Reply to comment by V. Lesur et al. on "Can core-surface flow models be used to improve the forecast of the Earth's main magnetic field"

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[1] In their comment, *Lesur and Wardinski* [2009] question two different aspects of our original work [*Maus et al.*, 2008].

[2] They first claim that "The accuracy of the used magnetic field is not such that the time variation of the flow can be reasonably estimated."

[3] The way we look into the time variations of core flows of *Maus et al.* [2008] is different than in previous studies. In particular, rather than computing a suite of instantaneous estimates of the core flow at successive epochs (such as had been done by, e.g., *Pais and Hulot* [2000], which in fact led to satisfying predictions of the length of day variations), we decided to simultaneously estimate the core flow and its acceleration from estimates of the core field (the main field, MF), its first time derivative (the secular variation, SV) and its second time derivative (the secular acceleration, SA), at a single central epoch (2003.0). Those estimates have been taken from the POMME-3 model of *Maus et al.* [2006], which provides a degree-2 Taylor expansion, best fitting magnetic observations between 2000.6 and 2005.7. Deciding how much of the corresponding SV and of the SA should be accounted for by the core flow and acceleration computed in this way is indeed an important issue. Lesur and Wardinski argue that our results are not "reasonable" because we try to fit the POMME-3 model, and especially its SA, too closely. Moreover, they more generally claim that "the POMME-3 SA model cannot be used to robustly estimate the flow temporal variation." Is that so?

[4] It is first important that we briefly recall how we estimated the level of misfit we requested for a set of core flow and flow acceleration to correctly account for the POMME-3 SV and SA. As shown by *Eymin and Hulot* [2005], what matters most in the case of the SV, is not so much the intrinsic quality of the SV model (which is very high for all recent SV models [see, e.g., *Hulot et al.*, 2007]), but the unmodeled contribution of SV produced by the unknown (not modeled) small-scale core flows interacting with the MF (including its unknown small scales). This contribution can be viewed as a source of error and sets a much larger threshold of the SV misfit we should aim at. Estimating the effects of small-scale field and flow interactions guided us in deciding how much of the observed SV should be accounted for by our truncated flow model (as illustrated in Figures 7a and 7b of *Maus et al.* [2008]). In the same way, interaction between the unknown (not modeled) small-scale core flows interacting with the SV, and between the unknown (not modeled) small-scale core flow acceleration interacting with the MF, will produce significant un-modeled SA signal. This must also be considered as a source of noise. The way we chose the level of SA misfit was again guided by these considerations (as is illustrated in Figures 7c and 7d of our original paper). What we did not verify, though, is that this misfit is also compatible with the intrinsic error in the SA coefficients provided by POMME-3, which might indeed be larger than the un-modeled SA signal (note again that as shown by *Eymin and Hulot* [2005], this is already known not to be an issue in the case of the SV). How large is this error in the SA coefficients of the POMME-3 model really?

[5] In their comment, Lesur and Wardinski argue that this error can be assessed by comparing coefficients from POMME-3 and the CHAOS model of *Olsen et al.* [2006, Figure 1] for epoch 2003.0. This indeed leads to very high, and therefore worrying, estimates. To further make their case, they also compared POMME-3 to several other models (the GRIMM model of *Lesur et al.* [2008], the xCHAOS model of *Olsen and Mandea* [2008], and one (unspecified) version of the POMME-4 model (available at http://www.geomag.org/models/pomme4.html), none of which, we note, were available at the time of the study reported by *Maus et al.* [2008]). All of those models, they argue, provide "more consistent SA" than POMME-3. This leads them to conclude that in their opinion, "the POMME-3 SA model cannot be used to robustly estimate the flow temporal variations." This, however, is an unfair statement because, as we shall now show, the way they carried out the comparison between POMME-3 and CHAOS is inappropriate.

[6] The reason is that POMME-3 and CHAOS provide different representations of the SA. As already recalled, POMME-3 provides a degree-2 Taylor expansion of the MF, best fitting magnetic observations between 2000.6 and 2005.7. It has been optimized to provide the best estimate of the average SA over that period of time. In contrast, CHAOS provides a cubic B-spline temporal description of

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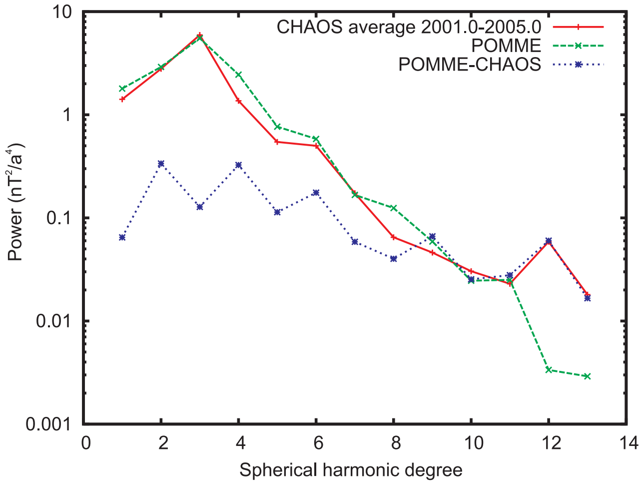

Figure 1. Comparison between the power spectrum of the POMME-3 SA and that of the averaged SA derived from the CHAOS model over the period 2001 to 2005. Also shown is the power spectrum of the difference between the two average SA.

the SV which aims at tracking the instantaneous SV, and thus also the instantaneous SA, between March 1999 and December 2005. Figure 1 of Lesur and Wardinski therefore primarilly illustrates that the instantaneous SA at epoch 2003.0 is quite different from the average SA over the time period 2000.6 to 2005.7. Thus, if any upper-bound estimate of the SA accuracy of POMME-3 is to be derived by comparing POMME-3 with CHAOS, one must first make sure that comparable quantities are being used. This can easily be achieved by first computing the average SA predicted by CHAOS over a comparable interval centered on 2003.0. Given the interval of validity of CHAOS, the interval of interest is clearly 2001–2005. Figure 1 shows that this average SA estimate from CHAOS is in much better agreement with the SA average estimate of POMME-3, than the instantaneous SA estimate of CHAOS for epoch 2003.0. Figure 1 (and not Figure 1 of Lesur and Wardinski) thus provides the appropriate estimate of error in the SA coefficients of POMME-3. Comparing Figure 1 with Figures 7c and 7d of *Maus et al.* [2008], clearly confirms our original claim that no stationary flow can account for both the average SV and SA over the 2000.6 to 2005.7 time period, and that a flow with acceleration is needed.

[7] An important aspect of our study that the above discussion also underlines, is that the various core flows and flow accelerations estimated by *Maus et al.* [2008] are not strictly instantaneous estimates for epoch 2003.0. They are estimates best accounting for the average SV and SA over the 2000.6 to 2005.7 time period. As originally stated by *Maus et al.* [2008], the reason we computed those flows is that we wanted to test whether an order-1 Taylor expansion of the flow could "provide a better means of predicting the magnetic field than a simple extrapolation of an order-2 Taylor expansion of the field itself." Of course, by definition, such flows are not meant to describe all possible short-term changes in the MF between 2000.6 to 2005.7.

[8] This then leads us to the second comment of Lesur and Wardinski that "the process proposed to predict the field is very unlikely to improve on the usual forecasting techniques."

[9] To make their point, Lesur and Wardinski first argue that a stationary flow cannot properly account for the SA, because the contribution of such a flow to the SA (second term in the right-hand side of their equation (2)) is too small compared to that of the neglected flow acceleration (first term in the right-hand side of their equation (2)). This we do not dispute. In fact, we precisely showed (and the above discussion based on Figure 1 further confirms) that a stationary flow cannot simultaneously account for the POMME-3 SV and SA, and that a flow acceleration is thus indeed needed.

[10] Lesur and Wardinski next more generally argue that since a flow (even with a flow acceleration) cannot exactly account for the POMME-3 SV and SA, it is unlikely to provide a better description of the MF evolution than POMME-3 itself. This is undoubtedly the case over the period of time (2000.6 to 2005.7) POMME-3 was optimized for (as was in fact pointed out and discussed by *Maus et al.* [2008], see the corresponding Figure 8). But that this should also be the case beyond the period of time for which POMME-3 was optimized is far less obvious. In fact, our hindcast tests precisely show that this is not the case. The reason for this was discussed by *Maus et al.* [2008] and can be summarized with the help of equation (2) of Lesur and Wardinski. Although, as just discussed, the first term of the right-hand side of this equation is crucial in accounting for the SA over the 2000.6 to 2005.7 time period, it can significantly average out over longer time periods, because of the fast-changing nature of the short-term flow acceleration. Thus, even though the average stationary flow computed from POMME-3 SV might not account for the POMME-3 SA, and might not even exactly account for the POMME-3 SV, it may very well give an accurate enough estimate of the long-term average core flow responsible for the MF evolution over longer periods of time. Of course, we do not claim that this is indeed what happens in the core. But we see no fundamental reasons why this might not be the case. It is therefore still our opinion that core flow based forecasts should further be considered and investigated.

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