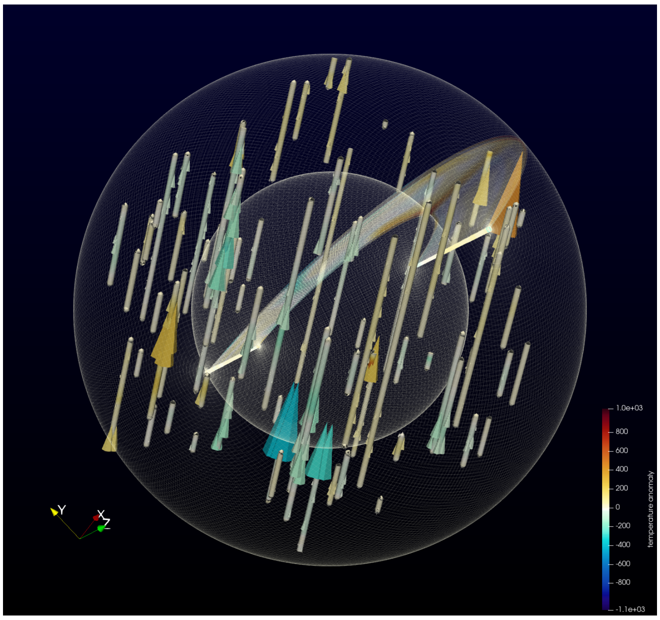

Figure 5: Temp. Anomaly Streams

Finally, we created an animation over 100 timesteps to create a video and notice the trend. [Link](#).

Key Takeaways/Trends: By examining the isosurfaces of temperature anomaly, we can observe that the cold slab/material starts at the surface and progressively descends into the mantle toward the core over millions of years (myrs). Additionally, we notice that the material spreads out on the surface, becomes shallow while descending, and then spreads out again at the core. Notably, a lateral flow occurs until 660km, after which the material begins to descend. Moreover, the vector stream visualization along a single axis provides insights into the overall trends beneath the earth's surface. The arrow glyphs represent the cold material descending, with the magnitude indicated by the tips, while the hot material rises up. Please refer to the visualization images at different time steps below for a clearer understanding of the trends. (For enhanced clarity, please watch the video.)

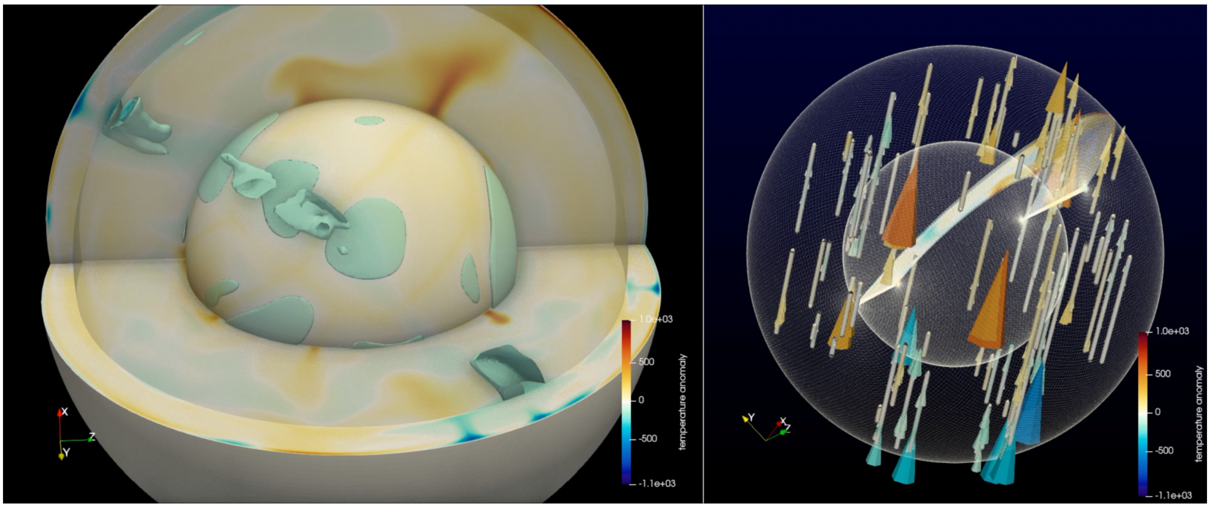

Figure 6: Timestep 1

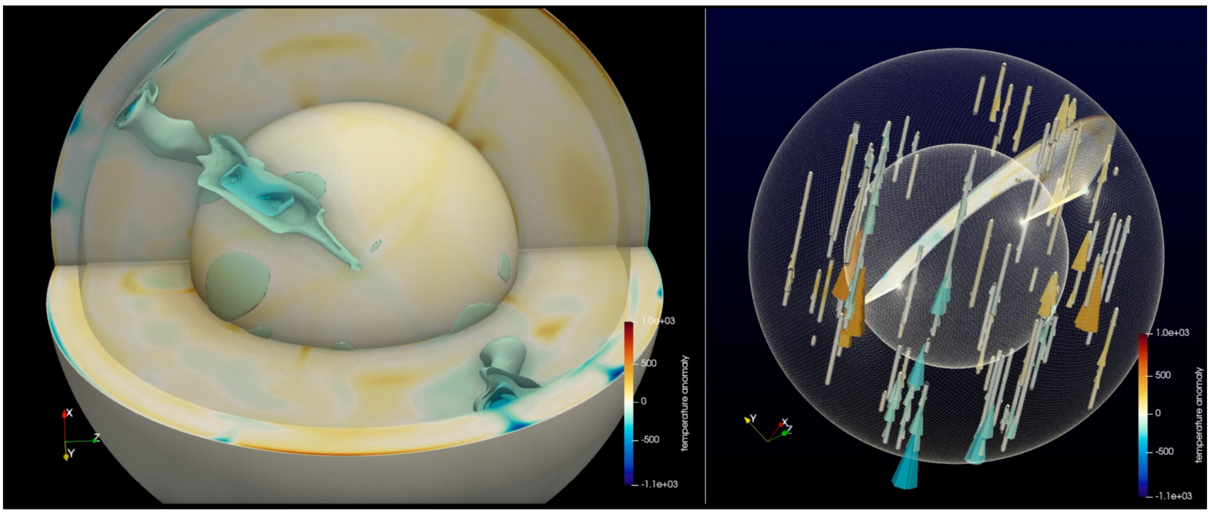

Figure 7: Timestep 20

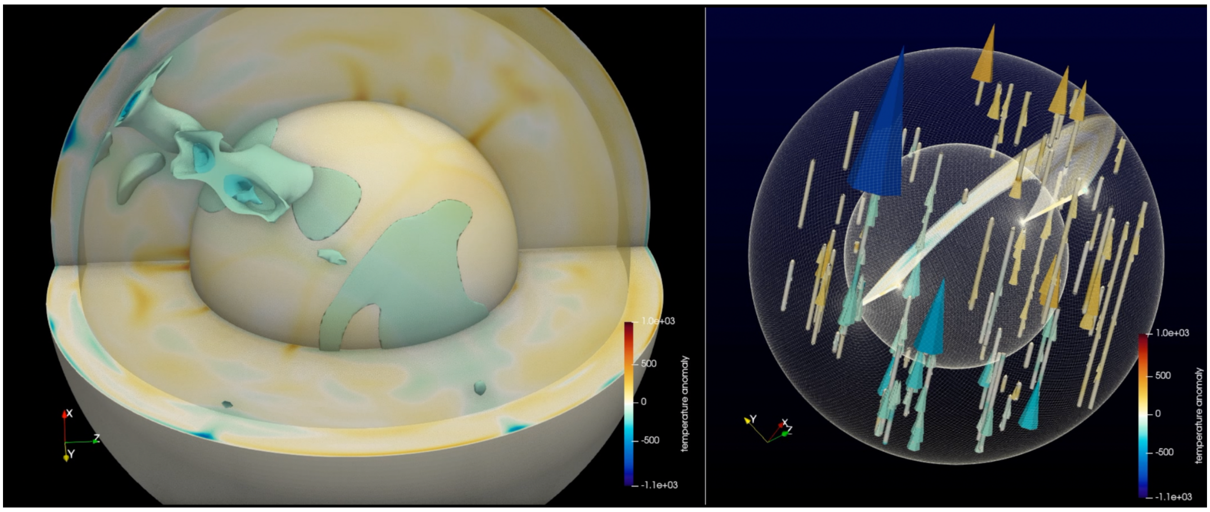

Figure 8: Timestep 40

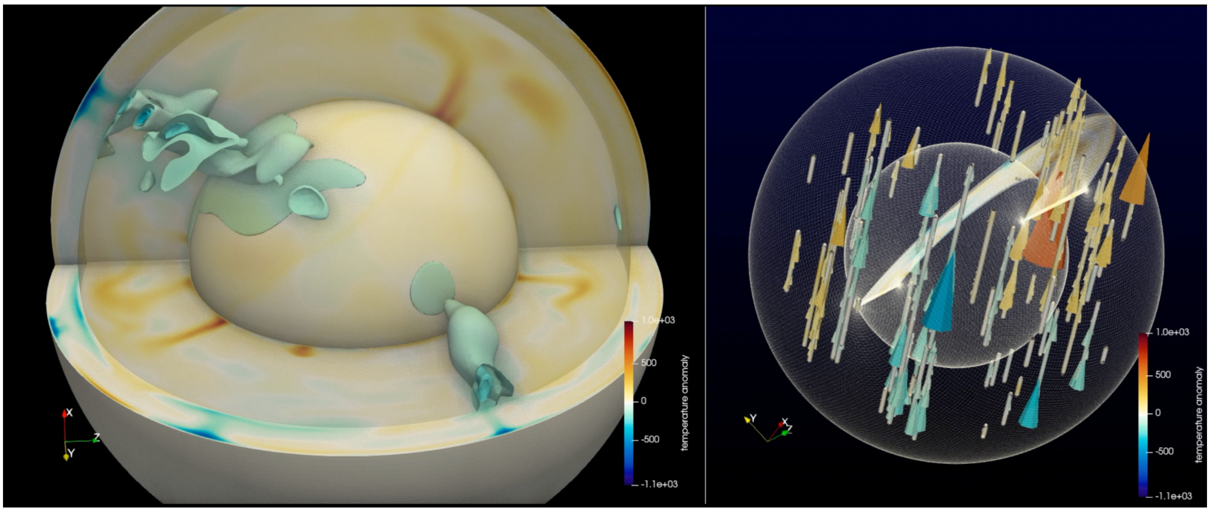

Figure 9: Timestep 75

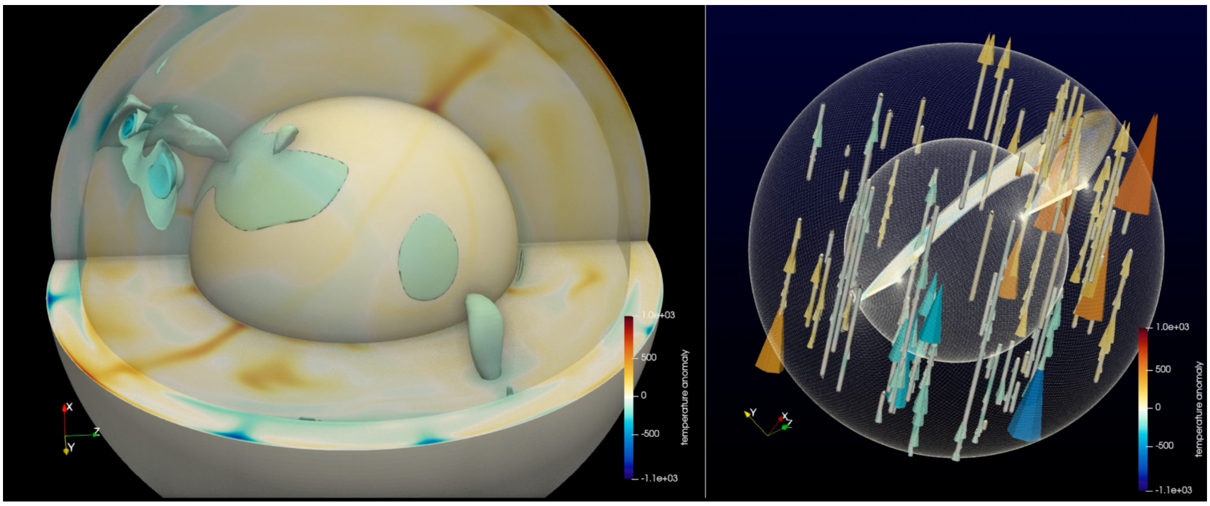

Figure 10: Timestep 95

Task 2: Visualize stagnated or diverted cold slabs at ~1600 km (mid-mantle) depth.

Task Overview: The flow patterns (e.g. avalanches or stagnations) at 660 km depth and 1600 km depth are very different in nature, making their visualization independent of each other. The former is caused by the endothermic phase transition at 660 km which has been known for the past few decades. The latter is due to the iron spin transition in the lower mantle minerals starting at ~1500 km depth. We attempt to see similar trends at 1600km.

Implementation: Same as above, we first convert cell data to point data. Additionally, we add a calculator filter to the data to get the velocity vector using the three scalars vx, vy, and vz. Formula - velocity = (iHat*vx + jHat*vy + kHat*vz) * 1e9.

Instead of using the same visualization as above, we decided to go for a different approach and display projections from a plane instead of viewing it in a traditional spherical approach.
I created 7 slice filters at different depths - equator, poles, 660km, and 1600km. The slice type was plane and all were in the X normal plane. I then applied a clip filter (Sphere type) for the core at 3485 km from the center. Finally, I applied my final clip filter at 1600km from the surface (not making this clip visible) and then applied two iso-surface contours to this.

To check the convection flow at 1600km, I tried to compare the temperature anomaly as above and also the spin-transition-induced density anomaly and compared them in a single view as well as parallel rendered views. I also used different color maps for both scalars to appropriately visualize them.

Finally, I used the velocity vector calculated to generate a glyph view of the vector flow along the three spherical slices (core, lower-mid mantle, and upper mantle).

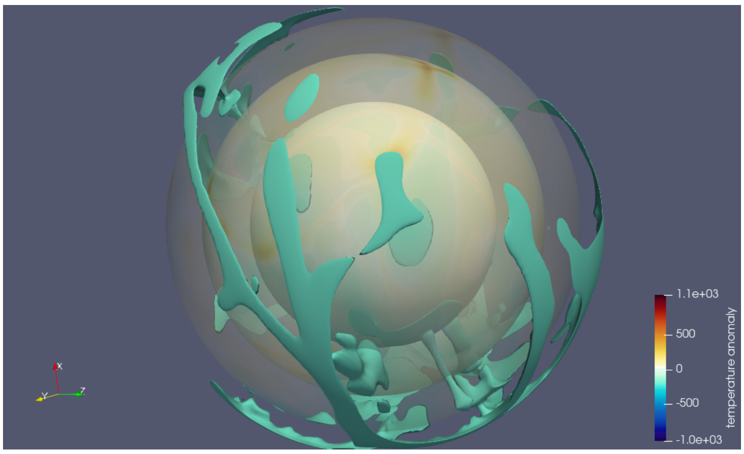

Figure 10: Temp. Anomaly at different depths

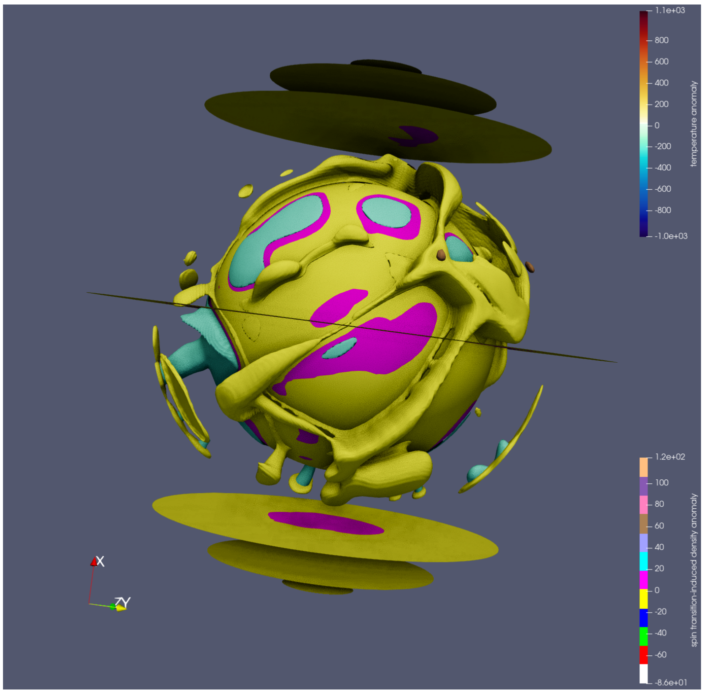

Figure 10: Sliced view (Multiple Anomalies)

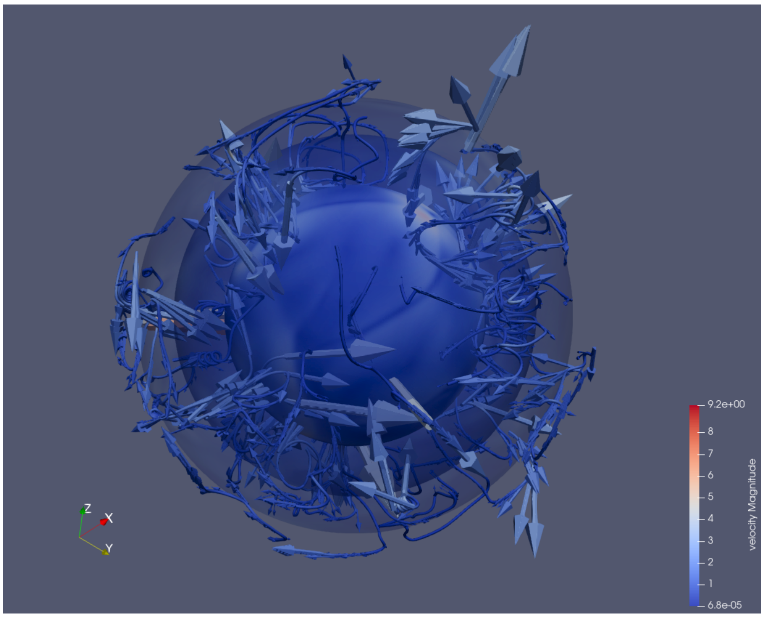

Figure 11: Glyph view (Velocity vector)

Takeaways: We created an animation for 100 timesteps for all the 3 views in parallel, along with them rotating around the axis (Link). Convections may diverge or stagnate at a spin-transition depth of 1600 km.

We can observe that the slabs continue to diverge from the surface to the 1600km, to the 660km, all the way to the core. They first spread at each depth and then diverge downwards.

The density anomaly on the other hand as compared to the temperature anomaly grows up and creates a boundary around the core. This indicates the comparison between the two anomalies and how their movement contradicts each other. The density anomaly for the convection material is more widespread compared to the narrower descent of the temperature anomaly.

We can also observe the velocity vector flow in the visualization. Around the surface of the depths, the velocity direction follows the surface compared to their movement across the depths where it flows and rises to the surface. The magnitude changes can also be observed throughout the video, they are much higher when trying to rise up to the surface.

Find the three views at three different timesteps below:

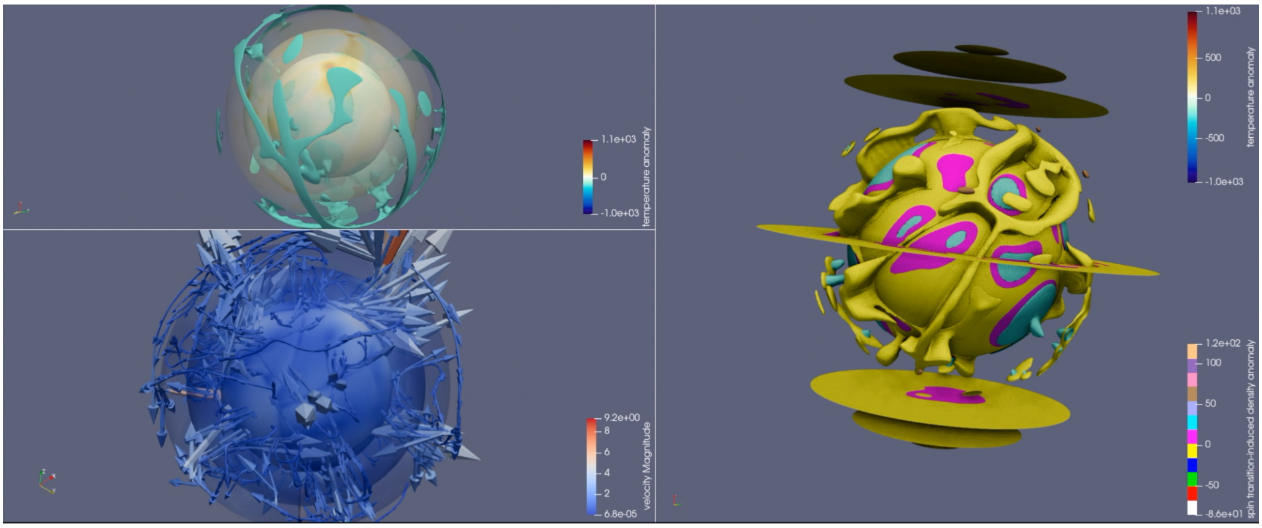

Figure 12: Timestep 7

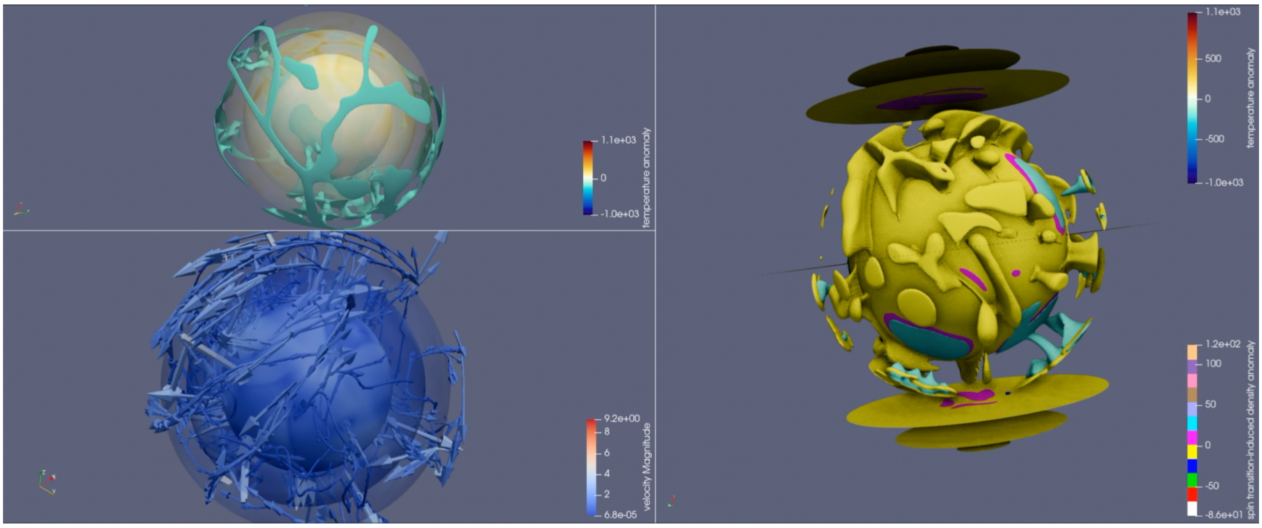

Figure 13: Timestep 50

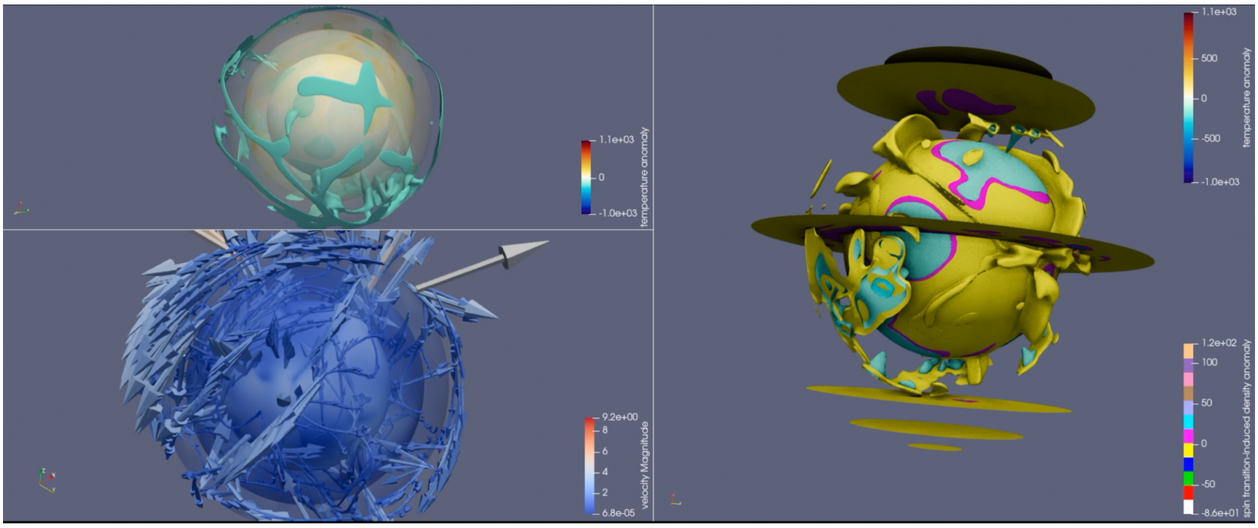

Figure 14: Timestep 87

Task 3: Visualize stagnated or diverted hot plumes (rising hot mantle material) at ~1600 km depth and their rise to the upper regions of the lower mantle.

Task Overview: This task requires us to visualize the hot temperatures moving from the deeper regions of the mantle to the upper regions of it i.e from ~1600 km to ~660 km.

Implementation: We first selected data for 10 Million Years (myrs) and implemented the required filters to it. The next step was to use the same implementation on the whole dataset. This was done to make sure that our laptops were able to handle the dataset efficiently and that there was no major lag between applying the filter and the output.

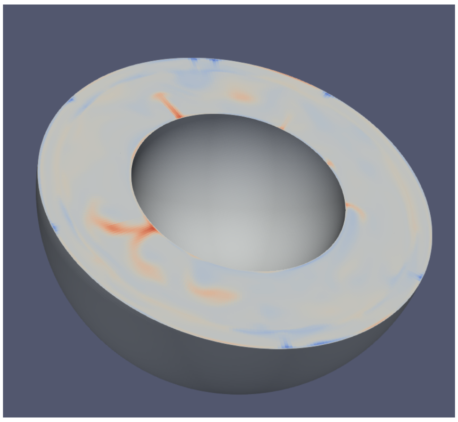

Figure 15: Temperature anomaly along the equator (X-normal)

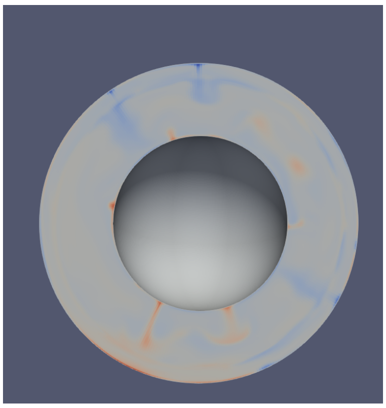

Figure 16: Temperature anomaly along the prime meridian (Y-normal)

Now we need to create a visualization that would make it easier for us to observe the flow of temperature throughout the surface. We do this by creating 4 clips, one planar clip along the X-normal, one planar clip along the Y-normal, one spherical clip at a depth of 1600 km from the outer mantle i.e at the radius of 4778 km, one spherical clip to depict the core i.e. radius = 3485 km.

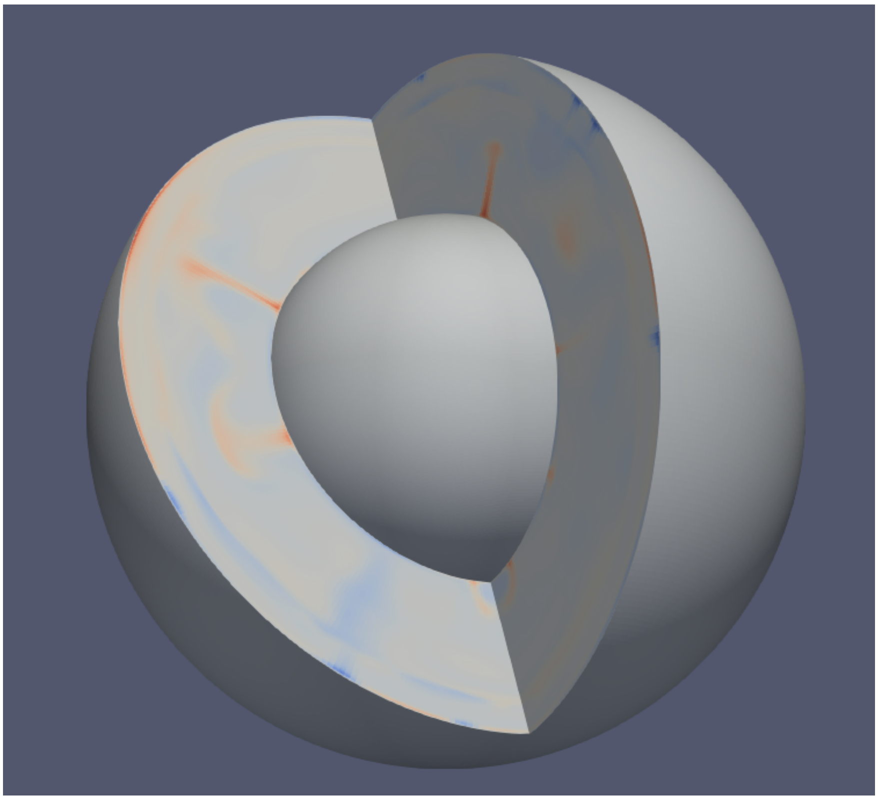

Figure 17: Clipped image with a view of the temperature anomaly

As we need to check how the hot plumes are moving toward the surface, we will use a contour filter to get the absolute values of the temperature at 1660 km depth.

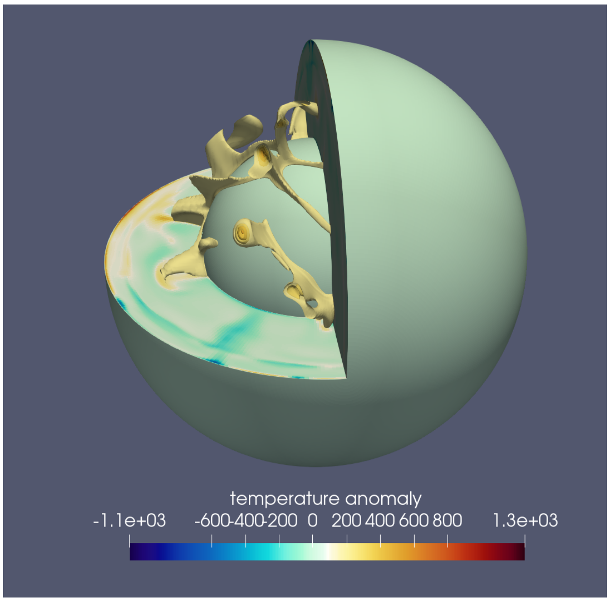

Figure 18: Contour filter showing the temperature at different points at 1660 km depth

Now, we apply the Glyph filter to take a look at how the hot plumes are moving across the crust.

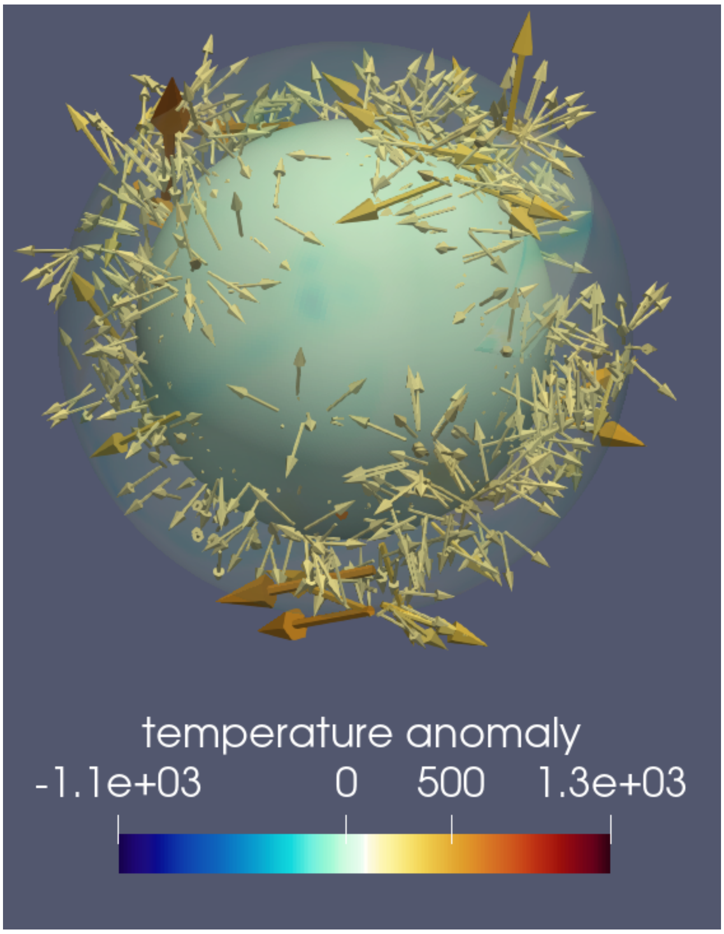

Figure 19: Glyph filters showing heat movement

The glyph filter shows us how the hot plumes move from the core through the mantle, the larger the arrow the further the plume travels, and the darker the arrow, the hotter the plume is.

Takeaways: By examining the isosurfaces of temperature anomaly, we can observe that the hot slab/material starts at the surface and progressively rises towards the mantle from the core over millions of years (myrs). Additionally, we notice that the material spreads out on the surface, becomes shallow while descending, and then spreads out again at the core. Notably, a lateral flow occurs until 660km, after which the material begins to descend. Moreover, the vector stream visualization along a single axis provides insights into the overall trends beneath the earth's surface. The arrow glyphs represent the cold material descending, with the magnitude indicated by the tips, while the hot material rises up. Please refer to the visualization images at different time steps below for a clearer understanding of the trends. (For enhanced clarity, please watch the video.)

Task 4: Visualize stagnated or diverted hot plumes at ~660 km depth.

Task Overview: The goal of this task is to visualize the convection flow of hot slabs at a depth of ~660 km from the earth's surface and observe the various trends within this flow.

Implementation: We first selected data for 10 Million Years (myrs) and implemented the required filters to it. The next step was to use the same implementation on the whole dataset. This was done to make sure that our laptops are able to handle the dataset efficiently and that there is no major lag between applying the filter and the output.

The next step was to take a look at the way the velocity components are affecting the movements of the hot slabs. The first that we need to do is convert the three velocity components i.e. vx, vy, and vz into a single vector, we use the following formula to do that:

$$Velocity = iHat * vx + jHat * vy + kHat * vz$$

This was implemented using the calculator filter in Paraview. Now, we needed to visualize the movement of hot slabs along with the velocity. We first used a stream tracer filter to observe the direction and magnitude of velocity around the globe.

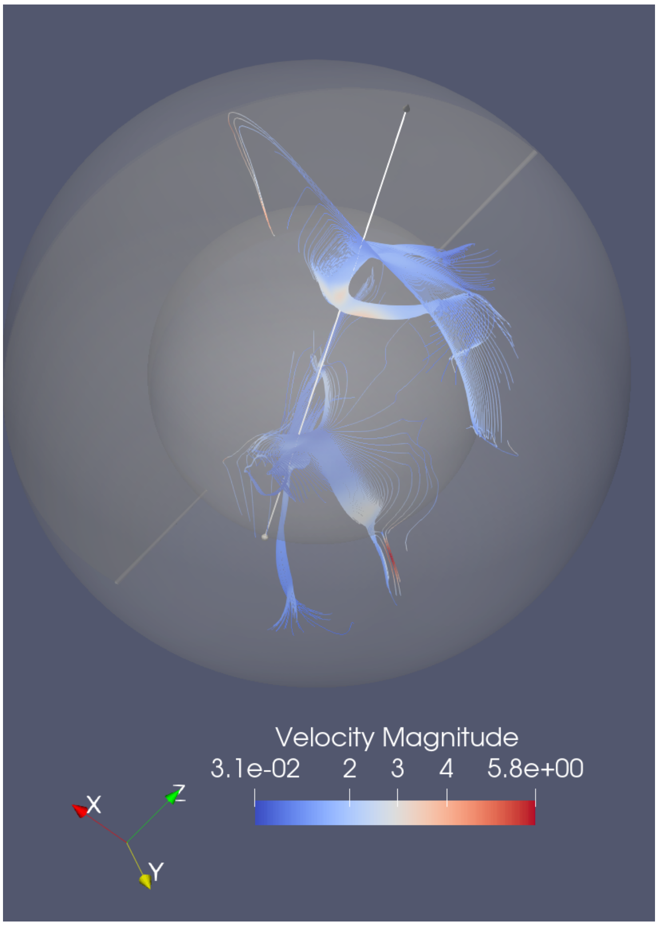

Figure 20: Streamtracer to see the velocity

The next step is to visualize how the velocity is causing the movement of the hot slabs, first, we use a threshold filter to make sure that we are taking a look at just the hot slabs. This is done to improve the readability of the visualization. Now we apply a glyph filter and change the coloring to “Temperature Anomaly”, using the calculated velocity vector as the orientation array. This gives us the following output

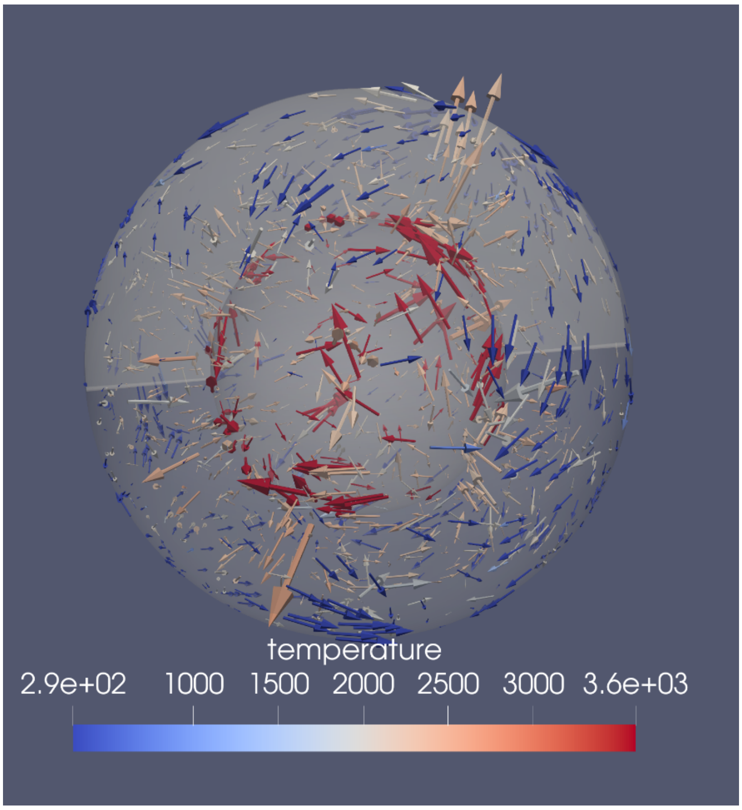

Figure 21: Arrow Glyphs depicting the change in temperature

Now our next step is to take a look at the absolute values of the temperature. We followed similar steps that we used in the previous task.

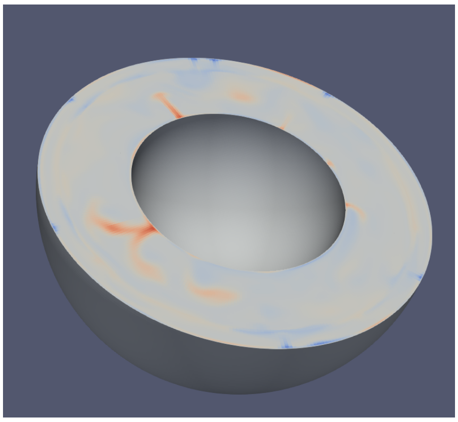

Figure 22: Temperature anomaly along the equator (X-normal)

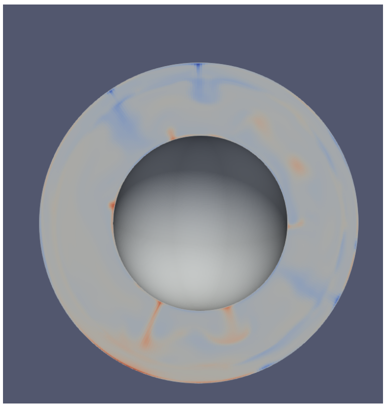

Figure 23: Temperature anomaly along the prime meridian (Y-normal)

Now we need to create a visualization that would make it easier for us to observe the flow of temperature throughout the surface. We do this by creating 4 clips, one planar clip along the X-normal, one planar clip along the Y-normal, one spherical clip at a depth of 660 km from the outer mantle i.e at the radius of 5718 km, one spherical clip to depict the core i.e. radius = 3485 km.

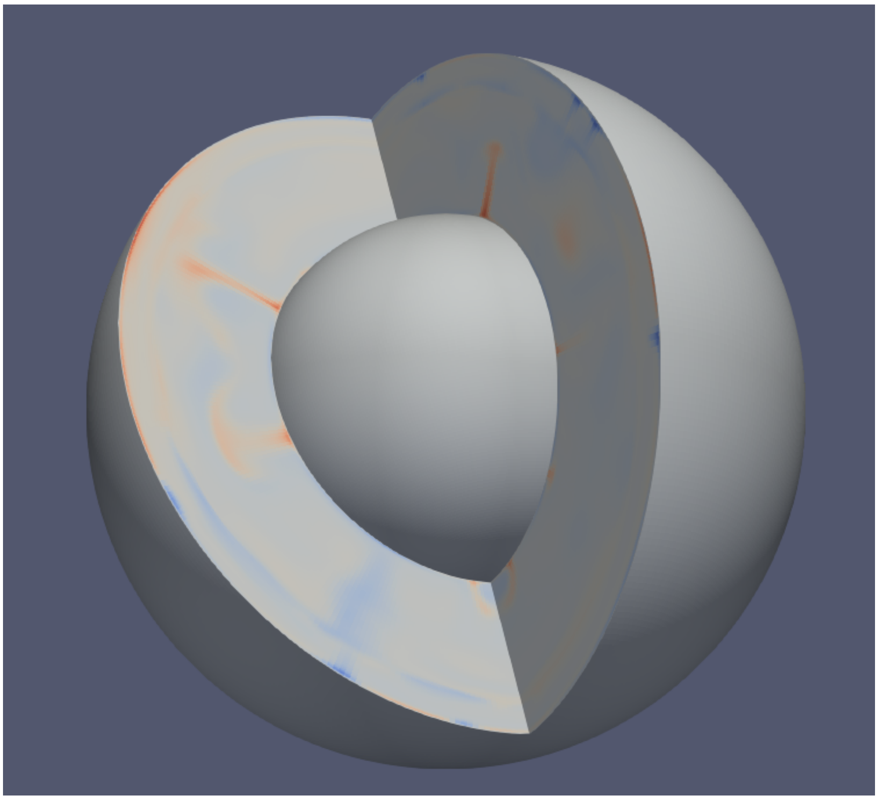

Figure 24: Clipped image with a view of the temperature anomaly

Now we will use the contour filter to take a look at the temperatures at ~660 km depth.

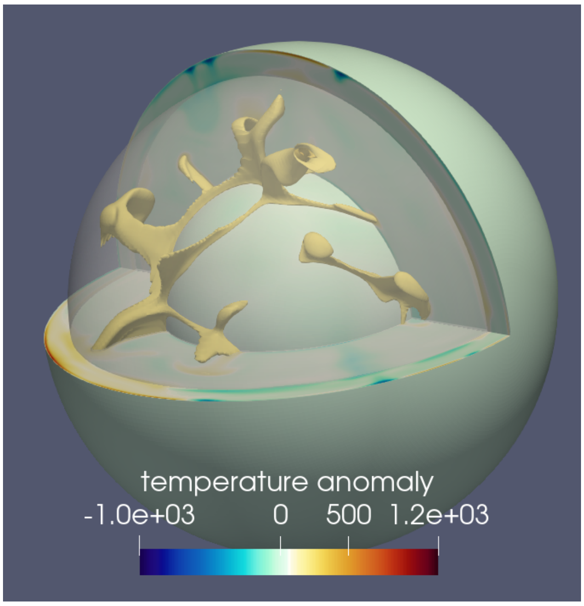

Figure 25: Contour filter showing the temperature at different points at 660 km depth

Takeaways: We created an animation for 100 timesteps for all the 3 views in parallel, along with them rotating around the axis . Convections may diverge or stagnate at a spin-transition depth of 660 km.

We can observe that the slabs continue to converge from the surface to the 660km, all the way to the core. They first converge at each depth and then diverge downwards. The density anomaly on the other hand as compared to the temperature anomaly grows up and creates a boundary around the core. This indicates the comparison between the two anomalies and how their movement contradicts each other. The density anomaly for the convection material is more widespread compared to the narrower descent of the temperature anomaly.

We can also observe the velocity vector flow in the visualization. Around the surface of the depths, the velocity direction follows the surface compared to their movement across the depths where it flows and rises to the surface. The magnitude changes can also be observed throughout the video, they are much higher when trying to rise up to the surface.

Task 5: Visualize correlations between the variables and the flow patterns described below.

Task overview: The main goal of this task was to visualize the flow of cold slabs and hot plumes and understand how this is affected by different physical variables. We created different visualizations to understand flow patterns at depths of 660 km and 1600 km.

Implementation: We selected data for 20 Myrs(million years) to perform the visualization. As the flow patterns at the depth of 660 km and 1600 km are different we have created separate visualizations for them. For understanding the flow pattern at 660 km, we created a contour and visualized the isosurfaces of temperature anomaly at depths above 660 km and below 660 km. For the depth above 660km, we checked for cold, horizontally-extended material, and at depths below 660 km we checked for hot rising material. We created a nested clip filter over our dataset to get the area between the earth's crust and the layer at 660 km depth. Similarly, we created a clip filter at 660 km depth to visualize hot mantle material.

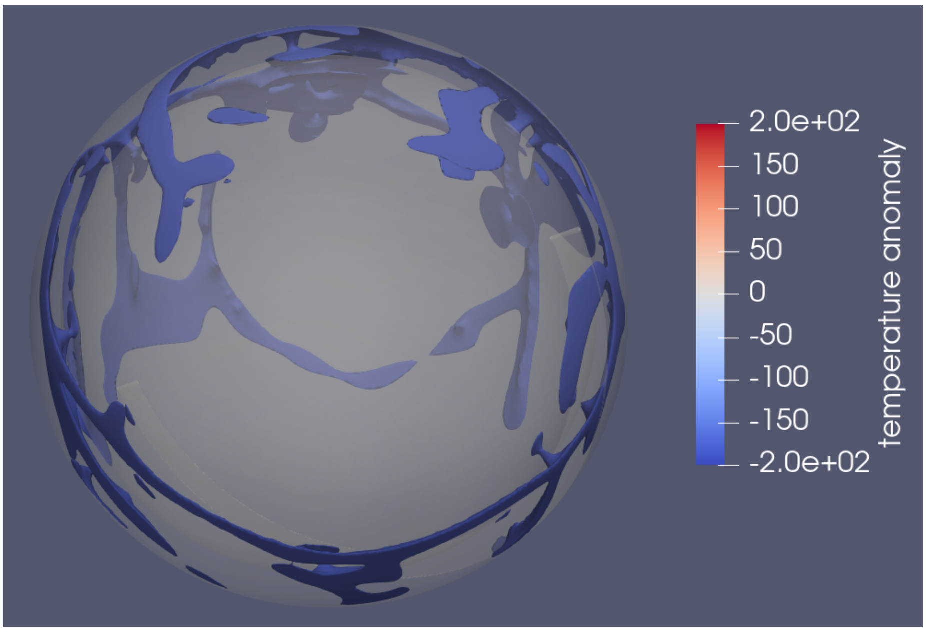

Figure 26: Cold, horizontally extended material above 660 km depth

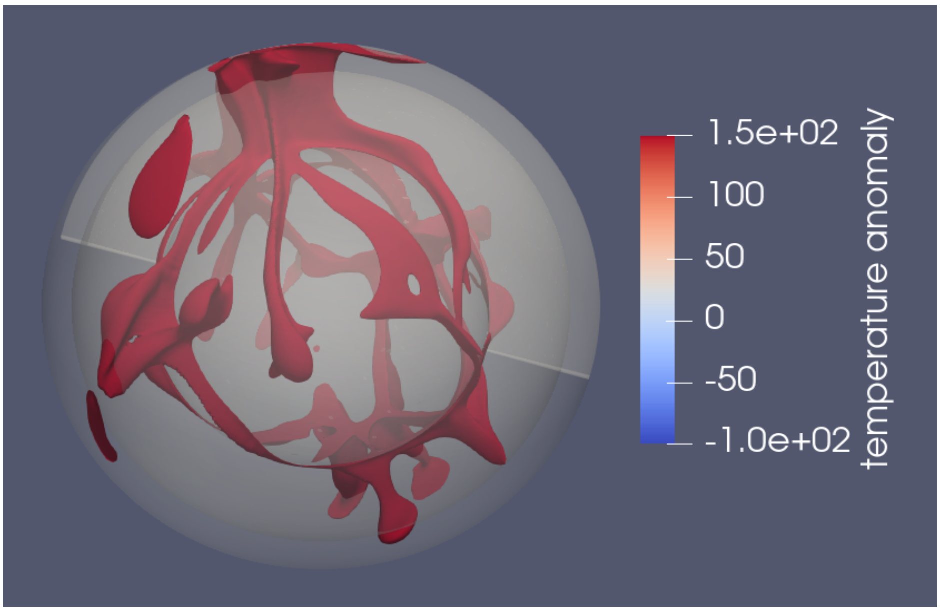

Figure 27: Hot rising material below 660 km depth

To understand the flow pattern below 1500 km depth, we applied a clip filter at a depth of 1500 km and generated a contour of temperature anomaly. The surface is colored according to spin transition-induced density anomaly at 1500 km of depth.

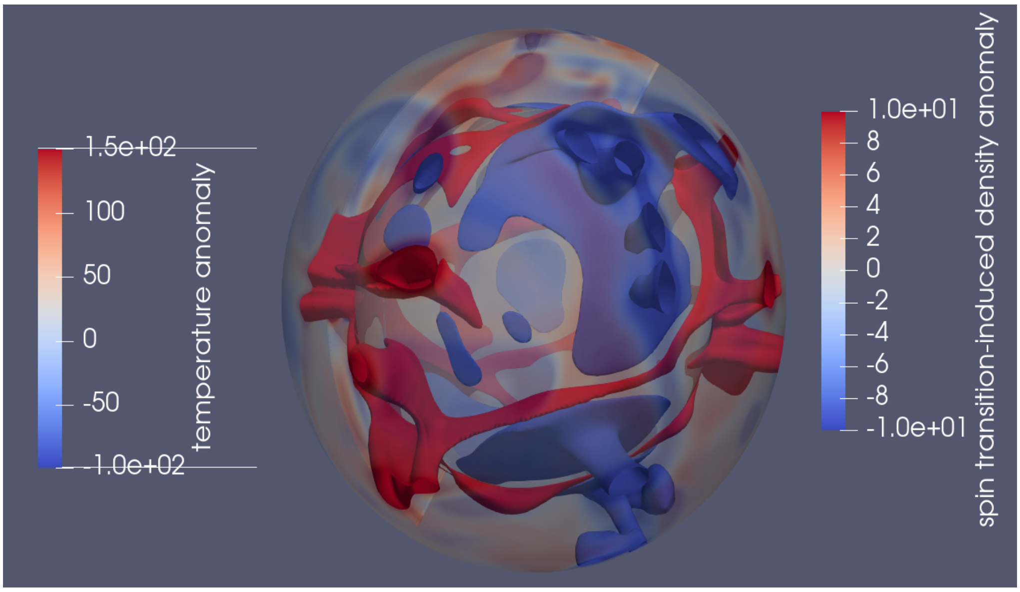

Figure 28: Temperature anomaly isosurfaces at 1500 km depth

The below few figures show the flow pattern of the material below the surface from the outer core to the crust. We will be able to visualize the flow pattern at different depths in one visualization. For that, we generated a contour of temperature anomaly and adjust the opacity of the surface to get the below visualizations.

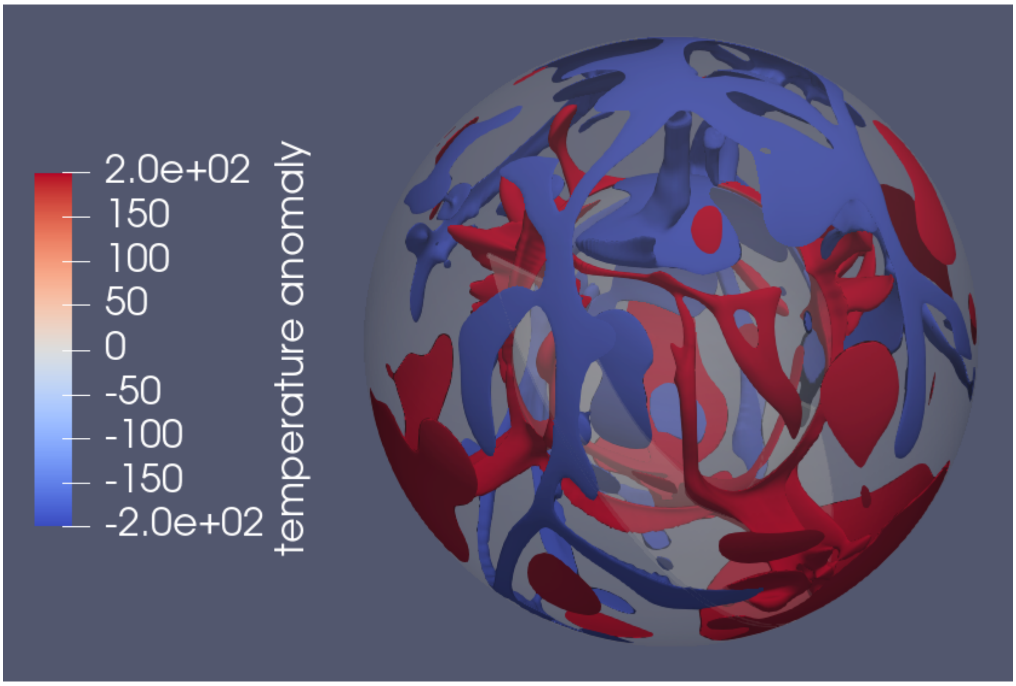

Figure 29: Movement of temperature anomaly from outer core to crust

The issue with the above visualization is that it's very obstructive and is very difficult to get a complete picture of the movement of the material below the surface. Therefore, we clipped and sliced along the y-axis to get this visualization and get a better understanding of the flow pattern of the material.

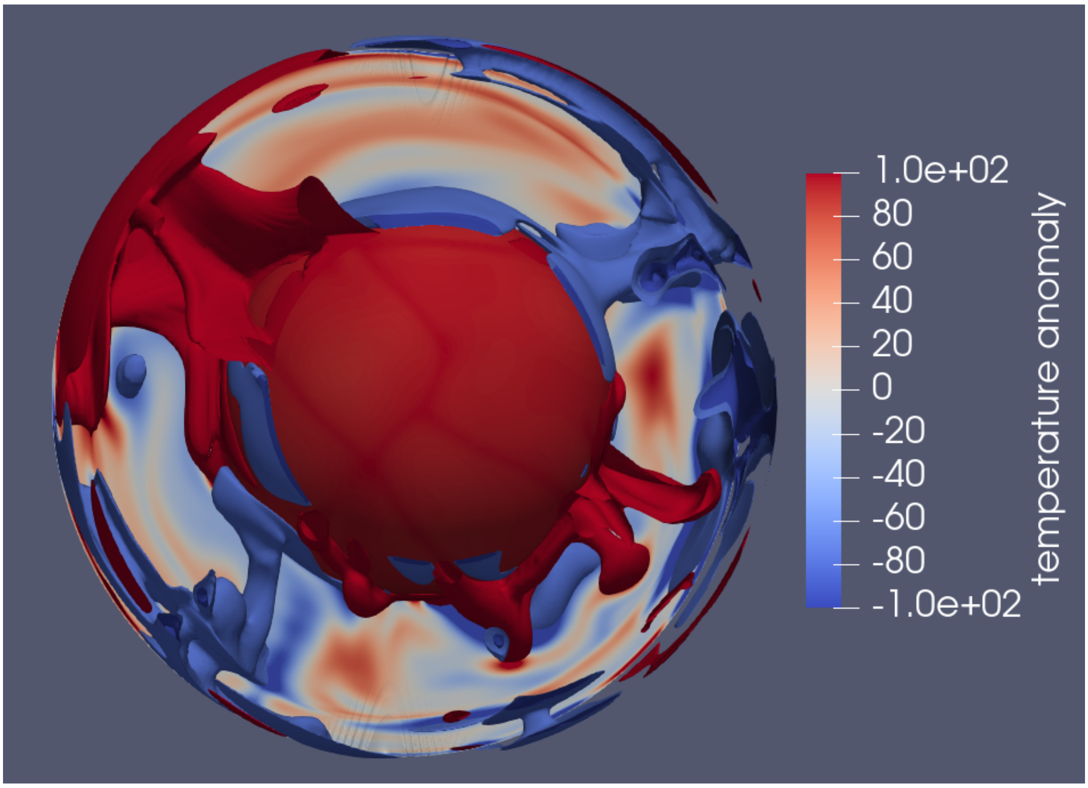

Figure 30: Flow pattern at various depths

Key takeaways: There are a few conclusions that are clearly visible when we produce animation through all timesteps and may not be apparent in the screenshots above. Therefore, we are also submitting our animation videos.

- Above 660 km of depth, there is a traverse(or horizontally-extended) movement of sinking cold material, and below 660 km of depth, there is the radial movement of hot rising material. At this depth, the flow pattern is because of the endothermic phase transition. Due to this phenomenon, the material flow partially slows down and hence the traverse movement of sinking the cold material. Similar behavior was seen with rising hot material as it stagnates and shows traverse movement at a depth of 660 km.

- We saw avalanches between 660 and 1500 km of depth but there is some slowdown and stagnation at 1500 km of depth because of spin transition-induced density anomaly. We saw some traversal movement in the flow of cold sinking material because of the negative density anomaly in certain regions. A similar trend was seen with rising hot material as it shows traverse movement at 1600 km of depth due to positive density anomaly in certain regions. Near the depth of 1600 km the density anomaly changed to positive and we saw an avalanche of sinking cold material.

5. Learnings and Accomplishments

Through this project, we gained valuable insights into the various anomalies that occur beneath the earth's surface. Our assignments on scalar field visualization enabled us to explore and implement a range of filters in ParaView, which proved immensely useful in visualizing the dataset. This contest provided us with a unique opportunity to assign significance to simulation data by undertaking diverse tasks that deepened our understanding of this domain. We gained knowledge about the diverse transitions and phenomena that occur at different depths in the mantle and the core. Collaborating with one another was an added advantage, allowing us to share our learnings and insights and better comprehend both the tool and the dataset.

We are delighted to announce that we achieved all the objectives set out in our initial proposal and even exceeded some by providing more detailed and parallel views to better comprehend the data. While we would have preferred to utilize additional tools such as the OpenGL interface for superior orthographic projections, we were constrained by time and thus chose to complete the project solely with ParaView. Nevertheless, we did explore tools that assess time series data and believe that they could be useful for future projects.

6. Evaluation

We are confident that our project implementation was executed with precision. Our original plan was to cover all the tasks listed in the contest link, but during the mid-progress report, we realized that the dataset was much larger than anticipated (covering 300 million years) - as was rightly pointed out by one of the TAs. Despite our attempts to work with the data on Cade servers, we encountered similar issues and almost decided to reduce some of the tasks. But with some extra effort, we were able to go beyond our initial proposal and complete all the tasks listed with some added visual comparison. As a result of the data complexity, we requested additional computation resources from CHPC servers, which allowed us to work with the data more efficiently.

However, we do acknowledge that we could have improved our time management skills to maximize the use of our resources. Additionally, we recognize that there are other tools apart from ParaView that we could have utilized for further analysis.

Overall, we are pleased with the outcome of this project and believe that we have gained valuable insights into this domain. It was a great learning experience for all three of us, and we look forward to utilizing the skills and knowledge we have gained in future projects.

7. Additional Comments

For future work, we would like to explore some of the tools that the contest winners used to demonstrate the visualizations. These include some biological computation tools as well as some well-known graphic libraries like OpenGL, JetBrains, etc.

8. References and Resources

Videos and State files: ScientificViz_Project

Contest, Data and Tasks link: https://scivis2021.netlify.app/

References: T. McGraw and M. Eddy, "Hybrid Rendering for Interactive Visualization of Mantle Convection" in IEEE Computer Graphics and Applications, vol. 42, no. 06, pp. 96-106, 2022. doi: 10.1109/MCG.2022.3173557

Additional References: Papers mentioned in the contest link.