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Physics of the Earth and Planetary Interiors xxx (2007) xxx–xxx

PHYSICS
OF THE EARTH
AND PLANETARY
INTERIORS

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Visualization of downwellings in 3-D spherical mantle convection

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Received 4 February 2007; accepted 20 March 2007

Abstract

Although the Amira visualization package has been available since 1999, not much effort has been made to use this powerful package for addressing the challenging problem that geodynamicists have in visualizing 3-D features of cold downwellings in spherical mantle convection simulations with high spatial resolution. In this paper, we present three approaches that exploit the functionalities of Amira to meet the needs of visualizing the complexity of these dynamic processes. The first task is to use the multiple isosurfaces combined with different colors and transparencies for showing the large-scale features from a global perspective. The second task is to localize the small-scale features of interest by cutting off the rest or splitting off a small part of image from the entire picture so that the details can be viewed locally. The third one is the use of multiple windows simultaneously for showing different portions of the same set data in different displaying formats from various angles of view. We will also present new geophysical findings based on these visualization approaches.

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Keywords: Scientific visualization; Downwellings; Amira

1. Introduction

Numerical simulations of 3-D spherical mantle convection (Glatzmaier, 1988; Bercovici et al., 1989) have played an important role for understanding the dynamical process of plate tectonics (Tackley et al., 2001) and the evolution of the Earth's mantle. Several spherical models of mantle convection have been available for over 20 years (e.g., Machetel et al., 1986; Baumgardner, 1985; Zhang and Yuen, 1995; Zhong et al., 2000). Much attention has been devoted to portraying the dynamics of upwellings and visualizing their structure and dynamical behavior. The cold downwelling processes play the

same important roles as the upwellings in the dynamical processes of mantle convection, but not much work has been devoted to the downwellings except in the works by H. Davies where he focused on the influences of the downwelling on interacting with the bottom thermal boundary layer and inducing secondary upwellings (Davies, 2005). The major obstacle is the spherical geometry constraint, which prevents an observer from viewing the downwellings from outside of the spherical shell. There is also the problem associated with the smaller volume of the lower mantle, where the downwellings are bunched up. Another method for viewing downwellings in 3-D spherical convection, albeit very expensive, is using immersive technology, such as the CAVE (Cruz-Neira et al., 1993), whereby one can peer at the descending slabs coming down from above.

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29 The importance of visualization in comprehending
30 the large datasets in the geosciences has already been
31 stressed in the recent report on computational geo-
32 sciences by Cohen (2005). The objective of this research
33 work was to develop a few graphic templates, which
34 will help the geodynamical community better visualize
35 and understand the dynamical process of downwellings.
36 Certainly, these graphic approaches or the same ideas
37 embedded in these approaches can also be applied to
38 effectively and efficiently visualize complicated fluid
39 dynamical processes in engineering and other geophys-
40 ical fluid dynamical applications.

41 2. Methodology

42 2.1. Numerical model

43 For generating the data, we used the hybrid spectral-
44 finite-difference code of 3-D spherical mantle convection
45 developed by Zhang and Christensen (1993). This code
46 solves time-dependent extended Boussinesq equations
47 of mass, momentum and energy conservations for the
48 fluids with infinite Prantl number and three-dimensional
49 variable viscosity. The datasets used for this manuscript
50 are from the model with an averaged Rayleigh number of
51 2×10^6 , a dimensionless thermal expansion coefficient
52 (Fig. 1a) and a depth-dependent viscosity (Fig. 1b) sub-
53 ject to the isothermal free-slip boundary conditions. The
54 model resolution consists of spherical harmonic degree

55 and order of 320 and 200 higher-order finite difference
56 points (Fornberg, 1996) in the radial direction.

57 2.2. Visualization approaches

58 We employed Amira 4.1 (<http://www.amiravis.com/>)
59 to visualize the 3-D mantle convection results. Erlebacher et al. (2001)
60 have described the use of Amira in the geosciences by means of numerous examples.
61 Hanyk et al. (in press) have employed the Amira package
62 in the post-glacial rebound problem and have presented
63 a detailed description on making movies over structured
64 and unstructured grids. Amira is a powerful commercial
65 tool developed by Mercury Computer Systems available
66 for Linux, Windows, and Macintosh. Amira provided
67 many pre-written modules for different visualization
68 functionalities in a simple user environment, where we
69 uploaded the data, and applied pre-written modules
70 to extract relevant information. The modules we have
71 employed are Heightfield, Isosurface, ObliqueSlice, and
72 TimeSeriesControl. More details on these modules are
73 presented in the description of each of the visualization
74 procedures below.

75 In the following graphic displays, the large-scale
76 downwelling features are characterized by the tempera-
77 ture distribution in 3-D spherical coordinates. The data
78 with value varying from 0 to 254 (corresponding to
79 0–3000 °C) are saved in the curvilinear format pre-
80 defined in Amira. Each dataset contains the temperature
81

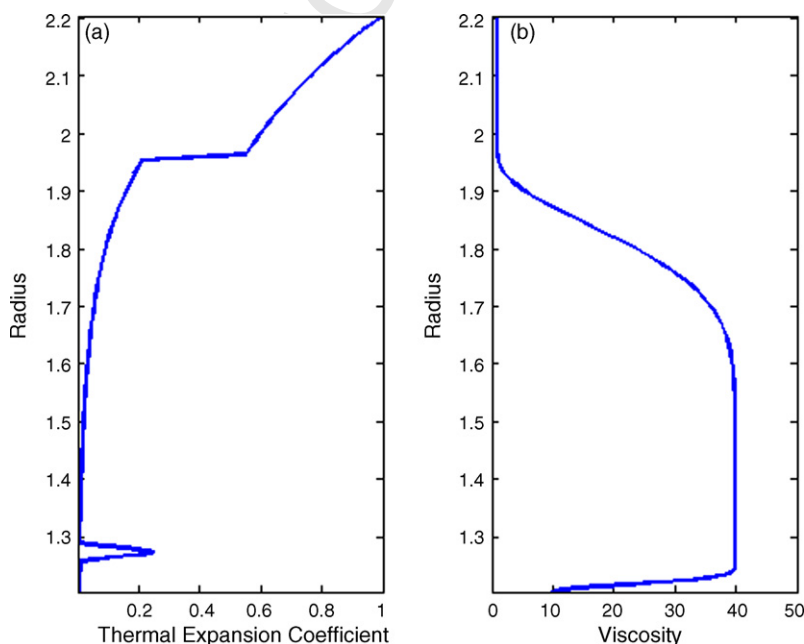


Fig. 1. (a) Dimensionless thermal expansion coefficient and (b) depth-dependent viscosity coefficient.

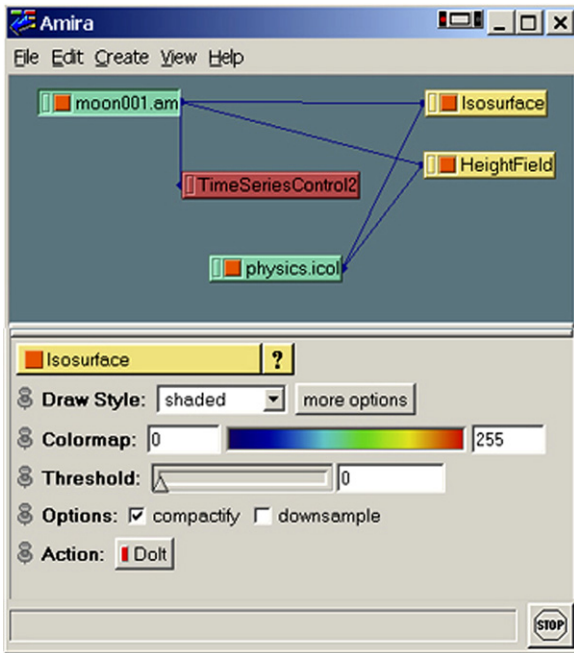


Fig. 2. A diagram showing Amira modules used for generating multiple iso-surfaces.

82 distribution at a given step of the time sequences. Over
83 1000 of these data sets were generated from the entire
84 time series of one single simulation. The size of each
85 data set varies from 22 MB (downsampled by 2 on each
86 side) to 178 MB (without downsampling).

87 2.2.1. Use of multiple isosurfaces

88 One of the virtues of Amira is the availability of the
89 diagrammatic setup, displaying the various connecting
90 modules. Fig. 2 is an example of such a diagram showing
91 the selected modules and their connections for displaying
92 the large-scale features. Moon001.am is the input
93 dataset, which is connected to a time series control
94 module. This module allows one to select one of the time
95 series datasets for generating one snapshot. This module
96 also allows Amira to cycle through each dataset auto-
97 matically and re-update the image in the viewer.

98 After a dataset is uploaded, one can apply other dis-
99 play modules, such as HeightFields, ObliqueSlices, and
100 Isosurfaces, to the dataset and adjust these modules to
101 focus on specific thresholds of interest. For instance, to
102 view the structure associated with the temperatures with
103 a value of 55, one can generate an isosurface of temper-
104 ature with a value of 55. Through the Isosurfaces model,
105 one can select the colormap ('physics.icol' in Fig. 2) for
106 this isosurface, and then change the alpha curve within
107 the colormap to change the transparency of the isosur-
108 face. We can use the Isosurfaces module multiple times

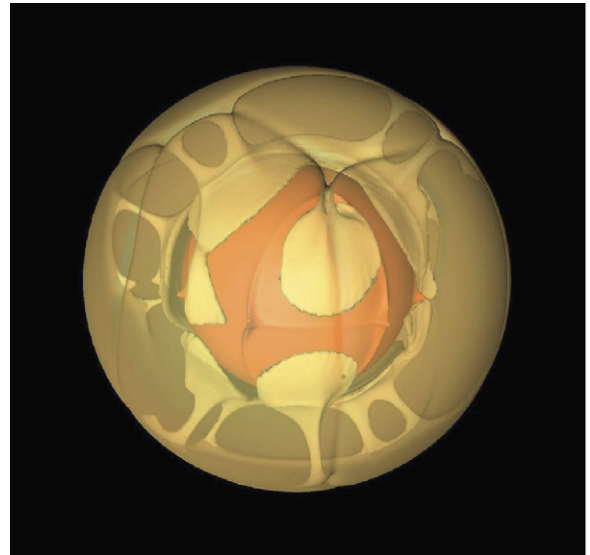


Fig. 3. A single isosurface showing the downwellings developed at the early time period when the convection started in an isoviscous model with a Rayleigh number of 3×10^5 .

109 to create multiple isosurfaces, each of which is assigned
110 with a specific value of temperature and a color. The col-
111 ors can be the same or different. But the transparency of
112 the isosurfaces must decrease exponentially with temper-
113 ature or toward an inner part of one or a few particular
114 downwellings so that the inner structures can be well
115 revealed. Repeating adjustments are needed to achieve
116 the best visual effects. This can be seen in Fig. 4. After
117 the multi-isosurfaces is set for one dataset, one can use
118 the same setting through the time control module to effi-
119 ciently produce movie for all the datasets that the time
120 control module can access.

121 Fig. 3 shows a snapshot of the downwellings devel-
122 oped at the early time period in an isoviscous convection
123 model with a Rayleigh number (Ra) of 3×10^5 subject
124 to the initial condition that small lateral perturbations
125 are placed in the mantle with a conductive or a radially
126 dependent temperature profile. We believe this is the first
127 time from the visualization perspective that we have been
128 able to show the clear presence of both linear and circular
129 downwelling structures in the 3-D spherical model.

130 The image in Fig. 3 demonstrates that the multi-
131 isosurfaces approach can be used to examine how the
132 cold flows are formed and how they move from the
133 surface into the deep mantle subject to various dynamical
134 conditions. Certainly this graphic approach can also
135 be used for displaying the structures of the upwellings.
136 Fig. 4 shows two images from different angles of view
137 of the convection model with $Ra = 2 \times 10^6$ and thermal
138 expansion coefficient (Fig. 1a) and radially dependent

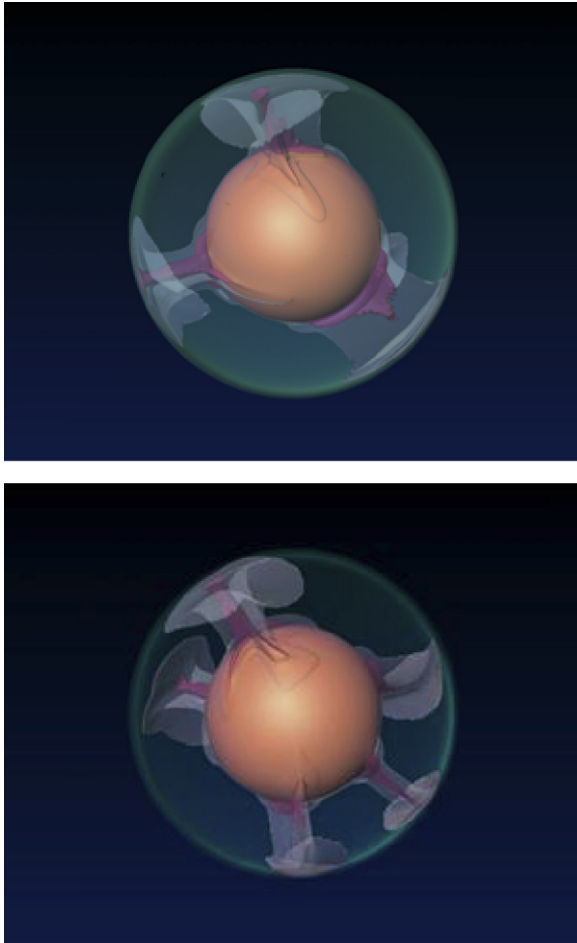


Fig. 4. Visualization of upwellings from two different perspectives. The four isosurfaces (green, white, purple, and orange) are respectively associated with 0, 40, 60, and 80% of the maximum temperature from the same dataset. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

139 viscosity (Fig. 1b). In addition, the multi-isosurfaces
140 approach provides a cost-efficient way to mimic the
141 volume-rendering of 3-D features. Volume-rendering
142 requires a mapping of the temperature from the non-
143 uniform spherical coordinates to uniform or regularly
144 spaced grids in Cartesian coordinates. Hence the com-
145 putational time of volume rendering would be at least five
146 times more, and this estimate does not include the cost
147 of data storage for revealing the same structures as those
148 in Fig. 4, than using the multi-isosurfaces approach.

149 The multi-isosurfaces approach is useful for reveal-
150 ing large-scale features, as shown in Figs. 3 and 4. But it
151 has limitations, because it is not effective in revealing the
152 small-scale structures inside the mantle. Fig. 5 shows this
153 limitation. There is a downwelling region in the center of
154 the image. Yet, no information can be ascertained about

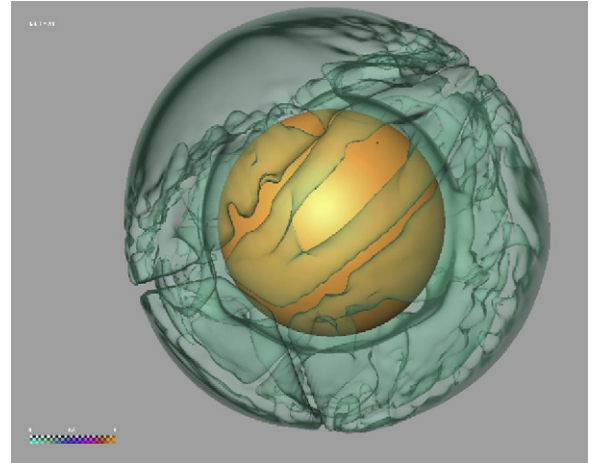


Fig. 5. Visualization of downwellings using the multi-isosurface approach for the same dataset used for Fig. 4. The isosurface has a value of 15% of the maximum temperature.

the precise depth of plume limbs. In the other down- 155
wellings, their features fade into one another; there is 156
neither clarity nor distinction of the small-scale features. 157

2.2.2. Localization of complicated small-scale features 158

The SelectRoi module in Amira allows the user to add 159
two cutting planes to a 3-D object, trim off the parts that 160
are not of interest so that a selected region of interest 161
can be displayed. By adding the SelectRoi module to 162
the multi-isosurfaces approach, we have been able to 163
generate a wedge of the 3-D image instead of the entire 164
sphere. Fig. 6 shows a quarter of the mantle, in which 165
the downwellings are the dominant flows and last over a 166
quarter of the mantle. 167

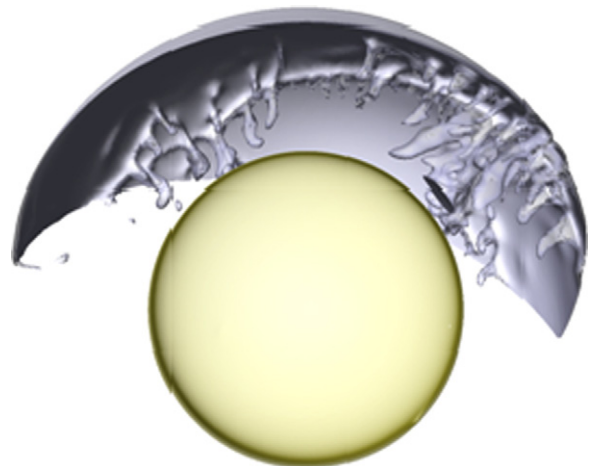


Fig. 6. View of small-scale downwellings along a long linear trench. This wedge is 1/4 of the mantle. The core is shown for marking the relative depths of the downwellings.

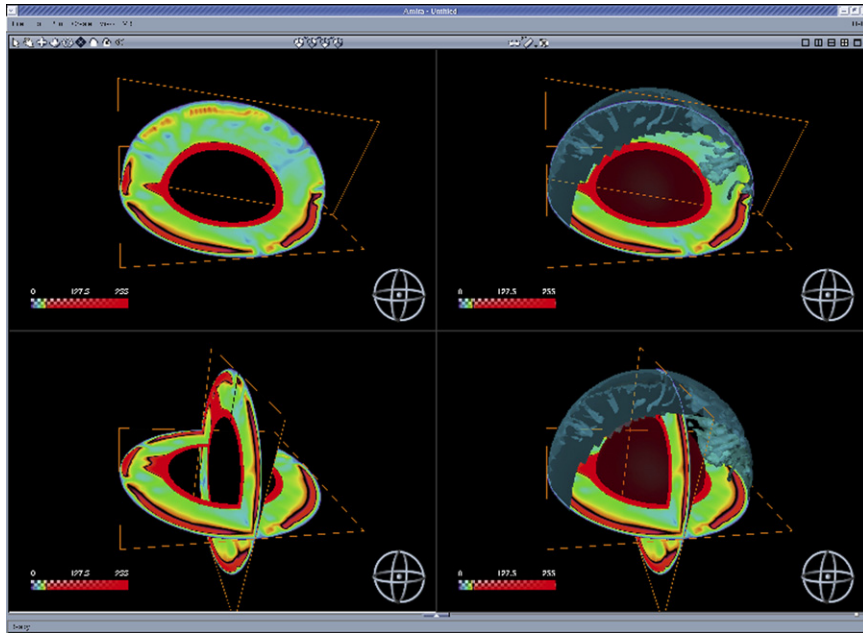


Fig. 7. Using 4-viewer mode to display different portions of the dataset by using different displaying formats.

168 long time period in the simulation. The core is shown in
169 the lower part of the Figure simply for referencing the
170 locations of the downwelling. The data used in Fig. 6
171 come from the same dataset used in Fig. 4.

172 Using the localizing approach, we have observed a
173 new phenomenon that was not reported in previous pub-
174 lications according to our knowledge. The downwellings
175 are of more complicated structures than the upwellings
176 in the convection model with $Ra=2 \times 10^6$ and radi-
177 ally dependent viscosity (Fig. 1a) and thermal expansion
178 coefficient (Fig. 1b). The upwellings start with several
179 plumes growing. As the convection process develops,
180 some of the plumes become weakened and disappear
181 and only a few large-scale plumes survive (Fig. 4). But
182 the downwellings consist of both large-scale features
183 appearing as a long linear trench near the surface and
184 small-scale sinking columns along side the long trench.
185 While the linear trench position remains relatively stable
186 on the surface over a long period of simulation time
187 corresponding to the upwellings, the positions of small-
188 scale sinking flows swing constantly on the surface, but
189 remain close to the trench.

2.2.3. Use of Amira's 4-viewer mode

191 From the above presentation, one can sense the great
192 challenge in visualizing the downwelling process in 3-D
193 spherical mantle convection. That is to say that it is very
194 difficult to show the detailed features comprehensively,
195 using a single view. More views or more slicing or seg-

196 menting from different angles are needed to reach this
197 elusive goal.

198 Amira 4.1 provides a new feature—the 4-viewer dis-
199 play mode, with which one can see simultaneously
200 different portions of the data in different displaying
201 formats from different angles of view (Fig. 7). Each of these
202 viewers can be independent of the others, but they can all
203 be controlled from the same module window. We now
204 have the ability to combine the use of multi-isosurfaces
205 with the wedge of a region and 2-D slices in one panel to
206 see both the movement of the sinking stalactites and the
207 flow motions along the 2-D sections. In another panel or
208 window we can display the downwellings, which occur
209 on the other side of the sphere or we can have a top-
210 down view of the same flows in the third window, etc.
211 In short, the 4-viewer mode provides great flexibility to
212 explore the interior complexity of the downwellings very
213 efficiently. This 4-viewer mode is also very easy to use.

3. Discussion and conclusions

214
215 So far we have described the three approaches
216 exploited from the powerful Amira graphic package for
217 visualizing the downwelling features with different level
218 of complexities. The multi-isosurfaces approach is good
219 for large-scale downwellings. The wedging approach
220 allows us to observe the details of small-scale fea-
221 tures locally. The 4-viewer mode is the most flexible
222 and cost-efficient tool for systematically visualizing and

223 understanding the dynamical structures of downwellings
224 in 3-D spherical mantle convection.

225 With these approaches we have observed the follow-
226 ing interesting features that have not been reported in
227 previous works: (1) a long lasting convergence zone
228 consists of many short-life small-scale downwellings,
229 like stalactites, when viewed from the viewpoint of the
230 core-mantle boundary; (2) persistent divergence zone
231 is filling with cold materials in between two shrinking
232 plumes, whose centers remain at the same locations; (3)
233 cold material flushes into lower mantle repeatedly from
234 the same downwelling region in the model without the
235 presence of the endothermic phase transition.

236 The goal of this research work is to find an effi-
237 cient way to deal with the tough problem of visualizing
238 the downwellings in 3-D spherical mantle convection
239 with high numerical resolution. Although the approaches
240 presented in this paper can be very helpful, there are
241 still technical issues challenging Amira developers. For
242 example, one can connect the *4-viewer* mode with the
243 movie-maker module to create a movie directly from the
244 dataset. But this feature does not generate a movie for
245 each of the four panels simultaneously. The movie mod-
246 ule will generate only one movie for one of the panels.
247 In order to create a movie for each of the panels, the
248 images for the other three panels at each time step must
249 be recorded by the user and then need to be recombined
250 into different movies. This creates a substantial overhead
251 in storage space and more is more time consuming.

252 Another problem that occurs with the *4-viewer* mode
253 is the loss of resolution. Most monitors have a maximum
254 resolution of 1600 by 1200. Dividing this resolution into
255 four panels results in each viewer having a maximum res-
256 olution of 800 by 600. This is not very big; it is likely the
257 small subtle features will be overlooked. To counteract
258 this, Amira allows users to perform off-screen display of
259 the viewers, which will increase the maximum potential
260 resolution. The problem with this approach is that each
261 viewer must be carried out separately and then recom-
262 bined in order to create a high-resolution movie. Unless
263 it is then displayed on a large-scale display wall, such as
264 the Power Wall, it will lose resolution once again when
265 it is viewed.

266 We have presented here some solutions to this prob-
267 lem of visualizing downwellings, in 3-D spherical
convection, which are different from Cartesian geom-

etry. We hope that this will help to stimulate others into
looking at these interesting issues.

Acknowledgments

We thank Larry Hanyk and Marc Monnereau for
our discussions. We also thank Max Rudolph and Ben
Kadlec for their reviews. Support of this research has
come from NSF ITR and Middleware grants.

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