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Weather at the core: Defining and categorizing geomagnetic excursions and reversals

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We thank both Reviewers for carefully reading our manuscript and for their insightful comments. We addressed all comments and requests made by the reviewers and provide brief answers to the reviewers' requests below. The review generated several changes to the manuscript and we provide a latex-diff so that the reviewers and the editor can track changes to the manuscript. In our response to reviewers, the reviewers' comments are reproduced in teal and our answers are in black.

We mention both reviewers in our acknowledgements and since one reviewer revealed his identity (Filipe Terra-Nova), we mention this reviewer by name. Please let us know if they want to be removed from the acknowledgments.

Response to Reviewer 1 - Filipe Terra-Nova

The paper attempts to categorize reversals and excursions of the geomagnetic field using a numerical dynamo simulation and then use those results to interpret two geomagnetic field models. The manuscript is a pleasure to read it. I consider a really valuable first attempt to categorize reversals and excursions. Hence I recommend the manuscript to publication. However, I have many problems with terms used. Unfortunately several Meteorology terms put me a little off. The use of the word 'field' when talking about a numerical dynamo simulation is wrong. Numerical simulations give magnetic field, velocity field and temperature inside the outer core. So the term magnetic field needs to be used often or always instead of field. The terms heat up and cooling down used to describe figure 3 are too misleading. Those need to be changed. So I'm giving many comments to the text that are specified below.

We thank the Reviewer for the accurate summary of our work. We do use the word "field" to refer to the magnetic field. Our work is almost exclusively about the magnetic field and it is clear from context what we are referring to. We avoid adding "magnetic" in front of every occurrence of the word "field" for readability. Our work makes analogies between the time evolution of the state of Earth's magnetic field and Earth's atmosphere. The words "cool down" and "heat up" are referring to the state of Earth's magnetic field being more stable (cool down) or more unstable (heat up). We find this wording to be a useful, imaginative way of thinking about the complex processes at Earth's core and decided to keep our wording as is.

Major comments

1. I am also a little bit concerned with the word "unambiguous" in line 123. Because the results are based on one solely numerical dynamo simulation. I can not contest the quality of the simulation because zero information is given. I don't know fdip, force balance, Magnetic over

Kinetic energy ratio, Reynolds magnetic number and how earthlike the simulation is in terms of any criteria. For example, today's field has an average PSV index of O(-1), the simulation seems to have a mean of O(-2), that is all the information that I have from the simulation itself. Since the simulation is not published, I suspect the tone of the paper should be recycled to a more precautions one. Several times the Authors say the Earth's magnetic field to refer to results coming from the simulation, that is wrong. The title of the paper "weather of the core" is too pushy for me. Because we talk about one simulation and two paleomagnetic field models. Even more when only what is being studied is the resulting field at the surface from upward continuation of the radial component of the field at the core-mantle boundary.

The simulation we use is well documented in earlier papers (Gwirtz et al. (2021, 2022)). Because paleomagnetic data is limited, we use the simulation to develop our ideas and then test our ideas on two field models. We explain all this clearly in the paper. We do not want to change the title of the paper. The title is accurate and summarizes the essence of our work: That thinking about Earth magnetic field and its excursions and reversals as being analogous to Earth's weather can help us decipher and categorize complex behaviors at the core.

2. Please use modified PSV index instead of PSV index, or choose another term, or even use P_{i_D} in the manuscript. I know it is about P_{i_D} that you talk about most of the time, but it can be confusing for the readers.

   We clearly distinguish between the PSV index P_i and the modified version P_{i_D}. We corrected several axis labels in our figures to clearly refer to P_{i_D}.

3. All figures are good with the exception of figure 7. Fig 7. caption is missing all kinds of information. What are the black dashed lines, the solid blue, white and green lines? Color bar please. What is this strange cut at t=10kyr?

   Actually, not all figures are good, we corrected several errors in the axis labels (see above). We also corrected the figure caption of Fig. 7 according to the reviewer's suggestions. A colorbar is useless here because histograms are qualitative, not quantitative (their height is meaningless).

Minor comments

1. Abstract: line 10 - Tell that is a new quantity

   We followed the reviewer's suggestion.

2. line 16 - drop the acronyms here

   We followed the reviewer's suggestion.

3. lines 29-30. Statement needs reference.

   No, this is textbook material.

4. lines 30-34. Statement needs reference.

   No, this is textbook material.

5. line 35. delete 'full'.

   We followed the reviewer's suggestion.

6. line 37. delete 'considered'

   We followed the reviewer's suggestion.

7. line 38-39. delete 'and may be...extent'

   No, it is unclear if excursions are always global or always regional.

8. lines 39-42. It only needs g01 to change signs to be classified as a reversal. I get that the categorization needs more, but not to define a reversal.

   No, if a reversal is defined by a change in sign of g_1^0, then a reversal can occur instantaneously. This is why we define reversals differently (see also Gwirtz et al. 2022, 2023).

9. lines 102. delete 'say.. field'

   We decided to keep "say" because one may consider other values.

10. lines 105. Why arbitrarily? I thought it was based on present-day field values. Can you clarify?

    We removed the word "arbitrarily."

11. line 115. For clarity, please give the equation used for λ_D.

    No, λ_D is a standard quantity that does not need to be defined.

12. line 124. You promised to show it below for P_i but I could not find it.

    We clarified our statement.

13. line 130. change excursions to P_{i_D} values. you did not present the table yet.

    It is unclear to us what this comment is asking for.

14. Small comment. I liked the adaptation from Pi to write equations (1) and (2).

    Good.

15. lines 146-147. Please rewrite. There is so much in a dynamo simulation, and stationary is not a good term for MHD high turbulence problem even if one of its properties has small standard deviation.

    We use the word "stationary" with its correct meaning: The statistics (e.g., the average value) do not change over time.

16. lines 150. "reflecting...field". How can you affirm that? The modern field is not reversing...

    The simulation exhibits reversals, similar to what was observed over the past 2-10 Myr.

17. line 152. PFM is used almost never and it can confuse the reader because of the family of models pfm9k of Adreas NIlsson.

    We clearly define the abbreviation and use it consistently.

18. line 167. change 'small-scale' to 'non-dipolar'. truncation 2, 3, 4... are still large scale.

    Yes, but smaller in scale than the terms we keep.

19. line 172. PSV indices? modified PSV indices

    We corrected this mistake.

20. line 186. Level 1 is unusual, but you say nothing about the other levels that have lower occurrence.

    We describe higher levels just after we describe Level 1. We are unsure what this comment asks us to do

21. line 193-194. Using only a simulation is dangerous, I would add a precaution statement here. Mostly explaining why we should believe in the simulation used.

    We have precaution statements in place (see paragraphs starting at lines 199 and 209).

22. Figure 2. Please define colors and solid black lines in the caption.

    We followed the reviewer's advice.

23. line 200. delete 'with warmer...levels'.

    We decided to keep our terminology.

24. line 209. This simulation has no remarkable high time resolution. It only has 1/3 advection time between snapshots. Please correct it. Numerical dynamo simulations can easily reach 0.1 advection times. In this case, because long runs are aimed the time-step is probably stretched to its maximum, but not too much to respect Courant–Friedrichs–Lewy condition.

    The time step of this simulation is 29 years. In comparison with paleofield models this is high resolution.

25. Lines 222,223,225,227: Please change the terms "cool down" and "heat up".

    We decided to keep our terminology.

26. Line 235 - PSV index to modified PSV index or P_{i_D}

    We followed the reviewer's advice.

27. Figure 4. The event duration for cat-3 event (cartoon) do not start at 0.5 (blue horizontal line).

    We corrected this mistake.

28. Line 240. Please change the "cooldown of the field." It sounds as if the temperature field is changing in the numerical dynamo simulation.

    We decided to keep our terminology.

29. Line 243. Is it not better to categorize by the average value of P_{i_D} during an event?

    Perhaps, but we don't pursue that idea in this paper.

30. Line 255. The Cat-1 event with reversal seems really special. I would give more attention to it.

    Please do. We think it's an unusual feature of the simulation and that a reversing Cat-1 event is too rare to be of large interest.

31. line 259. delete "that do not reverse"

    We followed the reviewer's advice.

32. line 252. Needs reference or to be explained why. Again, the PSV index is different from the modified PSV index. (e.g. line 272). Pole latitude could also be referred to as geomagnetic pole latitude from time to time. (e.g. line 272)

    Line 252 is a definition of this paper and hence does not need (or have) a reference.

33. Lines 295-296. Following the dynamo results should be the same? Can you explain better why this is not the case? Maybe give here the range of high probability of finding events of cat-2.

    We are unsure what the reviewer is referring to here. What should be the same? Cat-2 or Cat-3 events may or may not reverse.

34. Lines 304. Why red?

    We corrected this mistake.

35. Figure 8. Please unify with Figure 9. I prefer figure 9.

    The figures are generated by the same code. The MB model has a coarser time resolution, hence you see line segments in between dots.

36. line 316. The event duration of 27.4 kyr is consistent with the recent results of Mahgoub et al.2024 (21-32 kyr).

    Yes, we had noted this in the discussion section line 351.

37. line 319. 'the magnetic field' to its 'magnetic field'

    We already addressed this comment.

38. Line 330-331. 'We sought ... no definitive result'. It is not this statement somewhat not precise in the light of results of figure 5b.

    No, both durations are compatible with Cat-2 events.

39. Line 337-340. Not convinced. Paleomagnetic models should do ok until lmax=5. Moreover cat-1 reversal looks like the GGFMB model reversal. Please compare figures 9b and A1b.

    This comment does not require making changes to the manuscript.

40. lines 356-357. Could you explain it better? "often equated...polarity reversals".

    We already gave it our best shot.

41. Lines 372-375. "under core climate change". Please use better terminology. The core has much more going on than reversals. It sounds that you are talking about the solidification of the inner core more than about reversals and excursions, which is a core-mantle boundary phenomena of one component (axial dipole polarity change) of the radial component of the magnetic field.

    We already addressed this comment about our terminology.

42. Lines 396-399. If you don't have a reference to it please delete.

    We are unsure what "it" refers to.

Response to Reviewer 2

The manuscript presents a categorization of the geomagnetic field extreme events, showing their complex nature, strength, and duration. Seeing them as analogous to extreme weather is interesting and contributes to better comprehending the extreme field variations and associated core dynamics. Numerical dynamo simulations and two paleomagnetic models are used. My suggestions listed below are mostly for clarifying some points and choices made.

We thank the reviewer for this accurate summary of our work.

Line numbers refer to the numbers close to the text, as there are two columns of line numbers in the document I downloaded.

We apologize. The GJI template has line numbers and then line numbers are added (again) when we upload the files.

1. Line 10 in the abstract, add ... paleosecular variation index P_{i_D}, based on the dipole field, to define ...

   We followed the reviewer's suggestion.

2. Line 93: What is the reason for using only the dipole terms? Which index is recommended for future use? How much does the categorization change if the originally suggested index is used?

   The reason is that we only consider the global magnetic field. Strategies similar to what we explain here can be used with the original definition of the PSV index, but the situation is more complicated – is the field (globally) excursional if PSV peaks above a critical value at a single location? We basically eliminate questions of "size" of an excursion to simplify our thinking and to be able to make progress. We added an explanation of these issue to our paper.

3. Line 153: It would be useful to cite the paper that describes the LSMOD.2 model, not only the data supplement where the model is publicly available.

   We followed the reviewer's suggestion.

4. Line 167: The GGFMB model is built only with sediment data

   We corrected our inaccurate wording.

5. Line 237-240: Please explain why there are different threshold values for defining the start and end. I understood that an event may be complex (as in Fig. 4, Cat-3) and a lower value for the end-of-event will make sure that the field stabilizes. Should this value be used for paleomagnetic field models as well, because the median value of the PSV index in the normal state of a given model may differ? Again, it depends on how 'normal' is defined. Is 'normal' below 0.5 before an event, and below 0.035 after an event, or below 0.5 overall?

   The reason is that if the threshold values were identical, then the event would be over before the system has reached a steady state. Nearly every event would be immediately followed by another event and the event duration would be tiny (events with durations of less than 100 years). When using an end-of-event threshold that is lower than the start-of-event threshold we ensure that the entire system has reached a state that is no longer "excited" or nearly so. For example, the MB reversal would consist of three distinct events, two of which would be very short (see Figure 9). We explain our reasoning in lines 243–251.

6. Line 306: According to the thresholds set in the study, the duration of the Laschamp excursion is 3.6 kyr. However, a significant part of the Laschamp duration, about 1.5 kyr or more, is of level 0 (Fig. 8d), which is a normal state. This makes the excursion longer than actually is because the period of stable period is counted in the 'duration'. Isn't this a problem? The lower threshold works to ensure that the event ended, but the duration will be more realistic when the end-point is the Level 1 crossing, meaning once it is confirmed that the event ended, the backward scanning to the first value of 0.5 should give the end- time for the duration calculation. I wasn't expecting that excursions and reversals (i.e., non- reversing and reversing events) in the numerical simulations could not be distinguished based on the duration. Not sure if that's because of the way how the duration is defined. There is one order of magnitude difference in these two types of events in the paleomagnetic field models, at least in the Laschamp excursion and MB reversal analyzed in the study.

   The reviewer is right that one could pursue alternate definitions of events that are variations of the events defined here, but then adjusted in "hindsight." We do not consider these ideas in this paper. The fact that there is no distinction between reversals or excursions is not due to the details of our definition – the "lingering" at level zero before reaching the end-of-event threshold occurs for reversals and non-reversing events (see figure 6 and the figures in the appendix).

7. Line 313: how quickly oscillates between 0 and 60 degrees? What is the time step of the points in Fig. 9e? It seems the field spent more time in Level 2 before the zero-crossing of pole latitude and gradually (but faster?) stabilizes.

   The time step of the MB model is 0.2 kyr.

8. Line 334: ... for the Laschamp excursion and ... (since the name of the reversal is listed)

   We followed the reviewer's suggestion.

9. Line 335: Korte et al., 2019 (the reference for the LSMOD.2 model) gives a duration of 1.8 kyr, which is half of the duration reported here.

   The reference actually states (in the abstract) that "the Laschamp excursion, with the underlying excursion process lasting $\sim$ 5 ka (43–38 ka) and the surface field expression lasting $\sim$ 2 ka (42-40 ka)", which is compatible with the duration we obtained with our proposed categorization and classification.

10. Line 347: comment on the results of decrease/recovery when the events are separated into reversing and non-reversing. If this makes a difference, maybe add two additional figures in the Appendix, basically Fig 7 for reversing and non-reversing events. The Laschamp excursion shows fast decay and slow recovery, in contrast to the MB reversal (based on the models).

    We computed (for the 3D model) the average time it takes for an event to grow to level 2 (or 3) and the time it takes to decay from level 2 (or 3) back to the normal state. We distinguished between all events, reversing events and non-reversing events, and there is no statistically significant difference, but the standard deviation on the time intervals it takes to grow or decay is large. If the model is indicative of how Earth's magnetic field operates, then we must conclude that there is no difference in the time of growth or decay for significant excursions. We added this explanation to our manuscript on p.13 and also include a table (in the appendix) to show our results quantitatively.

11. Line 362: Are 0.07 and 0.09 median values over the 'normal' period of the models, and how are these defined?

    It's the median over all level 0 states (although this is irrelevant for the 3D model because the median does not change by much if we restrict ourselves to the "normal period" states).

12. Line 362: LSMOD.2 Line 363: ... that these ... Line 371: solar wind

    We fixed these typos.

13. Appendix: Is there a special reason for not presenting a Cat-2 reversing case?

    A Cat-2 reversal is shown in Figure 6.

14. Figure 1, y-axis, add units to pole latitude

    We fixed this issue.

15. Figure 4, the Cat-3 event starts slightly earlier (than what the colored block shows), when the PSV index exceeds the value of 0.5 (Level 1)

    We fixed this issue.

16. Figure 6 caption, description of the yellow curve is missing

    We fixed this issue.

17. Figure 7 caption, what do the white, blue, and green curves represent?

    We fixed this issue.

18. Figure 8, subplot (e) overlaps with (b) and (c) and part of the y- axis label is missing

    We fixed this issue.

19. Figures 8 and 9, it would be helpful to mark the levels.

    We fixed this issue.