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Reply to Yao et al.'s comment on "Origin of temporal changes of inner-core seismic waves"

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ABSTRACT

In this reply, we address the main issues raised by Yao et al. (2020) and conduct additional analyses, particularly on the seismic station clock problems and the influence of earthquake depth. We show that although the depth is an important issue to consider, the depth difference of our doublets is too small to be significant. Extensive analyses reaffirm our previous conclusions that (1) the inner core (IC) temporal changes come mostly from the interior (rather than its surface) and the proposal that the IC surface as the sole source of the temporal changes can be ruled out; (2) the most reasonable and simplest explanation so far for the temporal changes is an IC differential rotation; and (3) absolute-time based method in previous studies should be avoided for studies of temporal changes of less than 0.15 s unless the clock issue is resolved.

1. Introduction

In their comment, Yao et al. (2020) (hereafter YAO20) raised three points that they claimed to invalidate the main conclusions of our paper (Yang and Song, 2020a; hereafter YS20). YAO20 reaffirmed their previous conclusion (Wen, 2006; Yao et al., 2015, 2019; hereafter collectively WYY3) that all of the temporal changes of the inner core (IC) seismic waves come from the temporal changes of the IC surface. YS20's conclusion is on the opposite side that the seismic temporal changes come mostly (if not all) from the IC interior and the temporal changes of the IC boundary (ICB) are not statistically significant. Both cannot be valid. Debating the issues is important to understand the mechanism of the IC changes in particular and the evolution and dynamics of the earth's core in general.

YS20 used a comprehensive approach by studying available global high-quality (HQ) doublets (two repeating earthquakes at nearly identical location). The points that YAO20 raised include the following. (1) "The clock problems" of global seismic network (GSN) stations do not exist. (2) Our double differential time (ddt) approach is "faulty based on an erroneous claim" because of the influence of the source depth difference (hereafter dh) between the doublet (Fig. S1). (3) The authors disagree with our interpretation of the IC rotation as "the simplest and most reasonable explanation". We address the three points below. Due to the journal page limitation, we provide detailed information of our analyses and outline other body of evidence in YS20 that YAO20 didn't address in the Supplementary Material (SM).

2. YAO20's question on "the clock problems"

YAO20 didn't prove there are no clock problems, except referencing the GSN as "the standard-bearer network". Separately, they argued that the match of the DF phase between the 9303 doublet, after their relocation depth correction, suggests there is no clock error. We will address the relocation issue later.

In our separate study (Yang and Song, 2020b), we performed extensive clock analyses, which show the appearance of clock errors of over a fraction of a second and random small clock errors of 0.077 s (one standard deviation) for about 28% of the absolute time measurements at the permanent stations we used. Below we show more examples of the clock problems with detailed information in the SM. Another example is also given in the relocation of the 9303 doublet later.

The first example is station AAK, which is an important station in the debate (WYY3, YS20, and YAO20). There are actually two sites of 0.47 km apart, II.AAK (a GSN station) and KN.AAK in Kyrgyzstan. Because of the close proximity of the two sites, teleseismic events show identical waveforms and can be used to calibrate the relative clocks between the two sites. We measure systematically the relative times between the direct P waves recorded at the two sites of all global events with magnitude >= 5.0 since

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1991 (Fig. S2). The difference is around 0 most of the time. But other differences include shifts of 1 s or greater, fractions of second, and small fluctuations near 0 that are sometimes systematic and sometimes random. The last type of clock difference is very hard to detect from an individual seismogram and is impossible to separate from a real earth signal.

The second example is using a HQ doublet (Fig. S3). Because of the close proximity of the doublet events, the P arrival-time difference between the two events at the same station comes mostly from the origin time difference, without any relocation. As expected, most stations are along the flat line of the median value, but several stations depart by fractions of a second to 1 s. From Figs. S2 and S3, it is clear that the timing of station II.AAK was wrong by about 1 s in 2005 (which is confirmed by Pete Davis, personal communication). Such examples can be easily found using other doublets.

In summary, we affirm the conclusion on seismic station clock problems in our previous studies (YS20; Yang and Song, 2020b). Timing errors have been reported for several well-known stations, e.g., even between two of the best-maintained stations in the world, PFO and PAS, with timing errors of 0.03 to 0.23 s (SM S2). Large errors are easy to identify, but small random errors are impossible to remove completely in the absolute times of individual traces. It needs to be extremely cautious to rely on absolute travel times to study temporal changes of the media (usually small).

3. YAO20's question on YS20's approach of using the SKP reference

YS20 examined systematically temporal changes of PKP(DF) (traversing the IC) and PKP(CD) (reflected from the ICB) (see Fig. S1a for the description of the seismic phases in this reply) using a global data set of doublets, including 39 HQ pairs and 25 slightly inferior South Sandwich Islands (SSI) pairs. We also used non-IC phase for reference, i.e. SKP or PP, to form so called double differential time (ddt). For example,

$$ddt(SKP - CD) = dt(SKP) - dt(CD) = \big(t(SKP_2) - t(SKP_1)\big) - \big(t(CD_2) - t(CD_1)\big),$$

where the subscripts 1 and 2 denote the earlier and the later events of the doublet, respectively. Using ddt can largely eliminate errors from the tiny separation between the two sources and mantle heterogeneity of tiny path difference, but in particular, it can eliminate the origin time and clock (or any common station-related) errors as the common time errors are cancelled in the differentiation of two arrivals of the same event.

YAO20 stated that our approach of using ddt between SKP and CD/DF is "faulty based on an erroneous claim", because of the influence of the source depth difference (dh). Wen (2006) has dh of "within 0.7 km" from relocation of the 9303 doublet. The result indicates a range of the dh with the upper-bound of 0.7 km, but YAO20 made their case using the upper bound without a justification or considering the uncertainties. If we assume the dh of 0.7 km, the ddt(SKP-CD or DF) is nearly 0.08 s (at teleseismic distances of interest). Thus, indeed, the dh effect could be important if the dh is that large. Here we examine the dh and its influence, the details of which are provided in the SM S3 and Figs. S6-S9. We use four different methods that are sensitive to the dh.

(1) The global ddt dataset. The effect of the dh is the same on ddt(SKP-DF) or ddt(SKP-CD) and thus will be reflected similarly on both data of the global ddt dataset (Fig. 6 of YS20). (2) Relocation of the 9303 doublet. Using similar method and data to Wen (2006), we obtain a dh of 0.33 km, but there is strong trade-off between the dh and the origin time difference of the doublet. Selection of stations is another important source of error, where any stations could be subject to potential timing errors. (3) Depth phase (pP or sP) (Fig. S1). The sensitivity of ddt(pP-P) to the dh between the doublet is about 2.5 times that of ddt(SKP-DF or CD). Among the 15 doublets, we found 13 pairs with clear pP, 1 pair with sP, and the 9303 pair with possible pP. (4) SKP and PP phases for the 9303 doublet. Notably, the ddt(SKP-PP) measurement suggests dh in the opposite direction of YAO20.

Results of our various estimates of the dh and its influence on ddt(SKP-DF or CD) for the 9303 doublet and the 15 doublets in the global dataset are summarized in SM (Tables S3-S4). Fig. 1 plots the original measurements (YS20) and the data corrected for the estimated dh influence. Both of the two different estimates for the 9303 doublets (depth phase and SKP-PP) are plotted. The slopes of the linear regressions before and after the correction are quite similar, within the error of one standard deviation. Excluding all of the 9303 data entirely, the slopes are also similar.

We conclude: (1) Doublet relocation has a large error in dh, which cannot be used to infer the influence on ddt(SKP-DF or CD). (2) The analyses of the depth phase pP (or sP) and one measurement of ddt(SKP-PP) suggest no evidence of dh as large as 0.7 km in any of the 15 doublets of the global dataset. The dh is likely within 100 m for the 12 HQ doublets and within 150 m for the 3 SSI doublets. (3) Correcting for the dh influence does not show significant influence on whether the ddt(CD-DF) temporal changes are from DF or CD. (4) The consistency of the observed global ddt(SKP-CD) itself suggests little influence of the dh on the ddt(SKP-DF or CD).

4. YAO20's question on YS20's interpretation

YAO20 challenges our interpretation of a differential IC rotation as "the simplest and most reasonable explanation" to the temporal changes of the IC phases. We offered two reasons for our interpretation (YS20). First, electromagnetic torque provides a ready mechanism for a differential IC rotation (Glatzmaier and Roberts, 1995), which in fact provided the initial motivation for the search of evidence (Song and Richards, 1996). Second, virtually all the non-zero estimates of the differential rotation rate are positive - This fact itself supports IC rotation as the probability of coincidence is very low. We didn't state that the IC rotation is required and we do not rule out the possibility of alternative interpretations with credible evidence in the future. On the contrary, WYY3 build a case that all IC temporal changes (including DF, DF coda, and CD) come solely from the IC surface without any alternatives. YS20 argued this notion can be ruled out, because it is not compatible with a suite of observations (SM S1 and S3).

5. Conclusion and discussion

We assess YAO20's three main points briefly above with detailed assessments in the SM. We agree that the depth difference is an important issue to consider. But because of the quality of the doublets used, the difference is too small to be significant to our study. The extensive analyses reaffirm our previous conclusions (YS20), in particular, in the following.

(1) We conclude that the DF and CD temporal changes come mostly from the DF phase or the IC interior, rather than the CD phase or the ICB as in previous studies. Temporal changes of the ICB (Wen, 2006) as the sole source of the seismic wave changes (Yao et al., 2015, 2019) can be ruled out.
(2) The most reasonable and simplest explanation to the observed temporal changes is a differential rotation that shifts the position of the heterogeneous upper part of the IC.

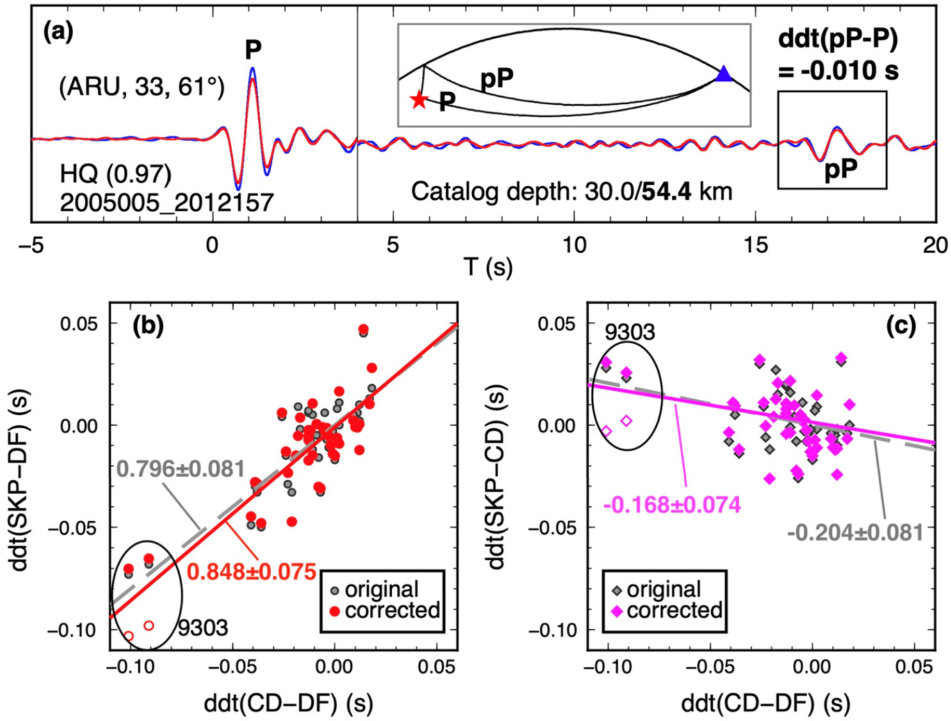

Fig. 1. Demonstration of method and result in this study. (**a**) Example of depth phase (pP) from doublet stacking. Inset shows example ray paths of P and pP from a source (star) at depth to a station (triangle) at Earth's surface. The P waveforms and coda are aligned with the P phase before stacking. Move-out corrections of pP-P are applied to the coda after 4 s (vertical line) using the highlighted catalog depth before stacking. Relevant information (labelled) includes the doublet identification (a HQ pair with average cross-correlation coefficient of 0.97 between non-IC phases) (Yang and Song, 2020b), reference station (ARU), the total number of stations (33), the average distance (61°) of the stations, the P and the identified pP phases, catalog depth, and the measured ddt(pP-P). (**b,c**) Original and corrected ddt(SKP-DF) and ddt(SKP-CD). The original data are from the 15 doublets (12 HQ and 3 SSI pairs) of YS20. The corrected data are the original data corrected for the estimated influence from the dh for each doublet pair. For the 9303 doublet (marked), two separate correction methods are used, one from ddt(pP-P) (solid red dots) and another from ddt(SKP-PP) (open red circles). The linear regressions (with slopes labelled) are for the original data (grey dashed lines) and the corrected data (colour solid lines) that include both corrections for the 9303 doublet. Excluding all of the 9303 data, the slopes of the remaining corrected data are 0.796 ± 0.149 for ddt(SKP-DF) in **b** and -0.204 ± 0.149 for ddt(SKP-CD) in **c** (coincidently the same slopes as the respective original estimations but with larger error bars). (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

(3) The absolute-time based method (WYY3) needs to be viewed with extreme caution in the future for studies of temporal changes due to possible clock errors (of about 0.15 s in two standard deviations) unless the precise timing can be assured.

YAO20 touched on the philosophy of science that the proof of the necessity of a proposal is required. We disagree with this line of scientific reasoning. It is not only common but also standard to test and reject alternative hypotheses in establishing a theory. We were open to the possibility of the ICB temporal changes (Song and Dai, 2008). To quote Harold Jeffreys (1924), "...a direct proof that a particular hypothesis will account for particular data is not very strong confirmation of the hypothesis when both the data and the consequences of the hypothesis are known only vaguely; but if it is shown that the results of the hypothesis agree with the facts as regards order of magnitude, while the results of denying it are in definite disagreement, the confirmation of the hypothesis will be almost as strong as if a close agreement had been obtained. The method of exhaustion of alternatives is specially useful in geophysics, because incorrect geophysical hypotheses usually fail by extremely large margins." We cannot rule out small contributions from the ICB, but we have demonstrated that the temporal change from the IC interior body is much stronger and the ICB contribution, if any, is not significant at 95% confidence level. The extreme proposal of IC surface changes as the sole source of the IC seismic wave changes (WYY3) fails by extremely large margins.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.epsl.2020.116639.

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