Outer core density heterogeneity and the discrepancy between PKP and PcP travel time observations

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Abstract. We derive 3-D maps of the Earth's mantle, CMB and outer core by means of least squares tomographic inversions. The data set includes compressional wave travel time measurements associated with the phases P, PcP, PKPbc, PKPdf, all based on the bulletins of the International Seismological Centre (1964-1995), after source relocation by *Antolik et al.* [2001]. Maps of the CMB derived independently from only core-reflected (PcP) or only core-refracted (PKP) phases are not well correlated. We study the radial coherence of whole-Earth tomographic images, to investigate potential trade-offs between CMB undulations and velocity anomalies in the mantle and/or outer core. We find that imaged lateral heterogeneities in the outer core are correlated with the topography of the CMB. This, together with the studies of *Wahr and De Vries* [1989] and *Piersanti et al.* [2001], suggests that the core anomalies might not be entirely fictitious.

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1. Introduction

Whether lateral heterogeneous structure could exist in the fluid outer core of the Earth is a controversial issue. This idea was first introduced to explain observed splitting in the eigenfrequencies of certain core-sensitive normal modes [*Ritzwoller et al.*, 1986; *Kohler and Tanimoto*, 1992; *Widmer et al.*, 1992]. More recently, *Vasco and Johnson* [1998] proved that a substantially higher variance reduction of PKP data is achieved by tomographic models that include laterally varying structure also within the outer core, rather than only in the mantle and inner core. *Boschi and Dziewonski* [2000] hypothesized that this effect could best be explained in terms of radial anisotropy of the lower mantle, but found that, even for solution models that include significant mantle anisotropy, lateral structure is still required in the outer core to fit the data. They also confirmed the finding of *Rodgers and Wahr* [1993], that images of the core-mantle boundary topography derived separately from PKP and PcP data are not correlated.

Stevenson [1987] proved that surfaces of constant density in the Earth's outer core should coincide with surfaces of constant potential; this result is often invoked to justify the assumption that the outer core be laterally homogeneous. On the other hand, *Wahr and de Vries* [1989] later showed that lateral variations, within the core, of the Earth's gravity field result in deformations of equipotential (and equidensity) surfaces with respect to spherical symmetry. From a seismological point of view, this is equivalent to recognizing that velocity anomalies are possible in the fluid outer core. *Piersanti et al.* [2001], on the basis of *Wahr and de Vries*'s [1989] theory, and *Boschi and Dziewonski*'s [2000] maps of the mantle and CMB, derived a theoretical image of outer core heterogeneity; their image is not correlated with any of the published tomographic maps of the outer core , and the question of understanding mapped velocity anomalies within the outer core remains open.

It is possible that tomographic heterogeneities in outer core structure be fictitious features generated by trade-off, in the solution of a mixed-determined inverse problem as the one in question. For example, an error can be introduced in the data by the absence of adequate station location and crustal correction, and this error might in principle introduce fictitious anomalies in any coefficient of the solution model. *Boschi and Dziewonski*'s [2000] data have been improved by *Antolik et al.* [2001], who used Crust 5.1 [*Mooney et al.*, 1998] for crustal correction and a more accurate method to locate sources. The improvement in data quality should result in an improvement in model resolution. Here, we apply *Boschi and Dziewonski*'s [2000] procedure to the new data set of *Antolik et al.* [2001]. We then analyze the resulting tomographic images with a comprehensive correlation analysis, in the same fashion as *Becker and Boschi* [2002].

2. CMB topography

We perform numerous least squares inversions of *Antolik et al.*'s [2001] data. As in *Boschi and Dziewonski* [2000], mantle and outer core P-velocity, and CMB topography, are described by a grid of blocks of constant angular extent. We repeat *Boschi and Dziewonski*'s [2000] experiment, seeking the solution with a number of independent, equally regularized inversions, in a set of different solution spaces. For each chosen solution space, we derive different solution models from different subsets of the data. Solution models include 3-D isotropic (1 through 4, 9-12) or radially anisotropic (5-8, 13-16) maps of P-velocity in the mantle, laterally variable CMB topography, and, where stated (9-16), isotropic 3-D maps of P-velocity in the outer core. The most significant discrepancies between models concern maps of CMB topography, all shown in Figure 1.

The improvement in data quality has not solved the PcP vs. PKP discrepancy. As in *Boschi and Dziewonski* [2000], PcP images of the CMB reproduce the result of previous studies [*Forte et al.*, 1993; *Obayashi and Fukao*, 1997; *Forte et al.*, 1995] better than the PKP ones. The maps of the CMB are more strongly affected by the introduction of lateral heterogeneities in the outer core (third column of Figure 1) than by allowing for laterally varying radial anisotropy in the mantle (second column). Solution models that include both features (fourth column) are very similar to those on the third column.

3. Correlation between CMB maps

We calculate, and show in Figure 2, the linear correlation [*Press et al.*, 1992, p. 630] in the spatial domain between all images of CMB topography from Figure 1. As these images are parameterized in terms of 1656 equal-area cells [*Boschi and Dziewonski*, 2000], the Student's t test [*Press et al.*, 1992, p. 631] indicates that the correlation coefficient should be ≥ 0.06 for correlation to be significant at the 99% level.

Correlation is systematically high between images of the CMB that were derived from the entire data set (4, 8, 12, 16). As for the other models, we find relatively high values of correlation between CMB models 1 through 8 (the ones that do not account for outer core heterogeneity) and between models 9 through 16 (the ones that do), but the two groups do not correlate equally well with each other.

If no outer core heterogeneity is allowed for in the inversions, a negative correlation is systematically found between PcP-based and PKP-based images of the CMB (models 1 and 2, 1 and 3, 5 and 6, 5 and 7). This effect disappears in models that include a laterally heterogeneous outer core, and we find a positive, though low, correlation (clearly significant at the 99% level) between models 9 and 10, 9 and 11, 13 and 14, 13 and 15.

4. Correlation matrices

In *Piersanti et al.*'s [2001] approximation, density heterogeneities within the mantle are the only driving mechanism for anomalies in the CMB topography and outer core structure. Neglecting dynamical forcing from the mantle itself [*Piersanti et al.*, 2001], we expect the CMB to be averagely depressed under fast (i.e. cold, dense) mantle regions, and elevated, with respect to its average radius, elsewhere. In other words, and if lower-than-average CMB topography is defined to be negative, we expect to find a negative correlation between CMB topography and lower mantle heterogeneites. As for the outer core, *Wahr and de Vries* [1989] have shown that a strong positive correlation is to be expected between the topography of equipotential surfaces at the CMB, and density (or seismic velocity) anomalies within the fluid core. In *Piersanti et al.*'s [2001] approximation, which corresponds to the limit case of no dynamical forcing from the mantle, the CMB topography coincides with the topography of the equipotential surface closest to the CMB; then, so far as such approximation is not too far from reality, we expect to find a positive correlation between seismic maps of the CMB and those of the outer core.

To a certain extent, we can also expect a fictitious nonzero radial correlation to arise from the limited resolution of deep Earth structure that the data have, and subsequent trade-off between different model coefficients. A positive PKP travel time anomaly could in principle be explained equally well by a negative velocity anomaly, along its path, in the Earth's mantle or core, or by a positive anomaly in the CMB topography (at the locations where it enters and exits the core). As PKP waves travel almost vertically through the mantle and part of the outer core, this ambiguity can result, in regions of limited resolution, in a fictitiously high radial coherence of tomographic models. Conversely, a larger-than-average PcP travel-time could be explained by a slow anomaly in the mantle, as well as by lower-than-average CMB topography [*Morelli and Dziewonski*, 1987].

Radial correlation matrices [e.g. *Becker and Boschi*, 2002] should evidence any of these, physical of fictitious, positive or negative correlations. Here, we have computed radial correlation matrices both in the spherical harmonic (Figure 3, left and center columns) and spatial (Figure 3, right column) domains. To isolate the long wavelength component of our maps, we have interrupted the spherical harmonic expansion both at degree 6 (Figure 3, left column) and 12 (Figure 3, center column). From the Student's t test the correlation coefficients are significant at the 99% level if they are ≥ 0.37 for $l = 6$, and ≥ 0.2 for $l = 12$ (≥ 0.06 if correlation is evaluated in the spatial domain).

We find that CMB topography and mantle heterogeneities are systematically anti-correlated, particularly as far as the long-wavelength component of our images is concerned (Figure 3, first column to the left), independently of the subset of data inverted.

Likewise, outer core heterogeneities are positively correlated to CMB topography in the case of models derived from PKPdf data, or from the entire data set (PKPbc data are too few to constrain, alone, the outer core structure). Based on the above discussion, this result is opposite to what we would have found, had lateral structure in our images of the outer core been generated by fictitious trade-off only, indicating, once again, that our observation requires a physical explanation.

The mentioned negative CMB-mantle correlation and positive CMB-outer core correlation, which we expect from physics, are still observable, although slightly attenuated, in the central column (correlation up to the harmonic degree l = 12), and in the correlation plots computed in the spatial domain (right columns).

5. Summary

Images derived from *Antolik et al.*'s [2001] P travel time data confirm the discrepancy between the travel times of P waves reflected, and those refracted by the Earth's core, already noted by *Rodgers and Wahr* [1993] and *Boschi and Dziewonski* [2000]. The presence of lateral density heterogeneities within the outer core, justified in theory by the studies of *Wahr and de Vries* [1989] and *Piersanti et al.* [2001], is one possible explanation for this controversial observation, and has been substantiated by some earlier observations. Figure 2 here shows that the correlation between PKP- and PcP-derived maps of the CMB topography is positive (as it should be) for solution models that are allowed to have lateral structure within the outer core, and negative otherwise.

We have found that there exists a systematic positive correlation between CMB topography and outer core heterogeneities, in tomographic images derived from P and PKPdf data. This result is the opposite of what we would have expected, based on the assumption that imaged heterogeneity of the outer core be a purely fictitious effect of radial trade-off. Instead, it is in agreement with the theoretical predictions of *Piersanti et al.*, [2001].

Images shown here were derived neglecting inner core anisotropy, but we have verified that the introduction of an inner core correction as in *Boschi and Dziewonski* [2000] does not alter our main observations.

Although we believe to have proven that a certain lateral heterogeneity is likely to be present in the Earth's outer core, we do not think that our data have the resolving power to constrain its character [*Vasco and Johnson*, 1998]. The amplitude of lateral anomalies that we have mapped in the outer core exceeds the upper bound (0.1%) given by *Piersanti et al.* [2001], and the same is true of *Vasco and Johnson*'s [1998] and *Boschi and Dziewonski*'s [2000] maps. Nonetheless, the hypothesis of gravity-induced outer core heterogeneities remains the best candidate to explain the widely accepted [*Antolik*, 2002] observation of PKP-PcP travel time discrepancy.

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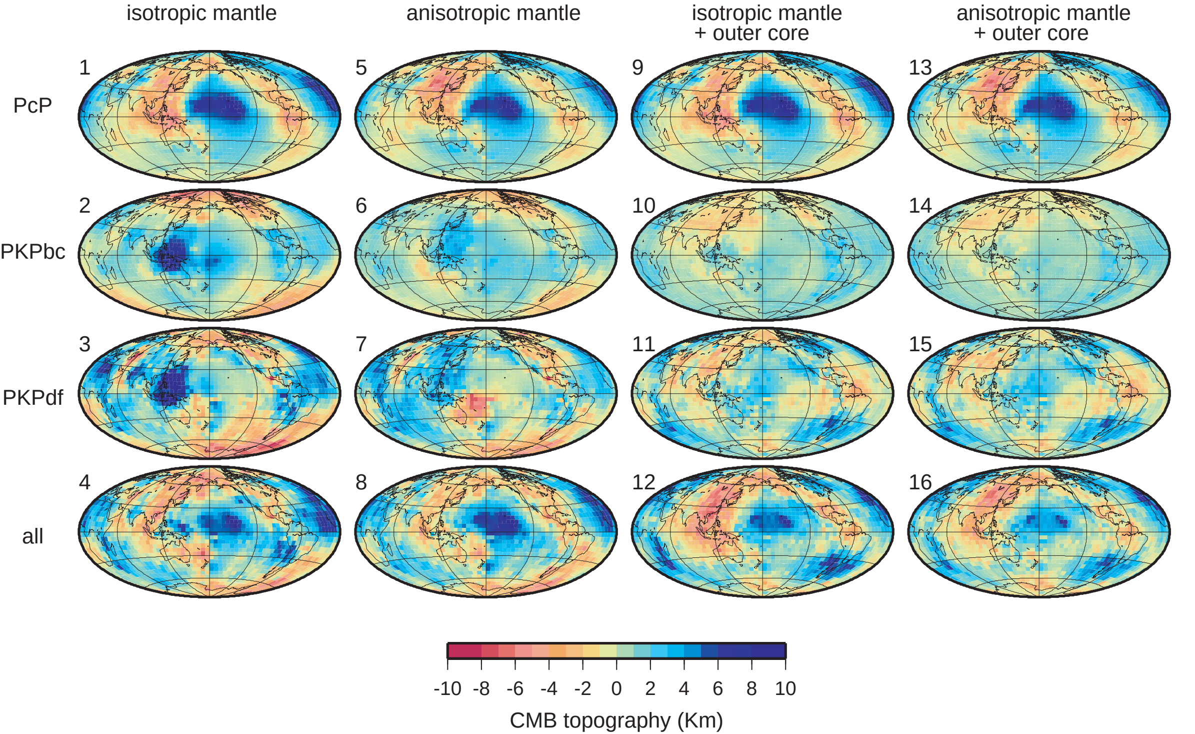
Figure 1. Seismic images of the CMB topography obtained from the joint direct P and PcP data set (first row), joint P and PKPbc (second row), joint P and PKPdf (third row), and entire P, PKP, PcP data set (fourth row). Each column includes model belonging to one solution space: from left to right, isotropic 3-D mantle and 1-D core, anisotropic 3-D mantle and 1-D core, isotropic 3-D mantle and 3-D core, anisotropic 3-D mantle and 3-D core.

Figure 2. Values of correlation coefficients (in the spatial domain) between all the images of the CMB discussed here, numbered as in Figure 1.

Figure 3. Correlation matrices for models number 9-12 from Figure 1, characterized by 3-D isotropic mantle and 3-D outer core. The correlation matrices provide a measure of the radial coherence of each model, including mantle layers (rows/columns 1 through 15), the CMB topography (row/column 16) and outer core layers (rows/columns 17 through 25).



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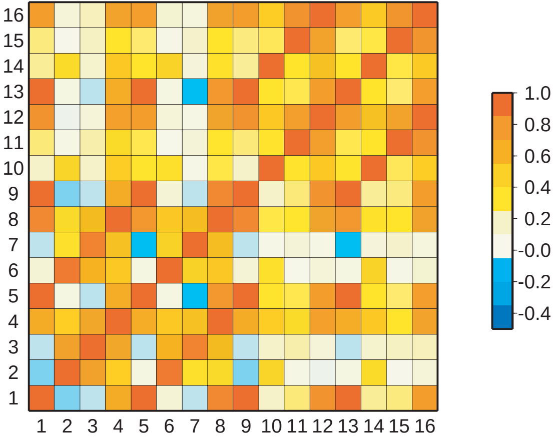

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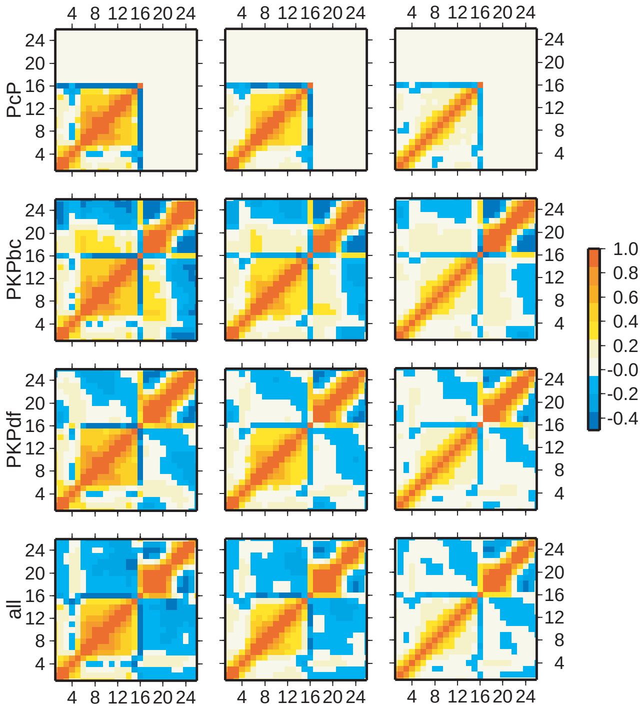

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