Hybrid rendering for interactive visualization of mantle convection

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Abstract
In this paper we describe our system for visualizing convection in the Earth's mantle using hybrid rendering - a combination of interactive raytracing and conventional rasterization graphics. The dataset for the SciVis 2021 contest includes a velocity vector field and multiple scalar fields, such as temperature and thermal conductivity, which we display using isosurface raycasting, streamlines, and line integral convolution, among other techniques. We demonstrate how these these methods can be used to explore the dataset, identify slabs and plumes, and see the connection between these phenomena and the spin-transition effect in the mantle.

Methods
The dataset provided for this challenge was generated by a simulation of mantle convection spanning 500 million years, and includes multiple scalar fields (e.g. temperature, thermal expansivity) and a velocity field. The graphics and visualization features used in our system include

- Raytraced proxy geometry for scalar and vector data display
- Filled contour plots for visualizing scalar data
- Volume raycasting of scalar field isosurfaces **[1]**
- Tricubic filtered data for smooth contour plots and isosurfaces **[2]**
- Velocity field visualization using line integral convolution (LIC) **[3]**
- Velocity field visualization using rasterized streamtubes with a custom ambient occlusion volume **[4]** technique

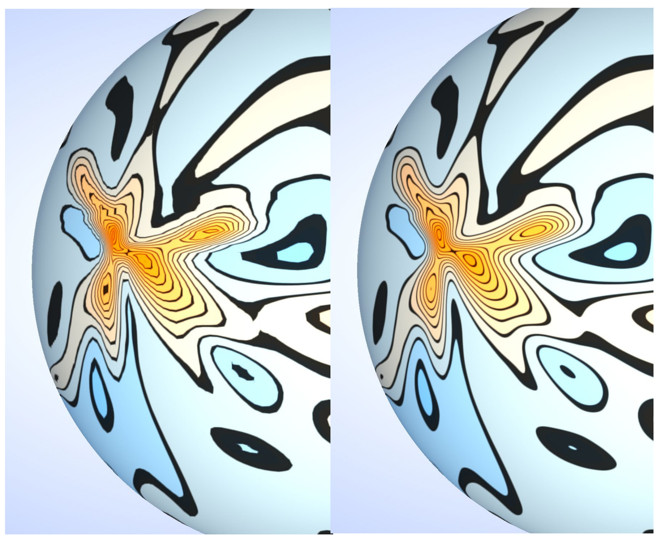

Figure 1: Filled contour plot computed with linear (left) and cubic texture filtering (right). Cubic filtering results in smoother contours, even for low resolution data.

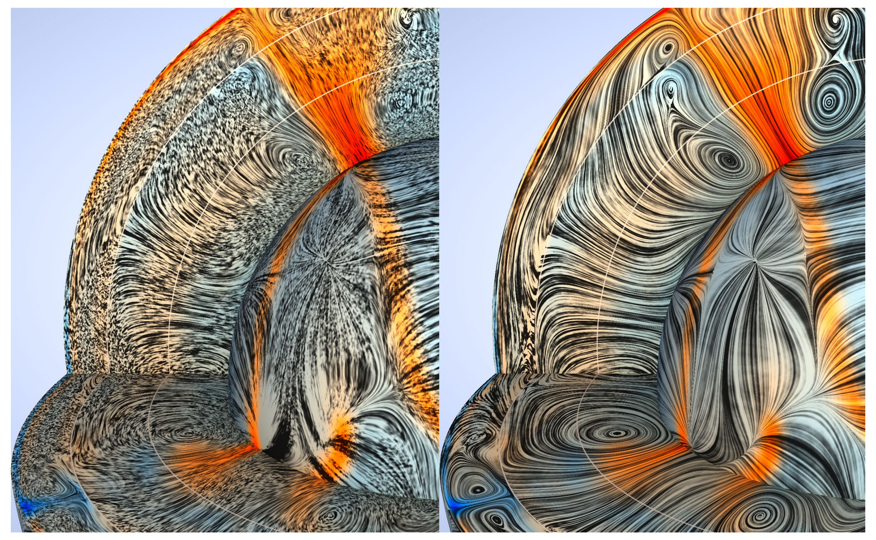

Figure 2: Convection velocity visualized with traditional LIC (left) and surface LIC, which projects vectors onto the proxy geometry to improve intensity coherence along streamlines (right).

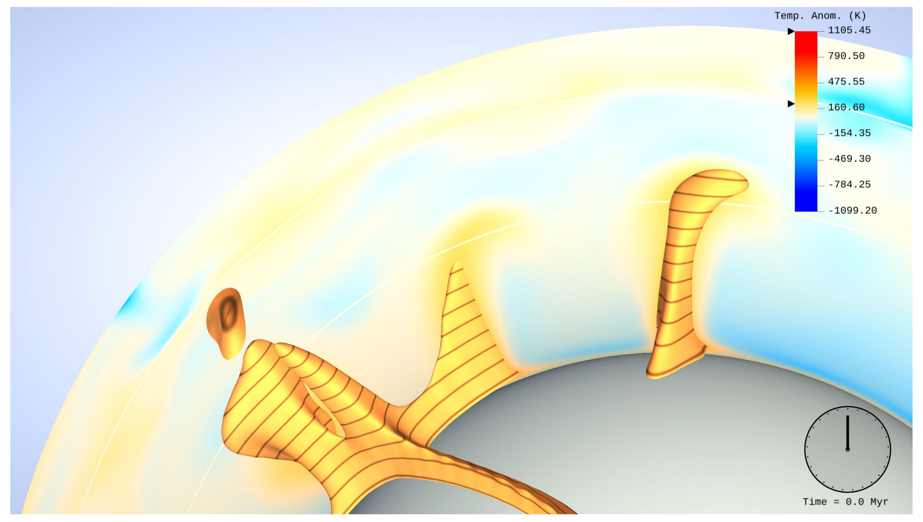

Figure 3: Isosurfaces are raycast using tricubic interpolated data. Here, isosurfaces of temperature anomaly indicate where hot plumes rise from the core-mantle boundary. Triangles to the left of the colorbar indicate the isovalues.

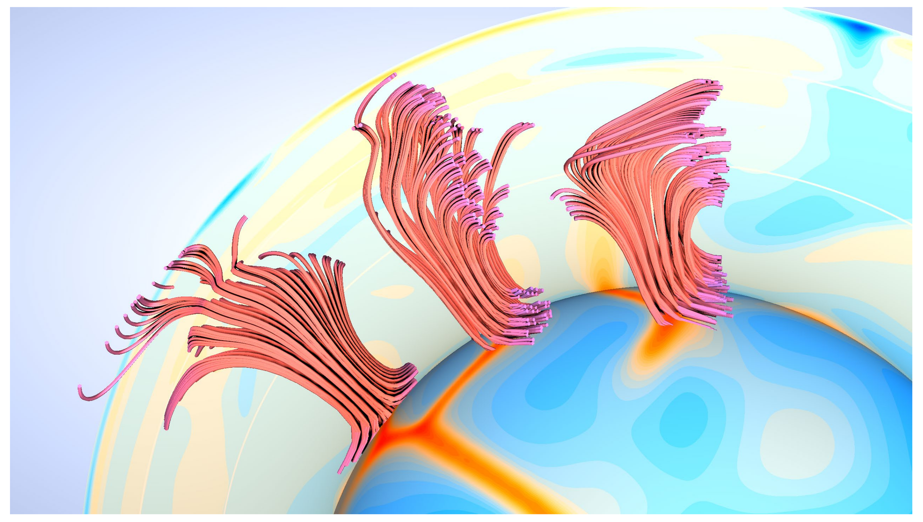

Figure 4: Streamtubes showing plumes in lower mantle. The streamlines are terminated before they reverse direction to avoid tracing an entire convection cell. The hot color denotes that the flow is in the outward direction. Ambient occlusion helps convey the spatial relations between the tubes.

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

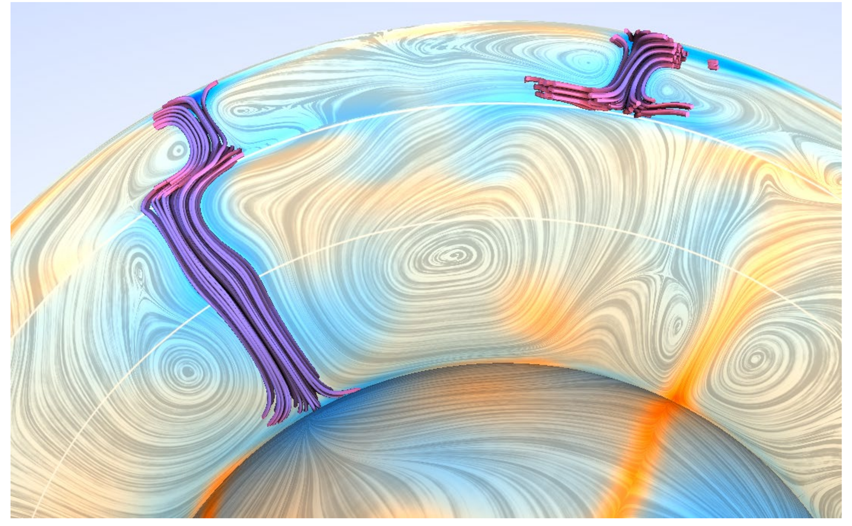

Figure 5: Slabs diverted and stagnated at 660 km, shown with streamtubes and surface LIC overlaid with temperature anomaly in the background.

Streamtubes were manually seeded in these regions based on the appearance of temperature anomaly isosurfaces.

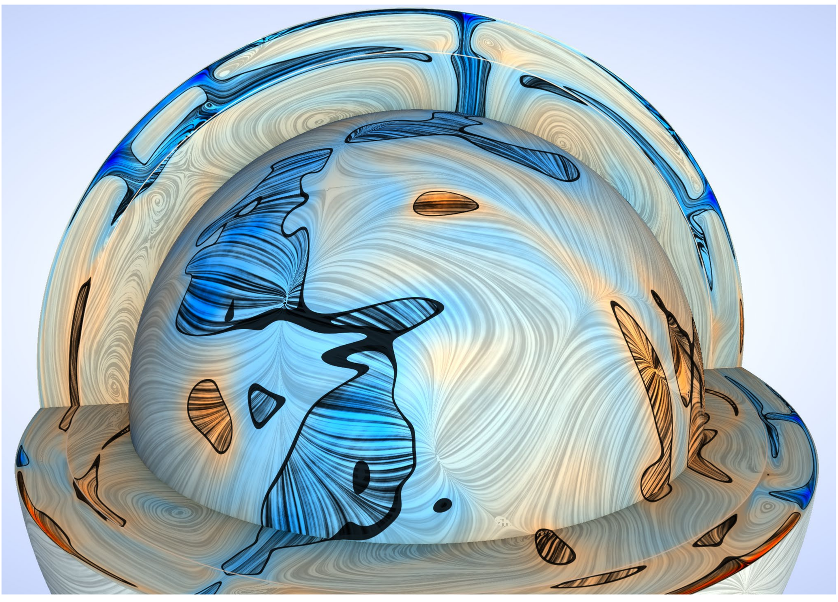

Figure 6: To find slabs we use the temperature anomaly variable to look for cold material near the surface moving first horizontally, and then downward to the 660 km line.

Surface LIC shows slabs which are stagnating near 660 km depth. The LIC intensity fades outside of temperature anomaly thresholds to emphasize the slabs.

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

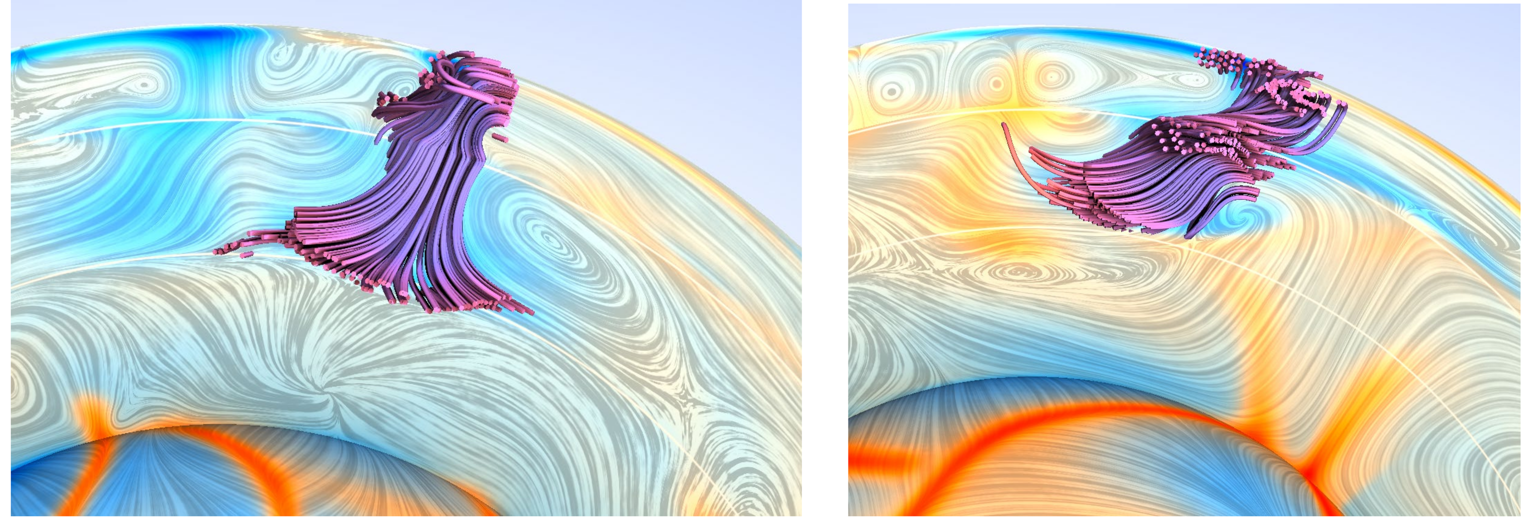

Figure 7: Streamtubes showing the 3d trajectory of slabs diverted at 1600 km depth. Surface LIC leaves some ambiguity about the 3D flow direction, but streamtubes make to flow patterns more explicit. For example, streamtubes can reveal features, like a twist due to vorticity in the flow.

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.

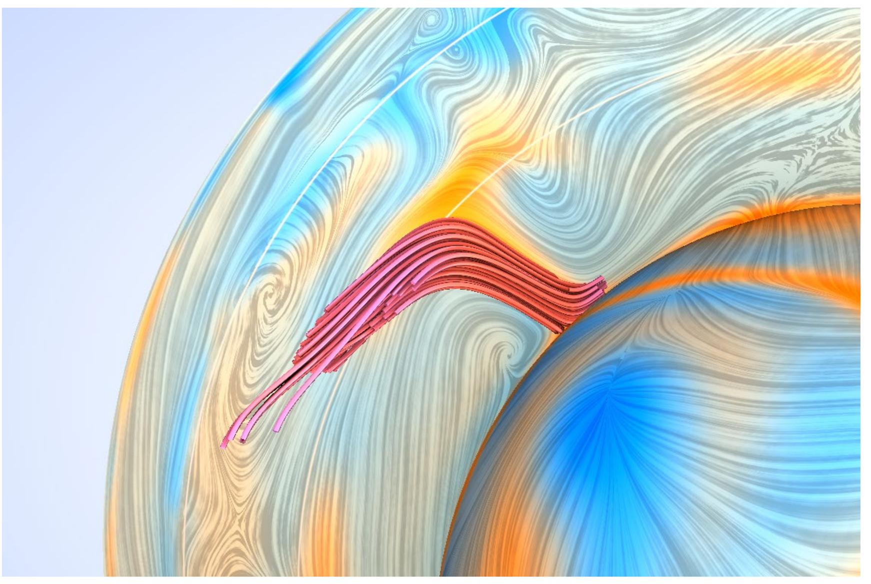

Figure 8: a plume diverted near the 1600 km depth. We identified this region by first looking for vertically extended regions of relatively hot material in the temperature anomaly isosurfaces.

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

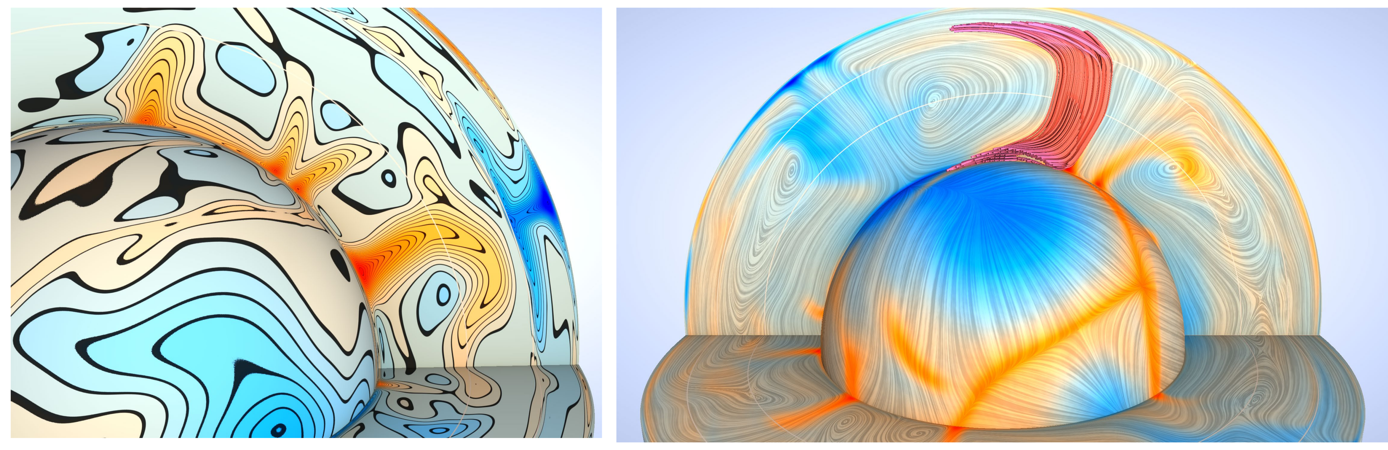

Figure 9: Isocontours (left) and streamtubes (right) showing plumes diverted at 660 km depth.

Task 5
Visualize correlations between the variables and the flow patterns.

Figure 10: The scalar field view can be split in the φ-direction. Correlations between variables can be seen by swiping the split back and forth.

In this case, thermal conductivity (left side of the split) can be seen to have negative correlation with temperature (right side of split).

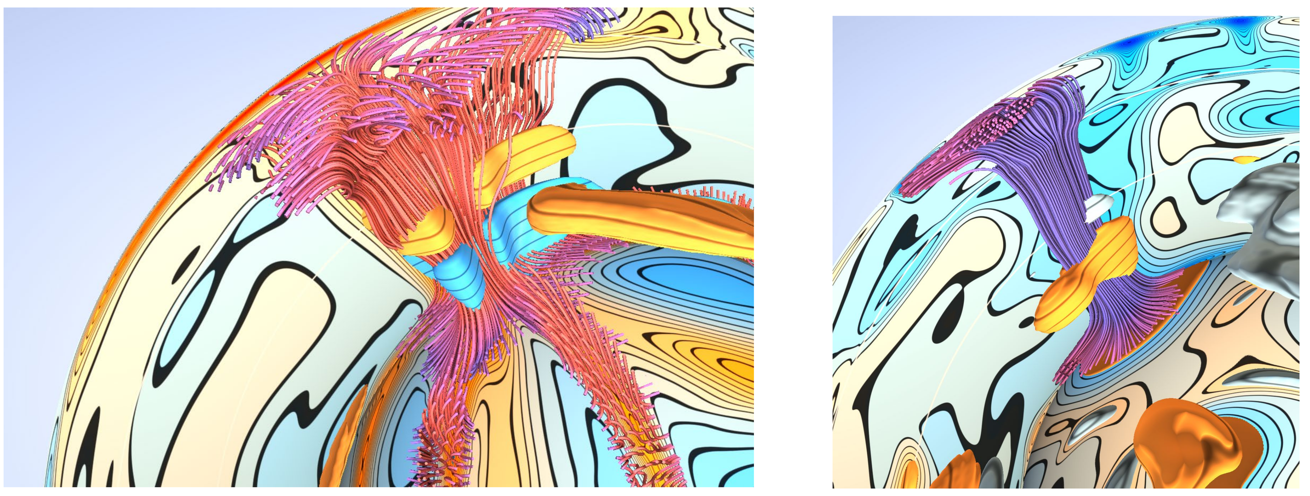

Figure 11: Streamtubes can also be displayed along with isosurfaces to determine correlations between scalar and vector fields. On the left we see a superplume as streamtubes which pass through regions of negative and positive density anomaly (displayed as blue and orange isosurfaces). On the right we see the opposite situation, a slab passing through a weak low density region, then a high density regions as it approaches the core-mantle boundary.

Conclusions
We found that some of the methods, like isosurfaces and LIC, allow users to explore the data at a global scale to identify features of interest, like slabs and plumes. Specific details can then be explored in more detail using streamtubes, and color-mapped contour plots of scalar values displayed on the proxy geometry. Using these techniques, we were able to identify slabs and plumes in the dataset, and observe their relation to patterns of layered convection in the mantle flow field. With our system we were also able to observe the relationship between slabs and plumes and the spin-transition induced density anomaly in the lower mantle.

References
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