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Comment on "Origin of temporal changes of inner-core seismic waves" by Yang and Song (2020)

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Recently, Yang and Song (2020) re-examined our studies on the issue of temporal changes of seismic inner core (IC) PKiKP (CD) phase (a compressional wave reflected off the IC boundary; Fig. 1a) (Wen, 2006; Yao et al., 2015, 2019). Specifically, in a detailed re-analysis of the seismic data presented in Wen (2006), they claimed there are "obvious clock problems" in the seismic data recorded in the seismic stations of AAK and ARU of the Global Seismographic Network (GSN) in a seismic doublet (a pair of earthquakes occurring at very close locations but at different times) that was used to discover the temporal change of the CD phase by Wen (2006). After putting forward an approach to eliminate those "obvious clock problems", they found both PKIKP (DF) (a compressional wave that transmits into the IC interior; Fig. 1a) and CD phases exhibit temporal changes. They further argued that the changes in CD phases are likely contaminated by the DF coda and determined that temporal changes occur on DF arrivals, but temporal changes cannot be confirmed on the CD arrivals as originally determined from our original study (Wen, 2006). They went on and performed statistical analyses on temporal changes of DF and CD phases observed elsewhere using the same approach of eliminating "the clock problems" in the seismic data, and concluded that the temporal changes come mostly (if not all) from the IC interior and the IC differentiation rotation is the simplest and most reasonable explanation for the origin of the time-varying IC waves. Not only do their conclusions raise questions on the validity of the observed temporal changes of the IC seismic phases (also including those of their own) as their reported "random clock errors" are in the same magnitudes of the observed temporal changes of the IC phases, they also cast doubt on the quality of the seismic data recorded in the GSN, the standard-bearer network in the seismological community.

However, their approach is faulty based on an erroneous claim. Their approach used a non-IC SKP phase (a seismic wave that starts with a shear wave, bottoms out in the outer core, and returns to seismic station as a compressional wave, without touching the IC; Fig. 1a) as reference and, by aligning SKP arrivals between the doublet, they determined temporal changes of DF and CD phases and clock errors. They illustrated their approach using a specific example of a doublet used in Wen (2006) that consists of two nearly co-located events occurring on 1993/12/01 and 2003/09/06. They found DF phases at stations AAK and ARU arrived 0.073 s and 0.068 s later in the later event as compared to the earlier event of doublet 9303, while CD phases only arrived 0.028 s and 0.023 s earlier (Figs. 2b–2e in Yang and Song (2020)). These DF and CD arrival time differences between the doublet are different from those reported in Wen (2006), where little differences in DF arrival

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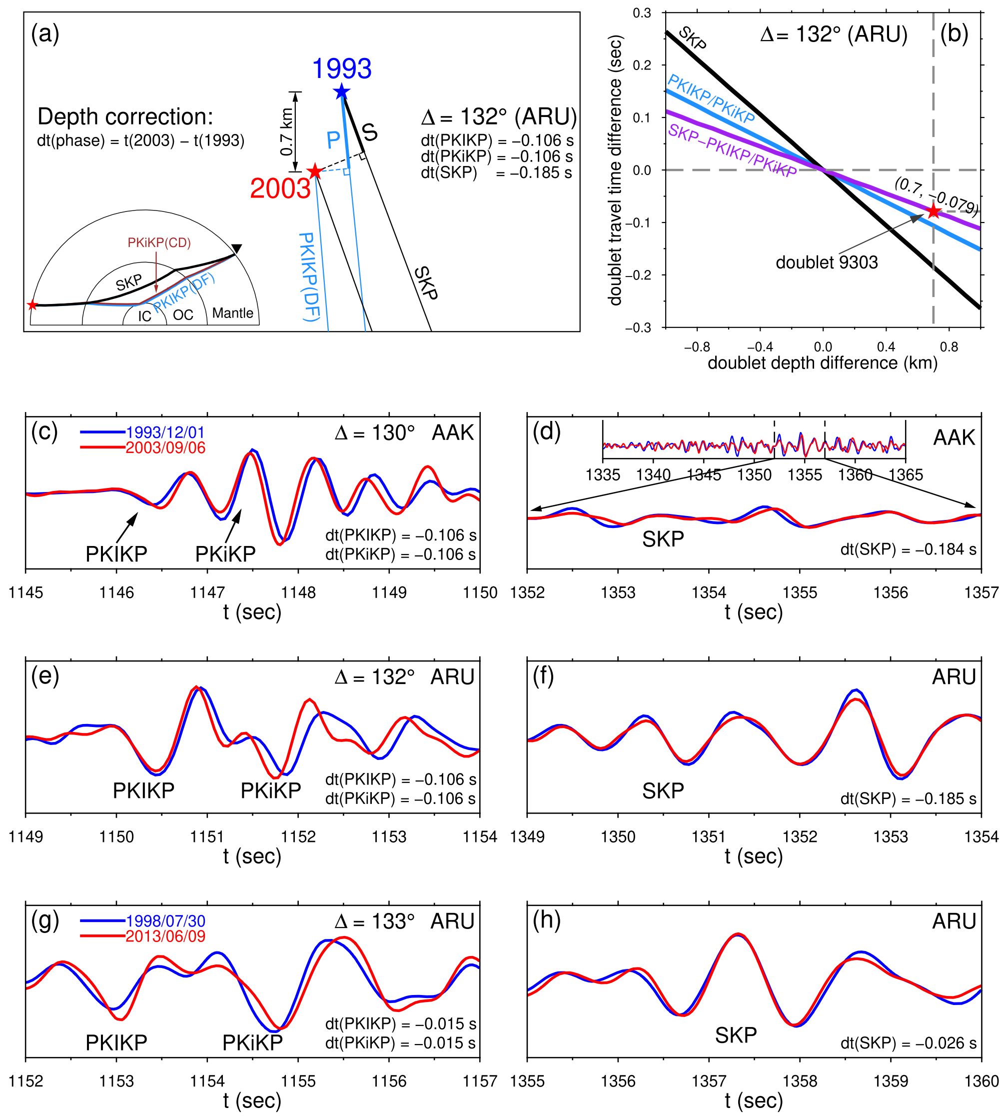

Fig. 1. Effects of doublet depth offset on the differential travel times of PKIKP (DF), PKiKP (CD) and SKP phases between doublet and alignments of the doublets 9303 and 9813 waveforms at stations AAK and ARU after depth correction. (a) Raypaths of PKIKP (DF) (light blue), PKiKP (CD) (brown) and SKP (black) waves plotted schematically near doublet source region and globally at an epicentral distance of 132°. Note that, for display purpose, the difference in the take-off angle between DF and SKP phases is exaggerated. IC: inner core; OC: outer core. **(b)** Travel time differences of DF (or CD) (light blue), SKP (black), and SKP-DF (or SKP-CD) (purple) phases between doublet as a function of doublet depth difference, with the red star showing the case of doublet 9303. Calculations are based on the IASP91 model (Kennett and Engdahl, 1991). **(c)** Superimposed PKIKP and PKiKP (DF and CD) waveforms recorded at station AAK, with that of event 1993/12/01 (blue traces) aligned along with the origin time and that of event 2003/09/06 (red traces) superimposed with a time shift that accounts for the travel time difference of DF (or CD) phases due to the depth difference between the doublet. **(d)** Superimposed SKP waveforms recorded at station AAK. Waveforms are aligned the same as in Fig. 1c except that time shift accounts for the travel time difference of SKP phases between the doublet. Note that this SKP phase exhibits lower quality than that at ARU (Fig. 1f) (a longer time window of the data is shown in the inset), but overall waveforms are well time-matched between the doublet. **(e-f)** Same as Figs. 1c–1d except for station ARU. **(g-h)** Same as Figs. 1c–1d except for station ARU between doublet 9813 reported in Yao et al. (2015). SKP phase at ARU exhibits an excellent quality, with its nature supported by its arrival time and strong signals in the vertical component and no visible signals in the horizontal components of the data. All the 9303 waveforms are pre-processed following the same procedures outlined in Yang and Song (2020), self-normalized, and plotted in the same ways as in Yang and Song (2020) but in a flipped way from those in Wen (2006) and Yao et al. (2015). The 9813 waveforms are pre-processed following the same procedures outlined in Yao et al. (2015). (For interpretation of the colors in the figure, the reader is referred to the web version of this article.)

times and significant differences in CD arrival times were reported between the doublet. Because the results in Wen (2006) were obtained using the real recorded absolute time of the seismic records, Yang and Song (2020) claimed that their results are the correct one as their approach is not affected by clock errors of the instruments. They concluded that the DF and CD arrival time differences obtained between the two studies are due to existence of "random clock errors" in the seismic instruments of AAK and ARU that Wen (2006) did not consider. Accordingly, Yang and Song (2020) claimed that the conclusions in a series of our studies (Wen, 2006; Yao et al., 2015, 2019) should be rejected because all the studies did not correct for "random clock errors" of the seismic instruments. Their approach is based on a claim that the relative location difference between a doublet has little and ignorable effect on the differential SKP-DF/CD (SKP-DF or SKP-CD) travel times between a doublet. That claim is erroneous. In fact, the relative depth difference between a doublet has a disproportionate effect on the relative time difference between DF/CD phases of the doublet and between SKP phases of the doublet (Figs. 1a–1b). DF/CD travel as a P wave between the depth difference of the doublet, while SKP travels as an S wave (Fig. 1a). It is wrong to use SKP phases as the reference to determine the differential travel times of the other phases between a doublet without considering the effect of the relative location between the doublet. We use the same example of seismic observations of AAK and ARU of doublet 9303 they used to refute the study of Wen (2006) to illustrate the point. The doublet has a depth difference of 0.7 km as reported in our previous studies (Wen, 2006; Yao et al., 2015, 2019) and fully aware of by Yang and Song (2020). That depth offset of the doublet would generate a differential travel time of −0.106 s (AAK and ARU) of DF and CD phases, but a differential travel time of −0.184 s (AAK) or −0.185 s (ARU) of SKP phases between the doublet (Figs. 1b–1f) (the minus sign means that the seismic phase arrives earlier in the later event). In fact, SKP phases are exactly time-matched between the doublet when the effect of the relative depth between the doublet is corrected (Figs. 1d and 1f). And, there are significant CD time-mismatches and no obvious DF time-mismatches between the doublet, which basically reproduce the results shown in the original study of Wen (2006) (Figs. 1c and 1e). Note that the corrections for the epicentral distance difference between the doublet are not applied in Figs. 1c and 1e for the simplicity of illustrating the effect of relative doublet depth (the corrections for the epicentral distance difference are small), while Wen (2006) considered corrections for both epicentral distance and relative depth. So, there is no evidence for any random clock errors in those GSN data and the "random clock errors" the authors reported are exactly the effect of relative source depth difference on SKP-DF/CD differential arrival time that the authors ignored (−0.078 s for AAK and −0.079 s for ARU). In another word, had Yang and Song (2020) applied relative depth corrections on SKP-DF/CD phases between the doublet, they would have exactly reproduced the results in Wen (2006) and had no need of introducing "clock errors" to blame the study of Wen (2006) for not considering them. We should note that, unlike Yang and Song (2020)'s relocation method that culls arrival time data to retain stations that yield similar locations biasing the locations closer together, our relocation procedure well resolves the relative depth between a doublet when it employed seismic phases with various take-off angles from the doublet, including P waves in the close epicentral distances, and PKKPbc, PKP precursor, PKPbc, and PKPab waves at large distances (Wen, 2006). We should also point out that SKP phases at stations AAK and ARU were not used to relocate the doublet in the original study of Wen (2006). The match of SKP travel times between the doublet after the relative depth correction serves a further independent affirmation of the results reported in Wen (2006). We further check the consistency of SKP phases in the doublet that exhibits clear SKP phases and noticeable temporal change of IC phases presented in our previous studies (Yao et al., 2015, 2019), the time-match between SKP phases is also independently confirmed between the doublet with our reported depth value (Fig. 1h). We should also note that the CD time changes are not just observed in the examples we present here, but are widely present in GSN stations (AAK, ARU, OBN, WRAB) and a seismic array (WRA) across different time periods (Yao et al., 2015, 2019). The rest of the analyses and discussions in Yang and Song (2020) were based on the results obtained by the faulty approach we just mentioned. As no relocation results were presented in Yang and Song (2020), we are not able to independently check the relocation results of other doublets in their study and their effects on SKP-DF/CD differential travel time. We will not comment further.

We do wish to comment on Yang and Song (2020)'s claim that the differential IC rotation is "the simplest and most reasonable explanation" to the temporal changes of the IC phases. Common logic of science has been that, when a proposal is put forward, it is up to the proposer to prove its necessity to the scientific evidence. This is not the case in the seismic studies of IC differential rotation. From its first appearance in the seismological literature to the present day, despite of its constant appearance in article titles such as "Seismological evidence for differential rotation of the Earth's inner core" (Song and Richards, 1996) and "Inner core differential motion confirmed by earthquake waveform doublets" (Zhang et al., 2005), etc., IC differential rotation was never proven to be required to explain the seismic data! It is still up to the proponents of IC differential rotation to provide a line of seismic evidence that requires IC differential rotation as the explanation. Even if unambiguous seismic evidence can be found in the future that some temporal changes come from the IC interior, we still disagree with Yang and Song (2020) on the statement that the IC differential rotation will be "the simplest and most reasonable explanation". There are many candidate mechanisms that are equally plausible, if not more, for explaining temporal change of seismic properties in the IC interior, to name a few: stress-induced seismic velocity or anisotropy change, or change of partial melt content in the IC.

To summarize the interpretation of IC differential rotation vs. the temporal change of IC surface in the context of the seismic evidence:

1) IC differential rotation has never been proven to be required by the seismic data. In fact, it would provide an inconsistent and unreasonable explanation to the seismic data, even if we invoke it in the absence of its requirement by the seismic data and in the presence of the temporal change of IC surface that is required by the seismic data (Yao et al., 2019). We refer the readers to Yao et al. (2019) for the detailed analysis and reasoning.
2) On the other hand, temporal change of IC surface is required by the temporal change of CD data and would provide an explanation to all the observed temporal changes of CD and DF data (Wen, 2006; Yao et al., 2015, 2019).

Which constitutes a good explanation to the temporal change of the seismic IC phases, we should let you, the reader, decide.

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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