Project Final Report

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Project title: Convection in Earth's Mantle - A Visualization

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Overview and goals of your project.

The project aims to visualize and analyze the time series data of the mid-mantle stagnation and spin transition-induced anomalies in a simulated Earth mantle. The focus will be on understanding the dynamic temperature, velocity, and density anomalies over time.

Background and related work. What books, papers, and websites did you learn from?

We learned about the data and the required scientific background knowledge using the SciVis 2021 contest webpage.

Provide a description of your project. What data did you use? What questions did you answer? Describe any new questions that arose throughout the project.

The dataset used contains data on mantle convection processes over geological time scales. The dataset spans 500 million years, comprising 251 time steps, with each step representing a 2 million-year interval. We were able to utilize only 100 time steps spanning over 200 million-years due to the download links being expired/inaccessible. The grid is defined in terms of latitude, longitude, and radius.

Variables:

- *Temperature:* Represents the thermal state of the mantle.
- *Velocity Components:* Describes the flow of mantle material in different directions.
- *Thermal Conductivity Anomaly:* Anomalies in thermal conductivity relative to the laterally-averaged values.
- *Thermal Expansivity Anomaly:* Anomalies in thermal expansivity relative to the laterally-averaged values.
- *Temperature Anomaly:* Anomalies in temperature relative to the laterally-averaged values.
- *Spin Transition-induced Density Anomaly:* Anomalies in density with the spin transition effect considered.

We visualized the different temperature regions of the earth to better understand how the regions evolved over time. We studied the change in thermal conductivity and expansivity over the period of 200 million years. We also understood the correlation between spin transition-induced density anomalies and thermal expansivity. We also tried to see if there was any correlation between velocity and temperature.

The results obtained are discussed below, and Google Drive links to all animations/videos are provided.

Discuss the implementation details of your project.

We implemented volume representations to visualize the different temperature levels of the earth. We could see a clear distinction between the core, mantle and outer layer by using threshold filters to segregate the temperature values into three groups.

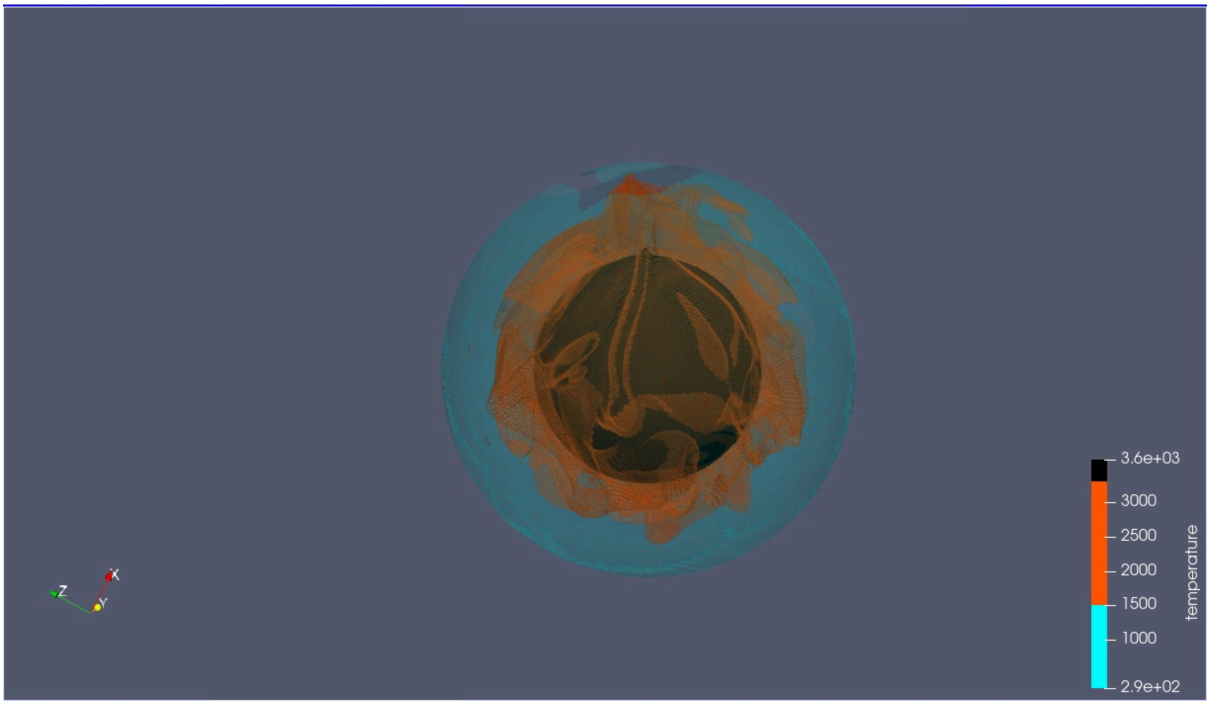

Fig 1. A time frame that shows the different temperature levels of the earth.

As seen in Figure 1, the blue region indicates the lower temperatures, the orange layer represents the moderate temperatures, and the black region denotes the higher temperature values. This segregation helps us understand the regions of the mantle and core. We can better visualize the temperature fluctuations over time using this animation.

To understand the deviations of the temperatures from the laterally averaged values, we visualized the temperature anomalies. Three different animations were generated to better understand the areas where the temperature anomalies are the highest or lowest, using 1D transfer functions with opacity mapping.

Figures 2, 3, and 4 represent time frames from the animations for the high, low, and combined temperature anomalies. The links to the animations are as follows -

- ➔ High-temperature anomalies
- ➔ Low-temperature anomalies
- ➔ Combined animation

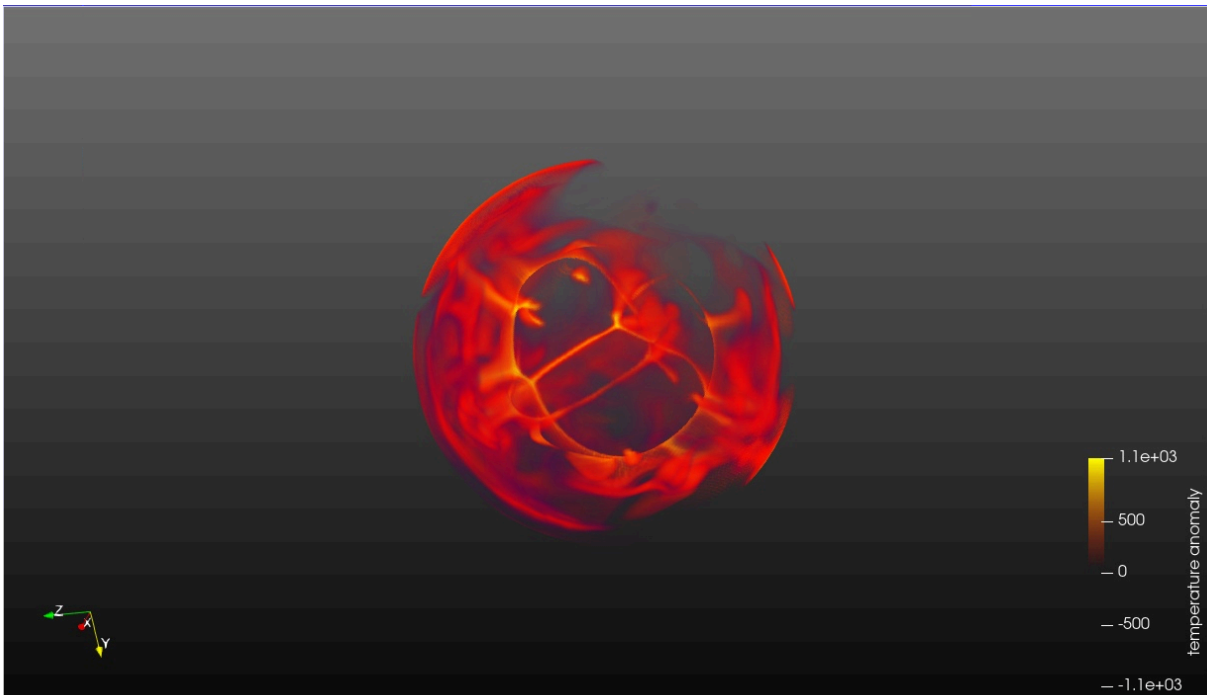

Fig 2. A time frame that shows the areas of high-temperature anomalies.

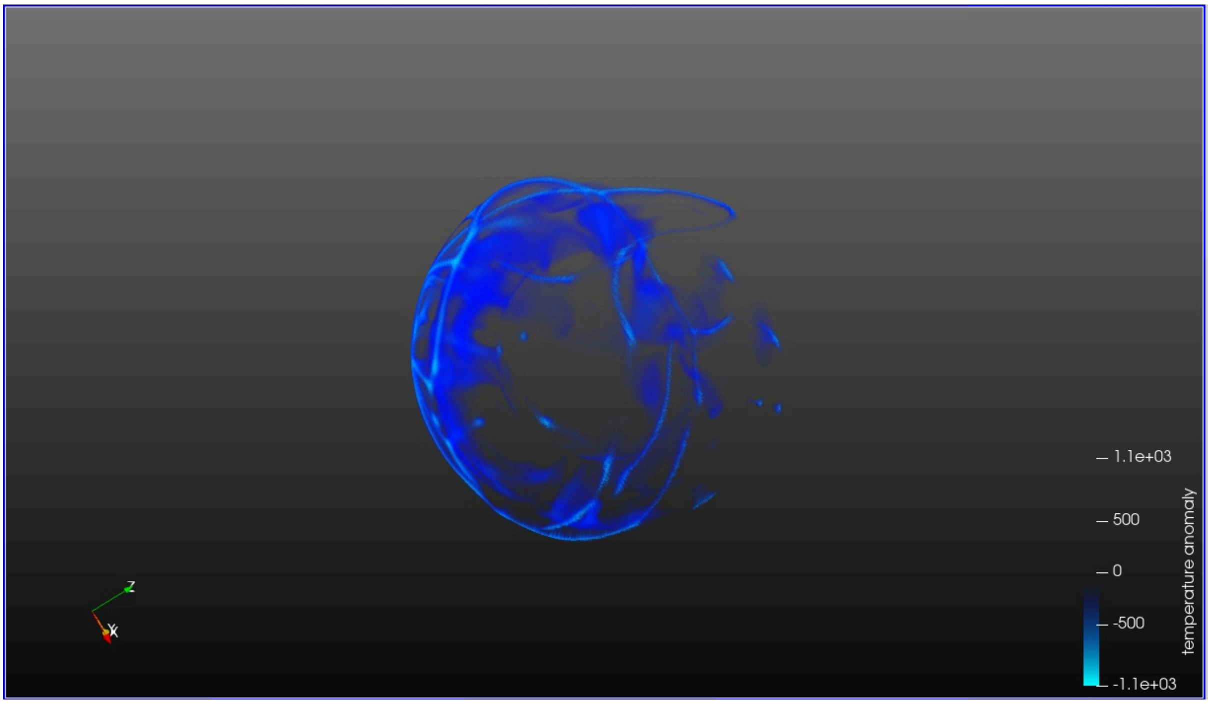

Fig 3. A time frame that shows the areas of low-temperature anomalies.

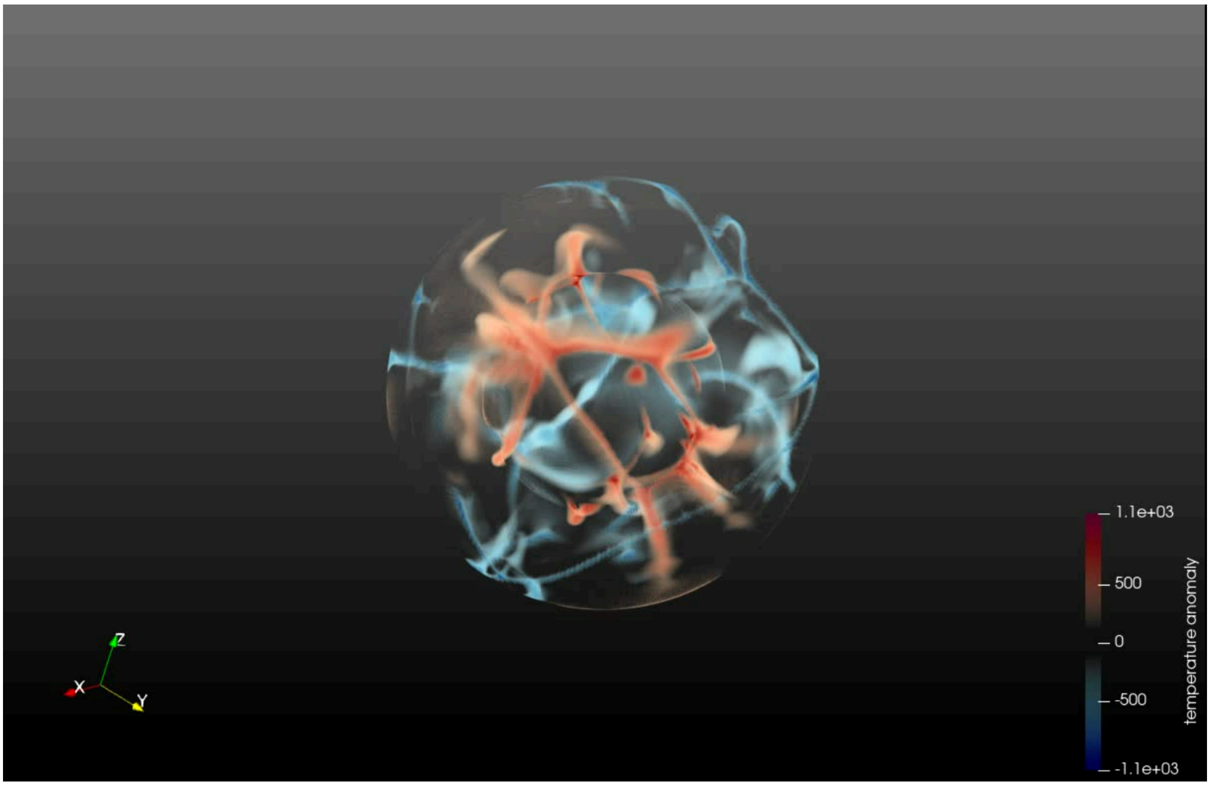

Fig 4. A time frame that shows the areas of both high and low-temperature anomalies.

In the context of the Earth's mantle, thermal conductivity plays a significant role in controlling the transfer of heat from the Earth's core to the surface. It influences mantle temperature gradients, thermal boundary layer thicknesses, and the efficiency of heat transfer within the mantle. Variations in thermal conductivity across different mantle materials can affect mantle convection patterns, geological processes, and the distribution of heat energy within the Earth's interior.

To further analyze this, we visualized the anomalies in the thermal conductivity of the mantle.

The visualizations clearly show that the inner regions tend to have spots with lower thermal conductivity than the laterally averaged values. Meanwhile, the outer regions tend to have spots with higher thermal conductivity than the laterally averaged values.

The discussed effects can be seen in this thermal conductivity anomaly animation.

Fig 5. A time frame that shows the areas of both high and low thermal conductivity anomalies.

Thermal expansivity is a measure of how much a material expands or contracts with changes in temperature. In the context of mantle materials, thermal expansivity affects how their volume changes with temperature variations, which in turn influences density and buoyancy.

The thermal expansivity anomalies were similarly visualized to reveal more characteristics of the earth's layers. Figure 6 represents a time frame from this visualization.

The animation for the same can be found in the given link.

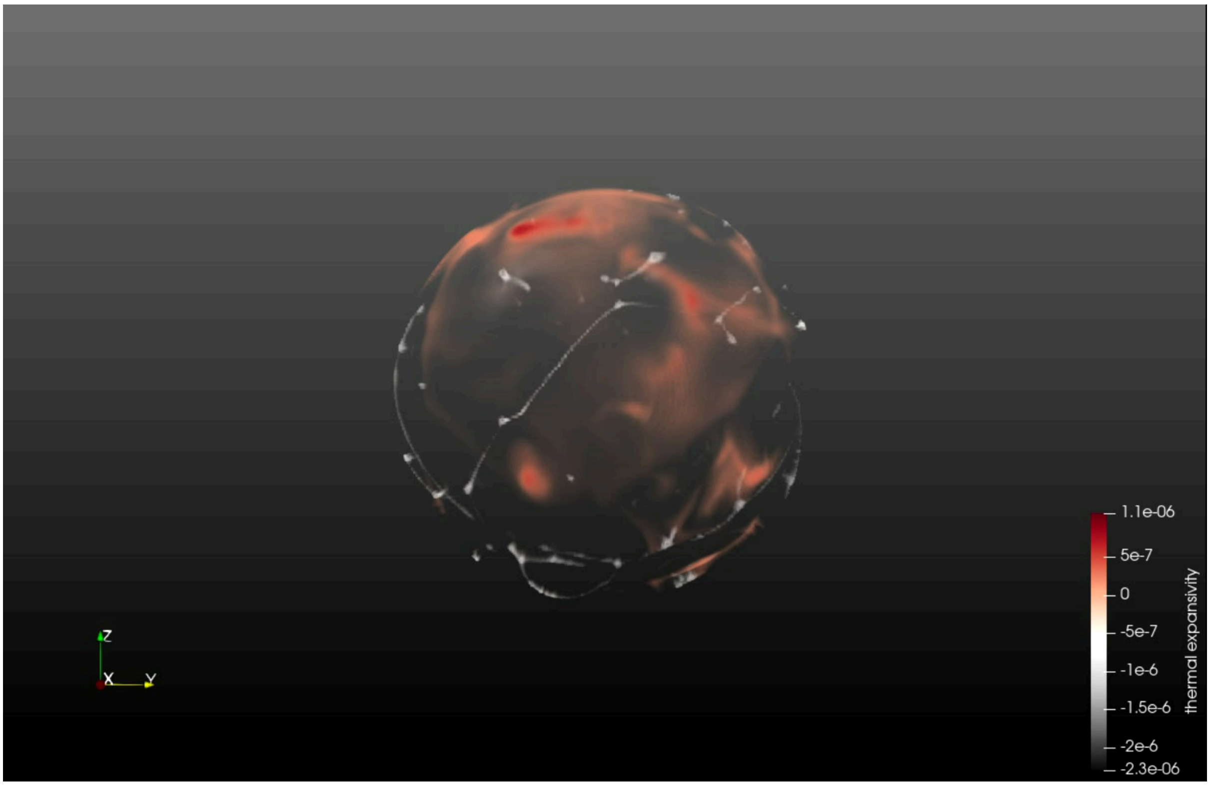

Fig 6. A time frame that shows the areas of both high and low thermal expansivity anomalies.

Spin transition-induced density anomaly refers to variations in the density of mantle minerals caused by changes in the electronic spin state of iron atoms under high-pressure conditions. As iron undergoes spin transitions, it can lead to local density anomalies compared to the surrounding mantle material.

This is visualized from the data, and the animation obtained is provided in the given link. Figure 7 shows a time frame from the rendered animation.

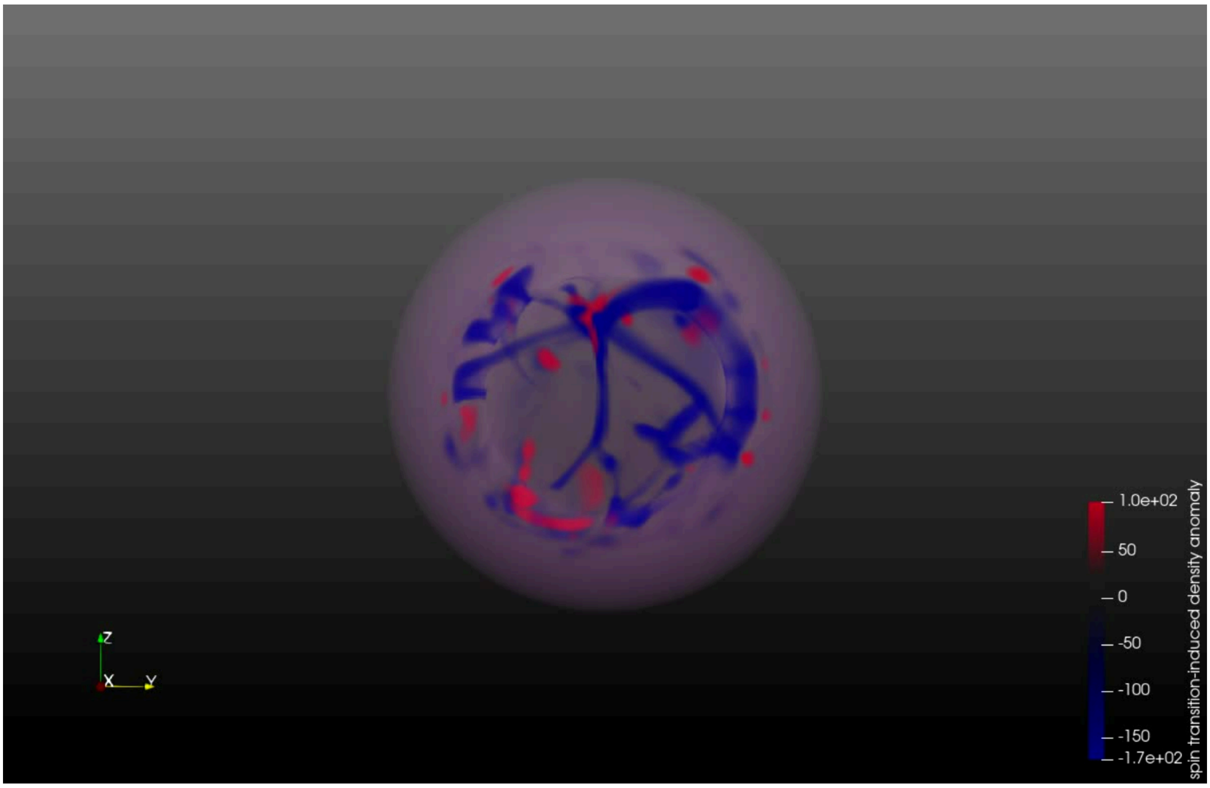

Fig 7. A time frame that shows the areas of high and low spin transition-induced density anomalies.

The spin transition-induced density anomaly and thermal expansivity are both properties of mantle minerals that can be influenced by changes in pressure and temperature. While they are distinct phenomena, they are correlated through their dependence on the same underlying factors, such as the electronic configuration of iron atoms in mineral structures.

This inverse correlation can be seen by comparing the two animations side by side and noticing areas of high and low anomalies. They tend to follow similar trends as time progresses and reveal the correlation between them. Figure 8 illustrates the same.

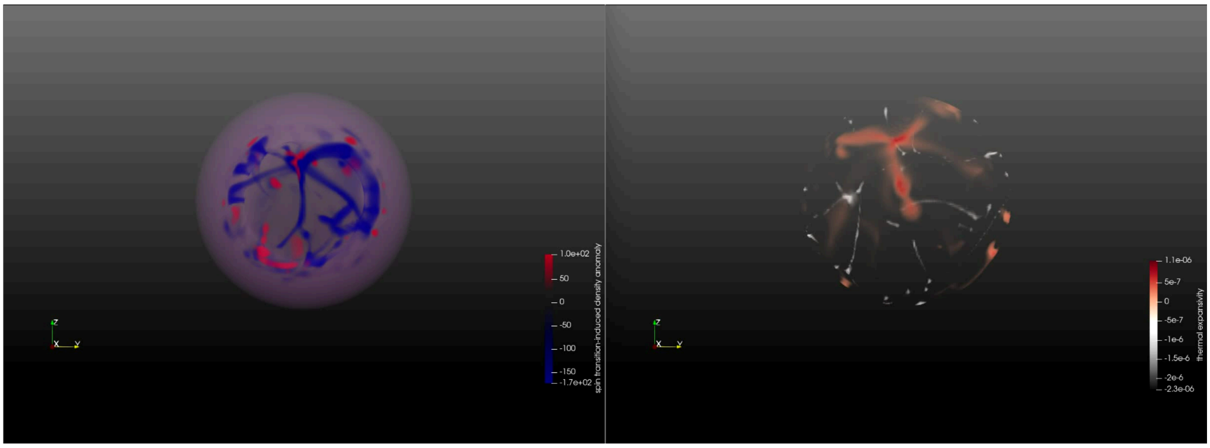

Fig 8. Inverse correlation between spin transition-induced density and thermal expansivity anomalies

The velocities of the mantle materials were calculated using the following formula in the Calculator filter.

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velocity = (iHat*vx + jHat*vy + kHat*vz) * 1e9
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This vector was then used to generate a multi-field visualization consisting of arrow glyphs representing the velocity vectors and a clipped surface representation of the earth's temperature. However, the velocity vectors obtained did not show any significant trends/correlations to the temperatures.

Figure 9 shows a time frame of the animation obtained.

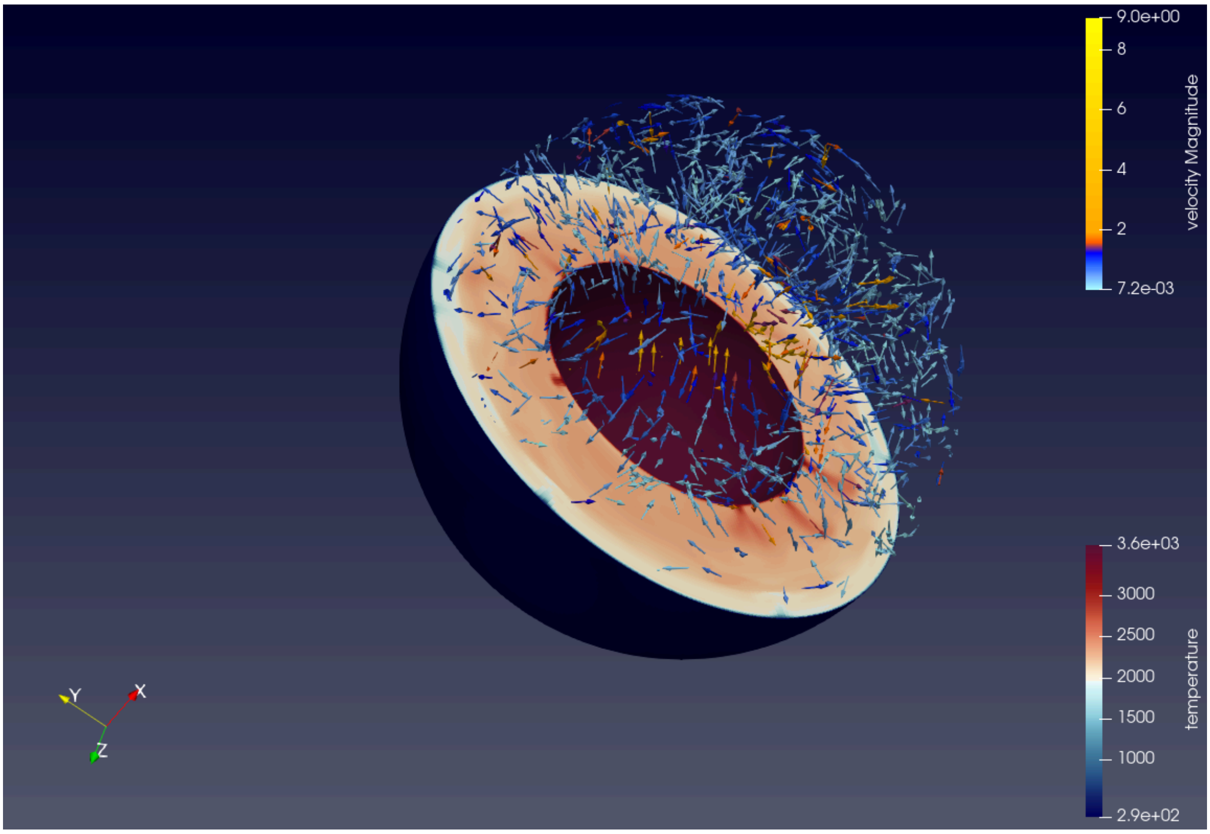

Fig 9. A time frame showing the velocity arrow glyphs and the surface representation of temperatures.

Outline what you learned from doing this project.

From this project, we learned several key insights into mantle convection processes and the dynamics of Earth's interior:

Understanding Temperature Evolution: By visualizing the temperature distribution over time, we gained insights into how temperature levels evolve within the Earth's mantle. This allowed us to observe fluctuations in temperature and identify regions of high and low temperatures.

Exploring Temperature Anomalies: Analyzing temperature anomalies provided valuable information about deviations from average temperature values. We identified regions with significant deviations and observed how these anomalies changed over time.

Examining Thermal Conductivity and Expansivity: Visualizing anomalies in thermal conductivity and expansivity helped us understand how these properties vary across the mantle. We observed spatial patterns in conductivity and expansivity anomalies, shedding light on their influence on mantle dynamics.

Investigating Spin Transition-induced Density Anomalies: By visualizing spin transition-induced density anomalies, we explored variations in mantle mineral density due to changes in iron spin states. This provided insights into the distribution of density anomalies and their correlation with other mantle properties.

Correlating Properties: We observed correlations between spin transition-induced density anomalies and thermal expansivity, indicating an inverse relationship between these properties. This correlation highlighted the interplay between mineral physics and mantle dynamics.

Velocity Analysis: While velocity analysis did not reveal significant correlations with temperature, it provided insights into mantle flow patterns and the distribution of mantle material velocities.

If you have not accomplished all the goals of your project, or if you have exceeded them, describe how the finished project differs from the description in your project design.

We managed to accomplish almost all of our goals. The only analysis which did not yield valuable insights was the velocity analysis of the mantle materials. We tried using different configurations, but none of them seemed to produce meaningful results.

Evaluate your project: how successful do you think it was? What are the strengths and weaknesses of your project?

Overall, we consider this to be a successful attempt at visualizing some of the characteristics and trends of the earth's mantle materials. Since the data was too large to be visualized on our personal computers, we had to utilize the CHPC's Frisco 1 node. The high-performance computers helped us make the volume renders, which were computationally expensive, consuming around 100 GB of RAM. These visualizations, which would have been harder to obtain if not for CHPC's resources, provide valuable insights into the earth's mantle materials. We were not able to visualize the camera resources since they turned out to be very computationally expensive, even for CHPC's resources. This led to the partial visibility of data in some of our visualizations.

Provide additional comments useful in evaluating your project.

Link to our ParaView state files (.pvsm) are provided for further evaluation.
A link to all our results can be found here.