Response to Reviewers - CPD

Editor

Three reviewers have carefully read and commented on the paper by Thomas et al. All reviewers find the paper interesting and worth publishing in principle. They suggest, however, major revisions before publication in Climate of the Past. Hence I encourage the authors to submit a revised version of their manuscript and a detailed point-by-point response to all comments raised by the reviewers. The revised version of the manuscript will be sent to the three reviewers again.

Dear Editor,
We thank all three reviewers for their constructive comments on our manuscript. We have very carefully considered these comments and have substantially restructured and reordered the manuscript which we feel greatly improves the clarity and ease of reading. We have also posted a detailed point-by-point response to all comments raised by each reviewer.
Best wishes
Zoë Thomas (on behalf of all co-authors)

Detailed list of changes:

- We have altered our abstract (line 20-32), reporting our results in the order that we now discuss in our revised manuscript.
- Paragraph 1 of Introduction unchanged.
- We have substantially altered the rest of the introduction, explaining the literature behind previous conceptual models and explaining the moisture-advection feedback (line 62-70).
- We have added an 'aims' paragraph to make the intentions of our study more clear (lines 78-83).
- We then use subheadings to separate the rest of our introduction (having moved some material from the methods/discussion) (lines 85-145).
- Section 'Using speleothem d18O as a proxy of past monsoon strength' is largely unchanged.
- We have substantially altered the methods section, by creating subsections dedicated to each method. We have expanded the section on assessing the significance of the tipping point analysis results, and added a more detailed description of the potential model (lines 148-324).
- We have separated the results and discussion sections, and added a short paragraph before each figure to explain each result.
- We have restructured the Discussion section discuss the results as explained in the previous section.
- We have altered our conclusions to reflect our discussion and updated the implications of our study.
- We have changed the order of the figures and ensured that we are consistent with our labelling.

Review #1

Reply: We thank the reviewer for their careful reading of the manuscript and their constructive remarks. We have taken the comments on board to improve and clarify the manuscript. N.B Since the reordering and restructuring of the manuscript was substantial, we have written bullet points of our major changes to the manuscript, rather than including a 'track changes' document. Line numbering refers to the revised manuscript, attached as a supplement.

Major changes:

- Altered the abstract to reflect the new structure of the manuscript.
- Added a clearer 'Aims' section.
- Provided more detail on the potential model.

- Altered the structure, separating the Results and Discussion sections and ensuring a consistent structure in the added sub-sections throughout the manuscript.
- The manuscript now follows a more logical format, with tipping point analysis of the entire speleothem sequence followed by the potential analysis results.
- Reordered the figures and added a paragraph of text to explain each figure sequentially.

The manuscript "Early warnings and missed alarms for abrupt monsoon transitions" by Thomas et al. poses the question whether there were bifurcation induced abrupt changes of East Asian monsoon intensity during the penultimate glacial cycle. They address this question by analysing trends in autocorrelation and variability in speleothem records from Chinese caves because linear stochastic theory suggests an increase of these properties before a bifurcation.

General comments

I think that this question and approach are very interesting and reasonable and within the scope of Climate of the Past. The analysis of different potential Tipping Elements using models, reconstructions and observations is an important issue in earth system science, and the authors' approach is a step in this direction. However, I also find it difficult to understand how and why different statistical methods are applied throughout the paper, what the results are, and how the authors interpret these results. I would suggest to explain these things more explicitly using a clearer structure and wording to make the results more transparent for readers unfamiliar with the technical details.

Reply: We have added further detail, and a better structure, to explain our choice of methods and make these explanations more easily understandable for those readers unfamiliar with the techniques used. Specifically, we apply two main methods to help determine whether the East Asian Summer Monsoon is characterised by a bistable system, with bifurcations between the strong and weak monsoon regimes, and whether 'early warning signals' of these bifurcations can be detected. Tipping point analysis uses techniques from Kleinen et al. 2003, Held and Kleinen 2004, Dakos et al. 2008, and many others, to identify the characteristic fluctuations that occur in data prior to a bifurcation, caused by a phenomenon called critical slowing down. Non-stationary potential analysis is used to create a simple model of the monsoon based on the speleothem data. We believe our substantial restructuring has helped make the aims, methods and results more transparent.

My main concern in terms of contents is whether the interpretation of the authors is fully justified by the results of the study. I get the impression that the record the authors analyse does not show "early warnings" (except before one of the abrupt transitions). Nonetheless, the authors maintain the interpretation of these abrupt shifts as bifurcations with the argument that the data is too scarce to see any signal. I would assume that other explanations are equally possible and I suggest to highlight such alternatives more clearly in the paper. The authors also fit a simple stochastic model to the data (which they call non-stationary potential analysis), whose parameters are coupled to the solar insolation at 30 N and which features bifurcations. In artificial time series from this model, significant early warning signals appear.

Reply: An alternative interpretation of the speleothem isotopic data is a linear response to orbital forcing. However, the abrupt nature of the data in comparison to the sinusoidal forcing argues against this, strongly implying a non-linear threshold. This has been emphasised in the revised manuscript (lines 47-51). By examining both palaeoclimate data as well as model-derived data, the presence of a bifurcation within the monsoon system appears to be the most plausible. We have however explained our aims more clearly (lines 78-83), and justified our conclusions.

I may have misunderstood the logic of the paper but I get the impression that this approach is flawed by circular reasoning. Is the model the authors fit to the data not built in a way that it must show such signals? In this case the question arises whether the original record is adequately described by the model. What is needed in my eyes is some kind of statistical test which allows to falsify a model or an hypothesis, e.g. that the framework of bifurcation theory (or some alternative explanation) is inconsistent with the data. Although the authors perform an ensemble of time series with their stochastic model and get significant results, the original data incorporated in the model was too badly resolved to see early warnings. I wonder why the fit of model parameters can be more precise than the scanning of the original record. Why is the potential stochastic model needed in the paper at all? I do have the feeling that the authors are somehow aware of this and follow a certain logic, but in order to understand and assess this logic it should be made much more transparent in my opinion.

Reply: The potential model is not built in a way that it necessarily exhibits bifurcations and hysteresis behaviour. It also has the possibility of two states always being available and the transitions being noise-induced with or without stochastic resonance. The parameter estimation reveals which mechanism is better supported by the data.

It would also be interesting to see physical arguments for the author's interpretation of the abrupt monsoon shifts, although I understand that this is not meant to be the focus of their paper. If there are bifurcations, what physical properties are involved, and what could be the different timescales the authors mention in the introduction? As the atmosphere adjusts very quickly to its boundary conditions, what is the element in the monsoon system that would show a memory in such a way that the authors expect to see it in palaeorecords?

Reply: As acknowledged by the reviewer, a thorough discussion of the physical mechanisms behind these abrupt monsoon shifts is really beyond the scope of this paper. However, we agree that the manuscript would benefit from a brief discussion of the physical mechanism(s). We speculate on possible mechanisms and focus on one likely contender: the moisture-advection feedback, as described by Schewe et al. (2012). We also direct the reader to other papers such as Zickfeld et al. 2005 that cover this in further detail. See line 62-73 "*A minimum conceptual model of the East Asian Summer Monsoon developed by (Zickfeld et al., 2005), stripped down by Levermann et al. (2009) and updated by Schewe et al. (2012), shows a non-linear solution structure…*"

Another aspect in this context is the reference to the concept model by Leverman et al. (2009) and Schewe et al. (2012). The authors introduce this model as consistent with the bifurcation hypothesis and state that "It has been hypothesised that ... the EASM exhibits two stable states with bifurcation-type tipping points between them (Schewe et al., 2012)". However, I take it from these publications that the monsoon is a "switch" in their model, where the on or off state is determined by a moisture threshold. I wonder why such a threshold should be consistent with the bifurcation hypothesis and why the authors expect early warning signals. It seems to me that the whole "off" state and the small hysteresis which exists in the model has been artificially built in at the threshold (Schewe et al., 2012) and is not an emergent result of the moisture advection feedback. Furthermore, the model only describes equilibrium solutions, but involves no timescales. I therefore do not find it compelling that the concept model is really in agreement with the bifurcation hypothesis, at least not without additional arguments.

Reply: Several papers refer to the Asian monsoon system being an important 'tipping element' in the Earth's climate system (e.g. Lenton et al. 2008; Zickfeld et al. 2005; Donges et al. 2015). The Schewe et al. (2012) paper directly refers to a 'critical threshold', and 'threshold behaviour', which is directly relevant to our bifurcation hypothesis. Indeed, Figures 5 and 6 in this paper show a bifurcation structure in the conceptual model, which implicitly infers a bifurcation. In this paper, the critical point refers to the bifurcation point. Zickfeld et al. 2005 also describes the Indian Summer Monsoon (which is closely linked to the East Asian Summer Monsoon) as being a multistable system, with saddle-node bifurcations. We have thus amended the revised manuscript to explain more fully the development of this conceptual model, and moisture advection feedback: '*A minimum conceptual model of the East Asian Summer Monsoon developed by Zickfeld et al. (2005), stripped down by Levermann et al. (2009) and updated by Schewe et al. (2012), shows a non-linear solution structure with thresholds for switching a monsoon system between 'on' or 'off' states that can be defined in terms of atmospheric humidity – in particular, atmospheric specific humidity over the adjacent ocean (Schewe et al., 2012). Critically, if specific humidity levels pass below a certain threshold, for instance, as a result of reduced sea surface temperatures, insufficient latent heat is produced in the atmospheric column and the monsoon fails. This moisture-advection feedback allows for the existence of two stable states, separated by a saddle-node bifurcation (Zickfeld et al., 2005) (although interestingly, the conceptual models of Levermann et al. (2009) and Schewe et al. (2012) are characterised by a single bifurcation point for switching 'off' the monsoon and an arbitrary threshold to switch it back 'on'). Crucially, the* *presence of a critical threshold at the transition between the strong and weak regimes of the EASM means that early warning signals related to 'critical slowing down' (Dakos et al., 2008; Lenton et al., 2012) could be detectable in suitable proxy records.'* (lines 62-76).

Specific comments

Abstract

I suggest not to cite other papers in the abstract, at least it is not very common.

Reply: We have removed the citations from the abstract (lines 15-32).

The abstract mentions the conceptual Levermann/Schewe model, "model simulations" (referring to the author's stochastic model), and the detection of critical slowing down. It should be clarified that the Levermann/Schewe model is not the one the authors performed simulations with, and the early warnings are found in their model, not in the data itself. Also, what is "consistent with long-term orbital forcing", and why is it a result rather than an ingredient to the stochastic model? These aspects are examples why I find the paper hard to read and suggest to use a more precise wording throughout the paper.

Reply: We have amended the revised manuscript to be clearer that our model simulations are separate to the Levermann/Schewe model, both in the abstract and in the introductory section. We have also ensured that we explain which data we find the early warning signals in i.e. whether it is from the palaeoclimate data or the model output. We have also revised the abstract to clarify the wording.

Methods

- I wonder whether the paper would be easier to understand if the details of each method would be explained directly when it is applied. In the introduction or methods section one could instead explain the general logic of the methods and their role in the paper more generally and briefly.

Reply: We understand the reviewer's viewpoint here, and we do agree that a brief introduction to the general logic of the methods could be advantageous in the introduction to provide more context. We have added small section (lines 78-83) to this effect. Further subheadings *('Detecting early warning signals', 'Missed alarms'*, and *'Using speleothem $\delta^{18}O$ data as a proxy of past monsoon strength';* lines 85, 106 and 116 respectively) are used to explain what our intended aims of the paper are. We have restructured the methods section to clarify the approaches taken, which now reflects the structure of the results and discussion.

Is the relation between the d18O record and monsoon intensity not time dependent? What are the uncertainties in this regard? Is there a quantitative reasoning behind the authors' statement that dating uncertainties do not affect the results?

Reply: The relationship between $\delta^{18}O$ and monsoon intensity has a proven relationship on centennial to millennial timescales within speleothems in southeast China (e.g. Wang et al. 2008; 2012; Li et al 2013). As a result we do not investigate this aspect here. We are unsure where the author is referring to about dating uncertainties not affecting the results. The U-Th ages provide a robust chronological framework for the speleothem sequences investigated.

p. 1317, line 2: "we use an insolation latitude". At this point in the paper, it is not clear at all why and how the authors use the insolation.

Reply: We thank the reviewer for highlighting this point. We have reordered the methods section and to ensure that the relevance of the insolation latitude is explained in the appropriate place (now line 295). We have also added subheadings to improve the structure of the methods section.

Data selection

p. 1318, line 1 (and elsewhere): What is "tipping point analysis"?

Reply: We have provided additional information to explain 'tipping point analysis' *('This analysis aims to find early warning signs of impending tipping points that are characterised by a bifurcation (rather than a noise-induced or rate-induced tipping e.g. Ashwin et al. (2012)). These tipping points can be mathematically detected by looking at the pattern of fluctuations in the short-term trends of a time-series before the transition takes place'*; line 86-91). As mentioned above, we have restructured the methods section to ensure that each method is introduced in the appropriate context, and added subheadings to help this structure.

p. 1318, line 2, 3: what is meant with "clear climate proxy" and "adequate length"?

Reply: We have replaced the phrase 'clear climate proxy' with *'a measure of climate'* (line 140). By 'adequate length', we mean of sufficient length to enable a robust analysis over a sliding window (line 141-142); however we cannot be much more specific since the exact length inevitably depends on each record.

p. 1318, line 5: "Fig. 4 and 5 show that density of data points do not change" (sic). How do I see this in the figures? I find it hard to understand them.

Reply: We apologise for any confusion. We should have been referring to Figures 5 and 6 here; the figures have been reordered in the revised manuscript and are now are Figures 6 and 7. The density of the data points specifically refers to panel c) – this has been amended; Figure 6 (now Figure 7) panels are now also labelled a to e. Figures 6c and 7c shows the density of the data over time; this depicts how unequally spaced the data are. If the data were equally spaced, Figures 6c and 7c would depict a straight horizontal line. Figures 6c and 7c therefore show that although the data is not exactly evenly spaced, the density of the data points (how equally they are spaced) does not change significantly along the record; this is now better explained ('*In addition, since time series analysis methods require interpolation to equidistant data points, a relative constant density of data points is important, so that the interpolation does not skew the data. The speleothem $\delta^{18}O$ records that we have selected fulfil these criteria, as described in more detail in section 2.1*'; lines 142-145; line 154).

Tipping point analysis

p. 1318, line 18: "A sensitivity analysis was undertaken...". Is this Fig. 7? Then why not refer to it?

Reply: This did indeed refer to Figure 7; we have updated the revised manuscript and re-ordered the figures; this is now referred in the manuscript as Figure 5 (line 359).

p. 1318, line 20-27: I suggest to move such general explanations to the introduction.

Reply: As suggested by Reviewer #3, we have reordered the methods section and instead separate a general explanation of tipping points and the detailed method that we use in our paper. We believe that this makes the manuscript substantially clearer. The introduction now includes a sub-section on *'Detecting early warning signals'* (lines 85-104).

p. 1319, line 1-4: Why is this technical discussion relevant in this context?

Reply: We feel that it is important and relevant to at least briefly highlight that there is some dispute regarding whether autocorrelation and variance should increase together or not. Our substantial restructuring provides additional context for this particular point (now within the *'Detecting early warning signals'* sub-section; lines 96-99). This technical discussion also provides context for the discussion of the proportional positive trends in autocorrelation and variance in both autocorrelation and variance in the Results section (lines 383-385).

Non-stationary potential analysis

I don't clearly see from the paper how the parameters of the model are estimated. Is this estimate unique (including the noise level), and what are the uncertainties? It could also become clearer here why the potential model is used at all.

Reply: The parameters of the potential model are estimated according to maximum likelihood. The procedure is now described in more detail in the revised manuscript (lines 221-290). The parameter estimates and the noise level are unique and the uncertainties are very small.

p. 1321, line 1-15: These steps are not easy to follow and I find them too vague. For example, "we manipulated the noise level", "we linearized the solar insolation", "the same iteration of the model was used", ... I also cannot follow the argument why different sampling steps of the data are necessary.

Reply: The different sampling steps are necessary to investigate their effect on the indicators of critical slowing down. There has been little discussion of the importance of the sampling steps of palaeoclimate data; this paper presents the first examples of how autocorrelation and variance are affected by changing the sampling step. In particular, the memory of the system (measured by autocorrelation) is less represented under sparser sampling. The fact that the same iteration of the model is used is important since this eliminates noise as a factor in the sampling step changes. We have changed "we manipulated the noise level" to *"we manipulated the noise level of the model by altering the amplitude of the stochastic forcing (σ in Equation 1)"* (lines 318-319). In terms of the linearization of the solar forcing, we have added a sentence to explain this: "*This approach was preferred rather than using a sinusoidal forcing since early warning signals are known to work most effectively when there is a constant increase in the forcing*" (lines 313-315).

Results and discussion

p. 1321, line 22: "a ... potential model was fitted". How? And how was it "modulated by the solar forcing"?

Reply: The potential model is now explained in more detail in the revised manuscript (lines 221-290).

p. 1322, line 1-5: Do these clear trends in autocorrelation and variance concern the artificial time series or the record? I suggest to make this distinction clear every time such trends are mentioned because I consider it important for the conclusions we can draw from this study.

Reply: We agree that it is important to make this distinction clear; in this particular case the sentence directly refers to the Sanbao Cave record. When we use the phrase the Sanbao cave record, this means that we are referring to the palaeoclimate speleothem data. When we refer to the model simulations, we are referring to the data derived from our model. We have ensured that we are clear in this regard in the revised manuscript (helped also by the restructuring of the manuscript).

p. 1322, line 27-29: "To help interpret these results we applied the potential model...", "explaining the high degree of synchroneity between the transitions and solar forcing". I find it impossible to judge if this is really a confirmation of a hypothesis or just the result of how the model was tuned, especially because not much details are provided on the tuning. How hard would it be for the potential model to clearly contradict the bifurcation hypothesis? I think that these aspects are probably the most important to interpret the results of the study and should be made much clearer.

Reply: The rationale, construction and estimation of the potential model are now explained in more detail. The model does provide a test between alternative mechanisms.

p. 1323, line 3-4: "There are instances when bifurcations are not preceded by slowing down". This should be explained more precisely as it seems in conflict with what is stated in the introduction.

Reply: We agree that this wording could be unclear. We have amended this to *'there are instances when critical slowing down cannot be detected/recorded prior to a bifurcation'* (lines 491-492). As with most statistical techniques there are a number of circumstances when the theory does not always tie with reality. Although as stated in the introduction, critical slowing down theoretically precedes a bifurcation, there are indeed some occasions when this critical slowing down is not recorded in the data. There can be many reasons for this, including a high noise level, and an insufficient sampling resolution. We have explained this more precisely in the revised manuscript (lines 491-496).

p. 1324, line 3-4: The fact that palaeodata often has insufficient resolution for statistics like "early warnings" is a somewhat trivial remark and in my eyes no specific result of this paper.

Reply: The tipping point literature rarely discusses data resolution as an important aspect of early warning signals, perhaps largely because the majority of the tipping point literature analyses data from models or observational data, which is generally high resolution. We feel that although to a degree this is to be expected, our results actually illustrate how data resolution changes will affect the indicators of critical slowing down, rather than an arbitrary discussion of the limitations of resolution. We believe that highlighting this point will help to inform discussions of the limitations of the early warning signals, particularly when working with palaeoclimate data.

p. 1324, line 15 - end of section: It would be interesting to know how these hypotheses relate to the bifurcation hypothesis? Do they exclude each other, i.e. could this represent an alternative hypothesis to the authors' bifurcation scenario? I think these possibilities could be explained right away in the introduction instead in the very end of the paper. How should we proceed to eliminate some of the possible explanations and do the authors suggest that early warnings can play a role?

Reply: We fear the reviewer may have misunderstood us here. These hypotheses relate to possible reasons why the bifurcation is detected during termination II. They are not alternative hypotheses to bifurcation. The key point here is during earlier bifurcations no early warning signals were detected and we discuss here possible reasons why this might be so.

Conclusions

- "We detect a fold bifurcation structure... in data". I do not agree that this is what the authors do. As I understand their paper, they look for (but hardly find) indicators of slowing down in the data. If there were such indicators, how do the authors know they result from slowing down, and why must it be due to a fold bifurcation?

Reply: The fold bifurcation structure is detected by means of the potential model. We agree that slowing down is not necessarily linked to a fold bifurcation; it may also be associated to other bifurcation types.

- "Our results have important implications..." Which implications?

Reply: We have elaborated on this sentence to be clearer about the implications: *"Our results have important implications for identifying early warning signals in other natural archives, such as the importance of sampling resolution and the background state of the climate system (full glacial versus* *termination)."* (line 543-545). At present, these aspects are overlooked, and we feel that this is an important aspect to highlight in the conclusions.

- "a failure to identify slowing down does not preclude a bifurcation". Given the low resolution of the data this is a somewhat trivial statement. I suggest to highlight in the conclusions what the results mean for the potential mechanism of the abrupt shifts.

Reply: We agree with the reviewer here and have revised this section to change the implications (lines 543-549), as described above to highlight the significance of the background climate state; the significance of which previous work has not identified.

Figures and References - The Figures do not seem to be cited in order.

Reply: We have ensured that the figures are cited in order in the revised manuscript.

I suggest to reduce the number of figures. For example I wonder if all panels in Fig. 5 and 6 are needed. Also, it is not always clear to me what they show. What does the density data in Fig. 5 and 6 show and mean?

Reply: Whilst we agree that there are a large number of figures, we believe that these help to take the reader through our results. We have reordered the figures, which we believe now vastly improves the clarity, and explained each figure in more detail (e.g. lines 356-361, lines 379-387, lines 398-402, lines 414-422, lines 435-439, lines 452-456, lines 463-470). The density data in Figure 5 and 6 (now 6 and 7) demonstrate the comparable sampling resolution across the sequences, stressing the absence of early warning signals is not an artefact of the data. However, to help slightly with the reduction of figures we have removed the lower panels from Figure 11, as these results are easily explained in the text, and merged Figures 8 and 9 (now Figure 5) to remove unnecessary duplication.

How are the p-values in Fig. 5 and 6 calculated? This seems to be some kind of test result (implicitly mentioned on p. 1319, line 5-6?; p. 1322, line 15-17?), though at odds with the approach of the histograms in Fig. 8 and 9. As the analysis is about autocorrelation in the data, it seems contradictory to use a test, which assumes independent data points, but the authors do not comment on this.

Reply: The p-values are calculated as was discussed on p.1319 and p.1322; however we did not refer explicitly to p-values in this description; we have amended this in the revised manuscript to increase clarity (now lines 200-211). The p-values themselves do not refer to autocorrelation directly; they are based on the Kendall tau value of the trend in autocorrelation over 1000 realisations, as displayed in the histograms in Figures 8 and 9 (now Figure 5). This method has been used in several papers; we also include citations to these papers (e.g. Dakos et al. 2012) in our further explanation: '*This method for assessing significance of the results is based on Dakos et al. (2012a)…*' (lines 202-203).

The references mostly consist of very recent papers but sometimes ignore the original work. I suggest to also give credit to the more original papers. For example, the Levermann (2009) model seems to be identical to the more often cited Schewe et al. (2012) model. Also, the effect of slowing down was first introduced to climate research by Kleinen et al. (2003) and Held and Kleinen (2004). However, only the more recent work by Dakos, Lenton and Scheffer is cited.
Held, H.; Kleinen, T. (2004): Detection of climate system bifurcations by degenerate fingerprinting. Geophysical Research Letters, 31, L23207.
Kleinen, T., H. Held, and G. Petschel-Held (2003), The potential role of spectral properties in detecting thresholds in the Earth System: Application to the thermohaline circulation, Ocean Dyn., 53, 53– 63.

Reply: We have included citations to the Held and Kleinen (2004) and Kleinen et al. (2003) papers to acknowledge this original work in addition to the more recent papers (line 93). We do cite Levemann et al. (2009); however we tend to cite Schewe et al. (2012) more often due to the advances that this paper made to Levermann (2009) in terms of the application of their model to speleothem data, and the notion of a 'critical humidity threshold'. However, we have added a sentence to increase clarity about the Levermann/Zickfeld/Schewe papers: '*A minimum conceptual model of the East Asian Summer Monsoon developed by Zickfeld et al. (2005), stripped down by Levermann et al. (2009) and updated by Schewe et al. (2012), shows a non-linear solution structure…*' (lines 62-66).

Review #2

Review of Early warnings and missed alarms for abrupt monsoon transitions by Thomas et al. This review is influenced by the review of anonymous reviewer 1. I basically agree with his/her comments. The paper reflects a major technical effort, addresses an interesting topic and produces valuable results. What I miss is an overall critical attitude towards results and methods used from the authors. For instance, fig. 3a shows a non-Gaussian distribution. I doubt whether it is really bimodal and not just skewed. The authors could have used the Dip-test of Unimodality (or another suited test) to check whether this is really true. I am not a fan of potential well analysis. For instance, if there is just one equilibrium, but the system is subject to a large excursion from this equilibrium (due to enhanced noise or a transient perturbation in the forcing), the potential well analysis will identify two stable states. It assumes that any form of multimodality is associated with multiple equilibria, which is not necessarily the case. What if sigma changes or alpha (Eqs on line 8 and 12 of page 1320)? The ESW for this potential switch at 129 ka looks convincing. But the discussion on missed alarms seems somewhat biased. Could it also be that the EWS at 129 ka is a false alarm iso the absence of EWS at other events being missed alarms? In summary, the ms is unbalanced. Section 2.1 starts with "To test the proposed conceptual model of Schewe et al." The ms reads too much as an attempt to prove the model is right and not really investigates the alternative of it being wrong. I recommend a rewrite towards a more balanced interpretation of the proxy record.

Reply: We thank the reviewer for their constructive review of our manuscript. Line numbering refers to the revised manuscript.

Major changes:

- Altered the abstract to reflect the new structure of the manuscript.
- Added a clearer 'Aims' section.
- Provided more detail on the potential model.
- Altered the structure, separating the Results and Discussion sections and ensuring a consistent structure in the added sub-sections throughout the manuscript.
- The manuscript now follows a more logical format, with tipping point analysis of the entire speleothem sequence followed by the potential analysis results.
- Reordered the figures and added a paragraph of text to explain each figure sequentially.

There may have been some confusion in the previous draft of the manuscript regarding the aim of this study. We have now revised the text to read: 'The aim of this study was twofold: (1) to test whether shifts in the EASM during the penultimate glacial cycle (Marine Isotope Stage 6) are consistent with bifurcational tipping points, and (2) if so, is it possible to detect associated early warning signals.'

The issues raised by Reviewer #1 that Reviewer #2 refers to are addressed to the author response to Reviewer #1. Further comments are made below.

The histogram in Figure 3a is used as a first pass justification of why we believe that the EASM may be bimodal. We then apply more sophisticated techniques such as our potential model (as shown in Figure 3b and 3c). However, the Dip-test of Unimodality is a sensible test to use in this case; we have applied this test and indeed find that the null hypothesis that the data is unimodal is rejected, and thus that the data is at least bimodal (dip statistic D=0.018, p=0.0063). We thank the reviewer for this suggestion and have added this analysis to the revised manuscript (lines 170-173, lines 294-296).

There is a sound theoretical basis for potential well analysis, as discussed in some of the papers we reference such as Livina et al. (2010). The potential model is not built in a way that it necessarily exhibits bifurcations and hysteresis behaviour. It also has the possibility of two states always being available and the transitions being noise-induced with or without stochastic resonance. The parameter estimation reveals which mechanism is better supported by the data; the parameters of the potential model are estimated according to maximum likelihood. It is certainly true that the non-dimensional Langevin equation is an extremely simple skeleton model. The palaeoclimatic record results from a multitude of complex processes and cannot be expected to exactly be a realisation of such a simple model. Nevertheless, the potential model allows to test basic mechanisms such as directly forced versus noise-induced transitions. The procedure is now described in more detail in the revised manuscript (lines 221-290).

A new sub-section entitled 'Assessing significance' (lines 199-219) has been added, describing our thorough significance analysis. This technique uses surrogate data to determine whether the results we obtain could be due to chance and are likely false positives. We also discuss the possibility of type 1 and type 2 errors in the introduction (lines 106-114), however, to ensure a non-biased assessment we have added to the discussion the possibility that the critical slowing down signal at termination II is the result of a false positive, though note that: *'Type I errors are potentially easier to guard against by employing strict protocols by which to reject a null hypothesis'* (line 113-114).

Anonymous Referee #3

Received and published: 21 May 2015

Review of "Early warnings and missed alarms for abrupt monsoon transitions" by Z. A. Thomas, F. Kwasniok, C. A. Boulton, P. M. Cox, R. T. Jones, T. M. Lenton, and C. S. M. Turney.

In their manuscript, the authors present and discuss the application of two methods for the analysis of time series in nonlinear dynamical systems to palaeorecords of the East Asian Summer Monsoon. The authors hypothesize that there is a bifurcation in the monsoon system and attempt to detect critical slowing down in the time series data as an indicator for such a bifurcation. In addition they apply potential analysis to approximate the system. The authors report that they find critical slowing down for one case of an abrupt monsoon transition, but not for other instances. Overall I found the manuscript highly interesting and important in the subject matter, but not convincing in presentation. The presentation needs major improvements before being acceptable for publication in cp. I recommend major revisions before publication, though a rejection might also be warranted.

Reply: We thank the reviewer for their helpful comments. We are pleased to hear that the manuscript is found to be highly interesting and important in the subject matter. We believe that the issues that the reviewer has raised are generally straightforward to address satisfactorily, and we have substantially revised the manuscript to this effect. Line numbering refers to the revised manuscript.

Major changes:

- Altered the abstract to reflect the new structure of the manuscript.
- Added a clearer 'Aims' section.
- Provided more detail on the potential model.
- Altered the structure, separating the Results and Discussion sections and ensuring a consistent structure in the added sub-sections throughout the manuscript.
- The manuscript now follows a more logical format, with tipping point analysis of the entire speleothem sequence followed by the potential analysis results.
- Reordered the figures and added a paragraph of text to explain each figure sequentially.

Generally the manuscript is lacking clarity, on both the macro and the micro level. On the macro level, it is unclear to me, what the take-home message from the manuscript is. Do the authors want to test the

Schewe/Levermann model and confront it with data? This is indicated in the abstract and in sec. 2.1, but is not reflected in the conclusions. Or do the authors just want to test the palaeodata for early warning signals (EWS)? The main conclusion seems to be that the data is not of sufficiently high resolution, a rather weak statement, and more or less trivial. Are there other conclusions than too low a resolution of the data? On the micro level, the methodology is not clearly described in all respects, and most figures are described only superficially, with discussion of some parts of figures completely missing or lacking in depth.

Reply: We have restructured the revised manuscript, and added sub-headings to help guide the reader through the paper. We have clarified the aims and structure of the manuscript, which we hope addresses the concerns raised (e.g. lines 78-83: '*The aim of this study was twofold: (1) to test whether shifts in the EASM during the penultimate glacial cycle (Marine Isotope Stage 6) are consistent with bifurcational tipping points, and (2) if so, is it possible to detect associated early warning signals. To achieve this, we analyse two d^{18}O speleothem records from China, and construct a simple model that we derive directly from this data to test whether we can detect early warning signals of these transitions.')* We believe that our conclusions go further than simply saying that the resolution of the speleothem data is too low to consistently detected early warning signals. Firstly, our study finds that the system is bistable, with a strong regime and a weak regime, separated by a fold bifurcation. We then show that early warning signals can be detected in this data provided that the noise level and resolution are low enough. Crucially, we observe that the detection of critical slowing down is only detected during termination II. In contrast, during the glacial period no statistically significant critical slow down is detected. We speculate this difference is due to the change in the background state of the climate, causing a different response of the monsoon. Please refer to comments below regarding specific issues with some of the figure legends.

In the abstract, the authors write about bifurcations in the monsoon systems being a hypothesis, but in the text this hypothesis (and thereby the applicability of the Schewe/Levermann model) seems to be taken as a given, though it needs to be evaluated critically. This lack of a critical look at basic assumptions in their approaches is a general shortcoming of the manuscript.

Reply: We have clarified the aims of this study (see above for further details).

Unfortunately the text seems to have been written rather hastily. This is certainly reflected in the ordering and referencing of the figures: Figures 5 and 6 are referenced before figures 3 and 4 (also the numbers are wrong in the text: Page 1318, line 5 references Figs. 4 and 5, though 5 and 6 are meant). In addition, figure 7 is never referenced at all, though the reference on page 1322, line 10, could mean figure 7 and not figure 8, as written in the text.

Reply: We apologise for any confusion. During the restructuring of the manuscript we reordered the figures, and have updated the numbers accordingly.

Further, section 2.2 introduces autocorrelation and variance as EWS, never mentioning AR(1), though later in text and figures, AR(1) and autocorrelation seem to be exchanged randomly. For example Fig. 5c shows the AR(1), also labelled as such in the legend, while the corresponding text on page 1322, line 3 mentions autocorrelation. Figures 7, 8, and 9 then use autocorrelation, while figures 10 and 12 use AR(1). Figure 11 is even more striking, since it shows histogram plots for AR(1) (11b) and autocorrelation (11c). I would suggest the authors clarify whether they discuss ACF or AR(1) and redo all figures to make sure that they are consistent in their usage.

Reply: We apologise for any confusion and have amended the text and the figures to refer only to autocorrelation.

Some more specific points:

Abstract

Page 1314, line 9-10: how do you derive a model simulation from data? I would suggest a reordering of the sentence: . . . and in multiple simulations with a model derived from the data.

Reply: We have reworded this (line 25).

Page 1314, line 10-11: "We find hysteresis behaviour in our model with transitions directly forced by solar insolation." This is a trivial statement, since the model was constructed to show just this behaviour. Therefore this is not a finding, which is implied by the sentence, and the fact that this was by construction should be mentioned.

Reply: The model is not constructed to necessarily show hysteresis behaviour and directly forced transitions. It also has the possibility of noise-induced transitions with or without stochastic resonance. This is now made clear in the revised manuscript (lines 221-290).

Section 2.1
Page 1318, lines 1-7, starting at "Tipping point analysis..." This section is placed badly: The first part up to line 5 ("is important.") would fit better in section 2.2, while the last sentence is already a result and should be moved to the results section.
Also, page 1318, line 5 references Figs. 4 and 5, though 5 and 6 are meant.

Reply: We agree that a reordering is beneficial and have reordered the methods section to ensure a more appropriate order, and added sub-headings. We include an introductory sentence to introduce tipping point analysis (lines 86-89). We have moved the parts that are more suited to section 2.2 there (lines 179-197). Although we agree that the last sentence is indeed a result of sorts, it is also highly relevant for the methods section since it is necessary to know this result before proceeding with the rest of the analysis; if this result was different, a different pre-processing would be necessary. Errors in the figure labelling have been rectified.

Section 2.2
Generally, I would suggest a reordering of the section, since the authors mix general things about tipping point analysis and specifics of the analysis they performed. Therefore the part starting on page 1318, line 20 "Autocorrelation and variance..." and ending on page 1319, line 4, should be moved to the beginning of the section. This way general points about the technique and specific application issues are separated.

Reply: We agree that this is a suitable way of rearranging. We have reordered as suggested in the revised manuscript.

I would also like to see more discussion of what constitutes a valid early warning signal, and what doesn't – part of the legend of Fig. 10 (increasing trend, as opposed to absolute value), as well as the sentence on page 1321, lines 10-12 ("Importantly it is ... signals detect."), should be moved to this place, where they make more sense, and be elaborated upon. In addition, this section mentions only autocorrelation and variance as EWS, but both in the text and in the figures the AR(1) also appears, which is never mentioned in section 2.2.

Reply: We have moved the information that was in the Figure 10 legend to Section 2.2 (lines 99-101). We have also added a discussion of false positives and negatives (lines 106-114), as well as a section on '*Assessing significance*' (lines 199-219). As mentioned above, we have amended the revised manuscript to ensure consistent nomenclature.

A further point: Page 1318, line 10: "carried out during each stable period (determined by deviation from the mean)" – I don't understand this. How exactly do the authors determine the stable periods?

Reply: Stable periods were initially identified visually and confirmed using by subsequent analysis using a climate regime detector method described by Rodionov (2004).

Results section

Page 1322, line 10: You reference Fig. 8 here. Do you mean figure 7? That would make more sense.

Reply: Yes, we did mean Figure 7; we have now restructured the manuscript and it is now Figure 5.

Page 1322, lines 25-26, as well as fig. 10: Why is there no clear evidence of critical slowing down? What is clear evidence should have been described in section 2.2, without that description this point is unclear. It is also unclear, why you reject the transition at 200 ka, which shows trends in both ACF and VAR.

Reply: On reflection we agree that our 'clear evidence of critical slowing down' is not explained as fully as necessary. Our selection criteria for whether these trends are significant are based on the relationship to the surrogate time series. If the Kendall tau value falls beyond the 90^{th} percentile of the histogram generated by the surrogate series then we deem this significant (p=0.1). We have updated Figure 8 to include the Kendall tau values for each tipping point analysis of the SB11 speleothem record. This now shows that only the termination at 129 ka BP gives an autocorrelation and variance Kendall tau value beyond the 90^{th} percentile from the surrogate time series. However, in terms of the wider tipping point literature, this is probably the most selective criteria – many papers simply link a simple visual trend as an indicator of critical slowing down. We have added a section to methods (*'2.3.1. Assessing significance',* lines 199-219) adapted the discussion of our results to reflect this.

Related to that: Figure 10, legend (p. 1339), lines 4-5: this sentence doesn't make sense to me: You claim that no values are annotated, though there are values on the y-axis of the figures. Also the second part of the sentence, where the authors clarify that it's the trend and not the absolute values that indicate the critical slowing down, is important enough that it should appear in section 2.2 and not just in the figure legend.
Figure 10, legend (p. 1339), lines 5-7: This sentence doesn't make sense, either. There is no colour legend in the figure!
Furthermore, the axis label refers to an "AR(1) indicator", while the figure legend mentions autocorrelation. This needs to be corrected.

Reply: We apologise for the confusing figure legend here; we have amended to remove the reference to the colour legend, and correct the annotation statement (now Figure 4, line 364). As also suggested by Reviewer #1, we have moved the statement about the trend versus the absolute values in the main text rather than the legend (line 100). Again, we have corrected the AR(1)/autocorrelation inconsistency.

Potential model (discussion on pages 1322-1323)
The authors construct a model of the monsoon transitions from the Langevin equation and a potential function they derived from the proxy-data in combination with a timedependent term, which is a function of solar insolation. Looking at Fig. 11a, this model seems less than convincing a model for the proxy time series. For one I don't see the "high degree of synchronicity between transitions and solar forcing" the authors claim (page 1322, line 29 to page 1323, line 1), if I compare insolation and proxy data. There seem to be time lags of variable length between forcing and transitions (compare insolation maxima at ~200 ka and ~175 ka or insolation minima at ~185 ka and ~140 ka), making the claimed synchronicity highly questionable. Also, the proxy timeseries seems to be at the very edge of the range of model simulations around 175 ka and 130 ka. To me this implies that the model may not be applicable to the entire proxy series (if it is applicable at all). For the paper to be more convincing, this discrepancy needs to be discussed. The authors seem to touch upon this point on page 1323, lines 9-11, where the authors mention that the model doesn't seem to fit at 129 ka, but some elaboration really is required here. For example, the applicability of the model might be questioned due to this discrepancy, either just for this time, or entirely.

Reply: It is certainly true that the non-dimensional Langevin equation is an extremely simple skeleton model. The palaeoclimatic record results from a multitude of complex processes and cannot be expected to exactly be a realisation of such a simple model. Nevertheless, the potential model allows to test basic mechanisms such as directly forced versus noise-induced transitions. As noted by the reviewer, we do touch upon the fact that the model simulations follow the speleothem data for all bar the transition at 129 ka, and further on in the manuscript we discuss possible reasons for this (see discussion regarding the weak monsoon interval at termination 2). More detail on the potential model has been added to the revised manuscript (lines 221-290).

Furthermore the search for early-warning-signals (EWS) in the model realisations discussed on page 1323, lines 12-14, is not convincingly explained. How were the histograms in Fig. 11 b-d actually derived? How does one interpret these? This does not become clear from either text or figure.

Reply: The methods used here are explained in the methods section, however we agree it would be useful to recap here and briefly explain this again. The explanation of how the histograms are derived is found in the methods section as well (p1319 lines 8-17). The histograms are derived from tipping point analysis of surrogate time series generated from 1000 randomisations of the original data. The Kendall tau values for autocorrelation and variance from these 1000 randomisations are plotted as histograms.

Page 1324, line 18: A new paragraph might be justified here. The discussion of alternate forcing mechanisms is not sufficiently motivated and the connection to the next paragraph. The WMI may play a role here, but the discussion in its present form doesn't make much sense.

Reply: As discussed above, the fact that the model simulations do not seem to fit the palaeoclimate data at 129 ka BP motivates the discussion of alternate forcing mechanisms. We have elaborated further here on possible mechanisms for why this is the case (and, inherently, why critical slowing down may be detected at this time) (lines 501-523).

With regard to the conclusions, I suggest a complete rewrite after the rest of the paper has been redone. The Schewe/Levermann model needs to be touched upon, after having been introduced in the abstract, and clear take-home messages need to be communicated.

Reply: We have substantially revised the manuscript and as a result the Schewe/Levermann model is not now explicitly introduced in the abstract. We have added a section in the introduction to introduce the Schewe/Levermann model (lines 62-76). We have also re-written the conclusions, and believe that a clearer take home message is now explicitly stated in the conclusions, with the structure of the conclusions now mirroring both the abstract and the results/discussion.

Is there a reference for Figure 2? It seems unlikely that the authors drew the map themselves. There might also be copyright issues involved...

Reply: Figure 2 was drawn by the Exeter University drawing office so there are no copyright issues. We have included this information in the acknowledgements (lines 706-707).

Early warnings and missed alarms for abrupt monsoon transitions

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Abstract

Palaeo-records from China demonstrate that the East Asian Summer Monsoon (EASM) is dominated by abrupt and large magnitude monsoon shifts on millennial timescales, switching between periods of high and weak monsoon rains. It has been hypothesised that over these timescales, the EASM exhibits two stable states with bifurcation-type tipping points between them. Here we test this hypothesis by looking for early warning signals of past bifurcations in speleothem $\delta^{18}O$ records from Sanbao Cave and Hulu Cave, China, spanning the penultimate glacial cycle. We find that although there are increases in both autocorrelation and variance preceding some of the monsoon transitions during this period, it is only immediately prior to the abrupt monsoon shift at the penultimate deglaciation (Termination II) that statistically significant increases are detected. To supplement our data analysis, we produce and analyse multiple model simulations that we derive from these

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data. We find hysteresis behaviour in our model simulations with transitions directly forced by solar insolation. However, signals of critical slowing down, which occur on the approach to a bifurcation, are only detectable in the model simulations when the change in system stability is sufficiently slow to be detected by the sampling resolution of the dataset. This raises the possibility that the early warning ‘alarms’ were missed in the speleothem data over the period 224-150 ka BP and it was only at the monsoon termination that the change in the system stability was sufficiently slow to detect early warning signals.

Keywords: Speleothem, monsoon, bifurcation, early warning signals, tipping point

1. Introduction

The Asian Summer Monsoon directly influences over 60% of the world’s population (Wu et al., 2012) and yet the drivers of past and future variability remain highly uncertain (Levermann et al., 2009; Zickfeld et al., 2005). Evidence based on radiometrically-dated speleothem records of past monsoon behaviour from East Asia (Yuan et al., 2004) suggests that on millennial timescales, the EASM is driven by a 23 kyr precession cycle (Kutzbach, 1981; Wang et al., 2008), but also influenced by feedbacks in sea surface temperatures and changing boundary conditions including Northern Hemisphere ice volume (An, 2000; Sun et al., 2015). The demise of Chinese dynasties have been linked to monsoon shifts over more recent millennia (Zhang et al., 2008), suggesting that any future changes, whether caused by solar or anthropogenic forcing, could have similarly devastating societal impacts. The abrupt nature of the monsoon behaviour in comparison to the sinusoidal insolation forcing strongly implies that this response is non-linear (Figure 1); whilst Northern Hemisphere Summer Insolation (NHSI) follows a quasi-sinusoidal cycle, the $\delta^{18}O$ profile in

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speleothems exhibits a step function, suggesting the presence of threshold behaviour in the monsoon system (Schewe et al., 2012).

Figure 1: (a) Northern Hemisphere Summer Insolation (NHSI) at June 30°N (Berger and Loutre, 1991) (grey), $\delta^{18}O$ speleothem data from Sanbao Cave (Wang et al., 2008) (dark blue), (b) $\delta^{18}O$ speleothem data from Hulu Cave (Wang et al., 2001); speleothem MSH (red), MSP (blue) and MSX (yellow), (c) CO_2 (ppmv) from the Antarctic Vostok ice core (Petit et al., 1999) (black), (d) $\delta^{18}O$ per mille benthic carbonate (Lisiecki and Raymo, 2005) (proxy for global ice volume) (purple).

A minimum conceptual model of the East Asian Summer Monsoon developed by Zickfeld et al. (2005), stripped down by Levermann et al. (2009) and updated by Schewe et al. (2012), shows a non-linear solution structure with thresholds for switching a monsoon system between 'on' or 'off' states that can be defined in terms of atmospheric humidity – in particular, atmospheric specific humidity over the adjacent ocean (Schewe et al., 2012). Critically, if specific humidity levels pass below a certain threshold, for instance, as a result of reduced sea surface temperatures, insufficient latent heat is produced in the atmospheric column and the monsoon fails. This moisture-advection feedback allows for the existence of two stable states, separated by a saddle-node bifurcation (Zickfeld et al., 2005) (although interestingly, the conceptual models of Levermann et al. (2009) and Schewe et al. (2012) are characterised by a single bifurcation point for switching 'off' the monsoon and an arbitrary threshold to switch it back 'on'). Crucially, the presence of a critical threshold at the transition between the strong and weak regimes of the EASM means that early warning

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signals related to 'critical slowing down' (Dakos et al., 2008; Lenton et al., 2012) could be detectable in suitable proxy records.

The aim of this study was twofold: (1) to test whether shifts in the EASM during the penultimate glacial cycle (Marine Isotope Stage 6) are consistent with bifurcational tipping points, and (2) if so, is it possible to detect associated early warning signals. To achieve this, we analyse two $\delta^{18}O$ speleothem records from China, and construct a simple model that we derive directly from this data to test whether we can detect early warning signals of these transitions.

Detecting early warning signals

We perform 'tipping point analysis' on both the $\delta^{18}O$ speleothem records and on multiple simulations derived from our model. This analysis aims to find early warning signs of impending tipping points that are characterised by a bifurcation (rather than a noise-induced or rate-induced tipping e.g. Ashwin et al. (2012)). These tipping points can be mathematically detected by looking at the pattern of fluctuations in the short-term trends of a time-series before the transition takes place. A phenomenon called 'critical slowing down' occurs on the approach to a tipping point, whereby the system takes longer to recover from small perturbations (Dakos et al., 2008; Held and Kleinen, 2004; Kleinen et al., 2003). This longer recovery rate causes the intrinsic rates of change in the system to decrease, which is detected as a short-term increase in the autocorrelation or 'memory' of the time-series (Ives, 1995), often accompanied by an increasing trend in variance (Lenton et al., 2012). While it has been theoretically established that autocorrelation and variance should both increase together (Ditlevsen and Johnsen, 2010; Thompson and Sieber, 2011), there are some factors which can negate this, discussed in detail in Dakos et al. (2012b, 2014). Importantly, it is

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the increasing trend, rather than the absolute values of the autocorrelation and variance that indicate critical slowing down. Detecting the phenomenon of critical slowing down relies on a timescale separation, whereby the timescale forcing the system is much slower than the timescale of the system's internal dynamics, which is in turn much longer than the frequency of data sampling the system (Held and Kleinen, 2004).

Missed alarms

Although efforts have been taken to reduce the chances of type I and type II errors by correct pre-processing of data e.g. (Lenton, 2011), totally eradicating the chances of false positive and false negative results remains a challenge (Dakos et al., 2014; Lenton et al., 2012; Scheffer, 2010). Type II errors or 'missed alarms', as discussed in Lenton (2011), may occur when internal noise levels are such that the system is 'tipped' into a different state prior to reaching the bifurcation point, precluding the detection of early warning signals. Type I errors are potentially easier to guard against by employing strict protocols by which to reject a null hypothesis.

Using speleothem $\delta^{18}O$ data as a proxy of past monsoon strength

Highly-resolved (~10^2 years) and precisely dated speleothem records of past monsoonal variability are well placed to test for early warning signals. The use of speleothem-based proxies to reconstruct patterns of palaeo-monsoon changes has increased rapidly over recent decades with the development of efficient sampling and dating techniques. However, there is currently some debate surrounding the climatic interpretation of Chinese speleothem $\delta^{18}O$ records (An et al., 2015), which can be influenced by competing factors that affect isotope fractionation. The oxygen isotopic composition of speleothem calcite is widely used to reconstruct palaeohydrological variations due to the premise that speleothem calcite $\delta^{18}O$

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records the stable isotopic content of precipitation, which has been shown to be inversely correlated with precipitation amount (Lee and Swann, 2010; Dansgaard, 1964), a relationship known as the 'amount effect'. Although the $\delta^{18}O$ of speleothem calcite in China has traditionally been used as a proxy for the 'amount effect' (Cheng et al., 2006, 2009; Wang, 2009; Wang et al., 2008), this has been challenged by other palaeo-wetness proxies, notably Maher (2008), who argues that speleothems may be influenced by changes in rainfall source rather than amount. The influence of the Indian Monsoon has also been proposed as an alternative cause for abrupt monsoon variations in China (Liu et al., 2006; Pausata et al., 2011), though this has since been disputed (Liu et al., 2014; Wang and Chen, 2012). Importantly, however, robust replications of the same $\delta^{18}O$ trends in speleothem records across the wider region suggest they principally represent changes in the delivery of precipitation $\delta^{18}O$ associated with the EASM (Baker et al., 2015; Cheng et al., 2009, 2012; Duan et al., 2014; Li et al., 2013; Liu et al., 2014).

Specific data requirements are necessary to search for early warning signs of tipping points in climate systems; not only does the data have to represent a measure of climate, it also must be of a sufficient length and resolution to enable the detection of critical slowing down. In addition, since time series analysis methods require interpolation to equidistant data points, a relative constant density of data points is important, so that the interpolation does not skew the data. The speleothem $\delta^{18}O$ records that we have selected fulfil these criteria, as described in more detail in section 2.1.

2. Methods

2.1 Data selection

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We used the Chinese speleothem sequences from Sanbao Cave (31°40’N, 110°26’E) (Wang et al., 2008), and Hulu Cave (32°30’N, 119°10’E) (Wang et al., 2001) to search for early warning signals. Sanbao Cave (speleothem SB11) and Hulu Cave (speleothem MSP) have two of the highest resolution chronologies in the time period of interest, with a relatively constant density of data points, providing some of the best records of Quaternary-scale monsoonal variation. Speleothem $\delta^{18}O$ offer considerable advantages for investigating past changes in the EASM: their long duration (10^3-10^4 years), high-resolution (~100 years) and precise and absolute-dated chronologies (typically 1 kyr at 1σ), make them ideal for time series analysis. Speleothem SB11 has one of the longest, continuous $\delta^{18}O$ records in China, and is the only series spanning an entire glacial cycle without using a spliced record (Wang et al. 2008). Speleothem MSP has a comparable resolution and density to SB11, though is significantly shorter. Crucially, the cave systems lie within two regionally distinct areas (Figure 2), indicating that parallel changes in $\delta^{18}O$ cannot be explained by local effects.

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Figure 2 Map showing the location of Sanbao and Hulu caves.

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2.2 Searching for bimodality

A visual inspection of a histogram of the speleothem $\delta^{18}O$ data was initially undertaken to determine whether the data are likely to be bimodal. We then applied a Dip-test of unimodality (Hartigan and Hartigan, 1985) to test whether our data is bimodal. To investigate further the dynamical origin of the modality of our data we applied non-stationary potential analysis (Kwasniok, 2013). A non-stationary potential model (discussed in more detail in section 2.4) was fitted, modulated by the solar forcing (NHSI June

30°N), covering the possibility of directly forced transitions as well as noise-induced transitions with or without stochastic resonance.

2.3 Tipping point analysis

A search for early warning signals of a bifurcation at each monsoon transition was carried out between 224-128 ka BP of the Sanbao Cave and Hulu Cave speleothem records. Stable periods of the Sanbao Cave $\delta^{18}O$ record (e.g. excluding the abrupt transitions) were initially identified visually and confirmed by subsequent analysis using a climate regime shift detection method described by Rodionov (2004). Data pre-processing involved removal of long term trends using a Gaussian kernel smoothing filter and interpolation to ensure that the data is equidistant (a necessary assumption for time-series analysis), before the trends in autocorrelation and variance (using the R functions *acf()* and *var()* respectively) are measured over a sliding window of half the data length (Lenton et al., 2012). The density of data points over time do not change significantly over either record and thus the observed trends in autocorrelation are not an artefact of the data interpolation. The smoothing bandwidth was chosen such that long-term trends were removed, without overfitting the data. A sensitivity analysis was undertaken by varying the size of the smoothing bandwidth and sliding window to ensure the results were robust over a range of parameter choices. The nonparametric Kendall's tau rank correlation coefficient was applied (Dakos et al., 2008; Kendall, 1948) to test for statistical dependence for a sequence of measurements against time, varying between +1 and -1, describing the sign and strength of any trends in autocorrelation and variance.

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2.3.1 Assessing significance

The results were tested against surrogate time series to ascertain the significance level of the results found, based on the null hypothesis that the data are generated by a stationary Gaussian linear stochastic process. This method for assessing significance of the results is based on Dakos et al. (2012a). The surrogate time series were generated by randomising the original data over 1000 permutations, which is sufficient to adequately estimate the probability distribution of the null model, and destroys the memory while retaining the amplitude distribution of the original time series. The autocorrelation and variance for the original and each of the surrogate time series was computed, and the statistical significance obtained for the original data by comparing against the frequency distribution of the trend statistic (Kendall tau values of autocorrelation and variance) from the surrogate data. The 90th and 95th percentiles provided the 90% and 95% rejection thresholds (or p-values of 0.1 and 0.05) respectively. According to the fluctuation-dissipation theorem (Ditlevsen and Johnsen, 2010), both autocorrelation and variance should increase together on the approach to a bifurcation. Previous tipping point literature has often used a visual increasing trend of autocorrelation and variance as indicators of critical slowing down. Although using surrogate data allows a quantitative assessment of the significance of the results, there is no consensus on what significance level is necessary to the declare the presence of precursors of critical slowing down. To guard against type I errors, we determine for this study that ‘statistically significant’ early warning indicators occur with increases in both autocorrelation and variance with p-values > 0.1.

2.4 Non-stationary potential analysis

To supplement the analysis of the speleothem records and help interpret the results, a simple stochastic model derived directly from this data was constructed. Non-stationary potential analysis (Kwasniok, 2013, 2015) is a method for deriving from time series data a simple dynamical model which is modulated by external factors, here solar insolation. The technique allows extraction of basic dynamical mechanisms and to distinguish between competing dynamical explanations.

The dynamics of the monsoon system are conceptually described as motion in a time-dependent one-dimensional potential landscape; the influence of unresolved spatial and tem- poral scales is accounted for by stochastic noise. The governing equation is a one-dimensional non-stationary effective Langevin equation:

$$\dot{x} = -V'(x;t) + \sigma\eta \tag{1}$$

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η is a white Gaussian noise process with zero mean and unit variance, and σ is the amplitude of the stochastic forcing. The potential landscape is time-dependent, modulated by the solar insolation:

$$V(x;t) = U(x) + \gamma I(t)x \tag{2}$$

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The time-independent part of the potential is modelled by a fourth-order polynomial, allowing for possible bi-stability (Kwasniok and Lohmann, 2009):

$$U(x) = \sum_{i=1}^{4} a_i x^i \tag{3}$$

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I(t) is the insolation forcing and γ is a coupling parameter. The modulation of the potential is only in the linear term, that is, the time-independent potential system is subject to the scaled insolation forcing $\gamma I(t)$. The model variable x is identified with the speleothem record. The insolation is represented as a superposition of three main frequencies as

$$I(t) = \alpha_0 + \sum_{i=1}^{3} [\alpha_i \cos(2\pi t/T_i) + \beta_i \sin(2\pi t/T_i)] \tag{4}$$

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with time t measured in ky. The expansion coefficients α_i and β_i are determined by least-squares regression on the insolation time series over the time interval of the speleothem record. The periods T_i are found by a search over a grid with mesh size 0.5ky. They are, in order of decreasing contribution $\alpha_i^2 + \beta_i^2$, $T_1 = 23$ky, $T_2 = 19.5$ky and $T_3 = 42$ky. This yields an excellent approximation of the insolation time series over the time interval under consideration here.

The potential model incorporates and allows to distinguish between two possible scenarios: (i) In the bifurcation scenario, the monsoon transitions are directly forced by the insolation. Two states are stable in turn, one at a time. (ii) Alternatively, two stable states could be available at all times with noise-induced switching between them. The height of the potential barrier separating the two states would be modulated by the insolation, possibly giving rise to a stochastic resonance which would explain the high degree of coherence between the solar forcing and the monsoon transitions.

The shape of the potential, as well as the noise level, are estimated from the data according to the maximum likelihood principle. We take a two-step approach, combining non-stationary probability density modelling (Kwasniok, 2013) and dynamical modeling (Kwasniok, 2015). The shape of the potential is estimated from the probability density of the data. The quasi-stationary probability density of the potential model is

$$p(x;t) = Z^{-1}(t)\exp[-2V(x;t)/\sigma^2] \qquad (5)$$

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with a time-dependent normalisation constant $Z(t)$. The coefficients a_i and the coupling constant γ are estimated by maximising the likelihood function

$$L(x_1,\ldots,x_N) = \prod_{i=1}^{N} p(x_n;t_n) \qquad (6)$$

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as described in Kwasniok (2013). The size of the data set is N. This leaves the noise level undetermined as a scaling of the potential with a constant c and a simultaneous scaling of the noise variance with c keeps the quasi-stationary probability density unchanged. We set $\sigma = 1$ for the (preliminary) estimation of a_i and γ. The noise level is now determined from the dynamical likelihood function based on the time evolution of the system (Kwasniok, 2015). The Langevin equation is discretised according to the Euler-Maruyama scheme:

$$x_{n+1} = x_n - \delta t_n V'(x_n; t_n) + \sqrt{\delta t_n} \sigma \eta_n \quad (7)$$

The sampling interval of the data is $\delta t_n = t_{n+1} - t_n$. The log-likelihood function of the data is

$$l(x_1, \ldots, x_N | x_0) = -\frac{N}{2} \log 2\pi - N \log \sigma - \sum_{n=0}^{N-1} \left[\frac{1}{2} \log \delta t_n + \frac{1}{2} \frac{[x_{n+1} - x_n + \delta t_n V'(x_n; t_n)]^2}{\delta t_n \sigma^2} \right] \quad (8)$$

The scaling constant c is searched on a grid with mesh size 0.01 and the log-likelihood maximised, giving the final estimates of all parameters. Both estimation procedures are applied directly to the unevenly sampled data without any prior interpolation. We remark that the more natural and simpler approach of estimating all parameters simultaneously from the dynamical likelihood (Kwasniok, 2015) here yields a negative leading-order coefficient a_4 and thus the model cannot be integrated over a longer time period without the trajectory escaping to infinity. This possibly points at limitations in the degree of validity of the one- dimensional potential model. Palaeoclimatic records reflect a multitude of complex processes and any model as simple as eq.(1) cannot be expected to be more than a crude skeleton model. The described estimation method guarantees a positive leading-order coefficient a_4 and therefore a globally stable model.

It has been suggested that the EASM system responds specifically to 65°N 21st July insolation with a "near-zero phase lag" (Ruddiman, 2006). However, given that EASM development is affected by both remote and local insolation forcing (Liu et al., 2006), we use an insolation latitude local to the Sanbao Cave record, consistent with earlier studies

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from this and other speleothem sequences (Wang et al., 2001). Since the monthly maximum insolation shifts in time with respect to the precession parameter, the 30°N June insolation was used, though we acknowledge that the insolation changes of 65°N 21 July as used by Wang et al. (2008) are similar with regard to the timing of maxima and minima. Crucially, immediately prior to Termination II, the Chinese speleothem data (including Sanbao Cave) record a 'Weak Monsoon Interval' between 135.5 and 129 ka BP (Cheng et al., 2009), suggesting a lag of approximately 6.5 kyrs following Northern Hemisphere summer insolation (Figure 1).

Having derived a model from the data, 100 realisations were analysed to test whether early warning signals could be detected in the model output, using the methods set out in section 2.3. We initially chose the sampling resolution of the model outputs to be comparable to the speleothem data (10^2 years). Sampling the same time series at different resolutions and noise levels allows us to explore the effect of these on the early warning signals. Accordingly, the model was manipulated by changing both the noise level and sampling resolution. To enable a straightforward comparison of the rate of forcing and the sampling resolution we linearized the solar insolation using the minimum and maximum values of the solar insolation over the time span of the model (224-128 ka BP). This approach was preferred rather than using a sinusoidal forcing since early warning signals are known to

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Moved up [6]: Speleothem MSP has a comparable resolution and density to SB11, though is significantly shorter. Crucially, the cave systems lie within two regionally distinct areas (Figure 2), indicating that parallel changes in $\delta^{18}O$ cannot be explained by local effects.

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Figure 2 Map showing the location of Sanbao and Hulu caves.

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work most effectively when there is a constant increase in the forcing. To detrend the time series data, we ran the model without any external noise forcing to obtain the equilibrium solution to the system, which we then subtracted from the time series, which did include noise. In addition, we manipulated the noise level of the model by altering the amplitude of the stochastic forcing (σ in Equation 1). The time step in the series was reduced so that 6000 time points were available prior to the bifurcation and to ensure no data from beyond the tipping point was included in the analysis. Sampling the same time series at different resolutions allowed us to explore the effect of this on the early warning signals. When comparing early warning signals for differing sample steps and noise levels, the same iteration of the model was used to enable a direct comparison.

3. Results

3.1 Searching for bimodality

A histogram of $\delta^{18}O$ values suggests that there are two modes in the EASM between 224-128 ka BP, as displayed by the double peak structure in Figure 3a, supporting a number of studies that observe bimodality in tropical monsoon systems (Schewe et al., 2012; Zickfeld et al., 2005). We also apply a Dip-test of unimodality (Hartigan and Hartigan, 1985) and find that our null hypothesis of unimodality is rejected (D=0.018, p=0.0063) and thus our data is at least bimodal. To investigate further the dynamical origin of this bimodality we applied non-stationary potential analysis (Kwasniok, 2013). This showed a bi-stable structure to the EASM with hysteresis (Figure 3b, c), suggesting that abrupt monsoon transitions may involve underlying bifurcations. The monsoon transitions appear to be predominantly directly forced by the insolation. There is a phase in the middle of the transition cycle between the extrema of the insolation where two stable states are available

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at the same time but this phase is too short for noise-induced switches to play a significant role.

Figure 3 (a) Histogram showing the probability density of the speleothem data aggregated over 224-128 ka BP, (b) Bifurcation diagram obtained from potential model analysis, showing bi-stability and hysteresis. Solid black lines indicate stable states, dotted line unstable states, and dashed vertical lines the jumps between the two stable branches. Coloured vertical lines correspond to the insolation values for which the potential curve is shown in panel c; (c) Shows how the shape of the potential well changes over one transition cycle (198-175 ka BP) (green long dash = 535 W/m^2, purple short dash = 531 W/m^2, blue solid = 490 W/m^2, red dotted = 449 W/m^2) (for more details see Figure 10).

3.2 Tipping point analysis

We applied tipping point analysis on the Sanbao Cave δ^{18}O record on each section of data prior to a monsoon transition. Although autocorrelation and variance do increase prior to some of the abrupt monsoon transitions (Figure 4), these increases are not consistent through the entire record. Surrogate datasets used to test for significance of our results showed that p-values associated with these increases are never <0.1 for both autocorrelation and variance (Figure 5). Although a visual increasing trend has been used in previous literature as an indicator of critical slowing down, we choose more selective criteria to guard against the possibility of false positives.

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Figure 4 a) $\delta^{18}O$ speleothem data from Sanbao Cave (SB11) (blue line) and NHSI at July 65°N (grey line). Grey hatched areas show the sections of data selected for tipping point analysis. b) These panels show the corresponding autocorrelation and variance for each period prior to a transition.

Figure 5 Histogram showing frequency distribution of Kendall tau values from 1000 realisations of a surrogate time series model, for Sanbao Cave (a, b) and Hulu Cave (c, d) $\delta^{18}O$ data. The grey dashed lines indicate the 90% and 95% significance level and the blue and red vertical lines show the Kendall tau values for autocorrelation and variance, for each section of speleothem data analysed. The blue circle in (a) and the red circle in (b) indicate the Kendall tau values for the section of data spanning the period 150 to 129 ka BP immediately prior to Termination II.

The only section of data prior to a monsoon transition that sees p-values of <0.1 for the increases in both autocorrelation and variance is for the data spanning the period 150 to 129 ka BP in the Sanbao Cave record, before Monsoon Termination II (Figure 6). We find that the Kendall tau value for autocorrelation has a significance level of $p < 0.05$ and for variance a significance level of $p < 0.1$ (Figure 5a and 5b). These proportional positive trends in both autocorrelation and variance are consistent with critical slowing down on the approach to a bifurcation (Ditlevsen and Johnsen, 2010). Figure 6c illustrates the density of data points before and after interpolation, showing that this pre-processing is unlikely to have biased the results.

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Figure 6 Tipping Point analysis on data from Sanbao Cave (Speleothem SB11) (31°40'N, 110°26'E). (a) Data was smoothed over an appropriate bandwidth (purple line) to produce data residuals (b), and analysed over a sliding window (of size between the two grey vertical lines). The grey vertical line at 131 ka BP indicates the tipping point, and the point up to which the data is analysed. (c,d) Data density, where the black points are the original data and the pink points are the data after interpolation. (e) AR(1) values and associated Kendall tau value, and (f) displays the variance and associated Kendall tau.

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To test whether the signal is present in other EASM records, we undertook the same analysis on a second speleothem sequence (Figure 7), covering the same time period. We find that speleothem MSP from Hulu Cave (32°30'N, 119°10'E) (Wang et al., 2001) displays a comparable increase in autocorrelation and variance to speleothem SB11 from Sanbao Cave, though these do display slightly lower p-values; see Figure 5c and 5d.

Figure 7 Tipping Point analysis on data from Hulu Cave (Speleothem MSP) (32°30' N, 119°10' E) (a) Data was smoothed over an appropriate bandwidth (purple line) to produce data residuals (b), and analysed over a sliding window (of size between the two grey vertical lines). The grey vertical line at 131 kaBP indicates the tipping point, and the point up to which the data is analysed. (c, d) Data density, where the black points are the original data and the pink points are the data after interpolation. (e) Autocorrelation values and associated Kendall tau value, and (f) the variance and associated Kendall tau.

Furthermore, a sensitivity analysis was performed (results shown for data preceding the monsoon termination in both speleothem SB11 and MSP, Figure 8) to ensure that the results were robust over a range of parameters by running repeats of the analysis with a range of smoothing bandwidths used to detrend the original data (5-15% of the time series length) and sliding window sizes in which indicators are estimated (25-75% of the time series length). The colour contours show how the Kendall tau values change when using different parameter choices; for the autocorrelation at Sanbao Cave the Kendall tau values are over 0.8 for the vast majority of smoothing bandwidth and sliding window sizes (Figure 8a), indicating a robust analysis.

Figure 8 Contour plots showing a range of window and bandwidth sizes for the analysis; (a) Sanbao SB11 autocorrelation, (b) Sanbao SB11 variance, (c) Hulu MSP autocorrelation, (d) Hulu MSP variance. Black stars indicate the parameters used for the analysis in Figures 6 and 7.

3.3 Non-stationary potential analysis

To help interpret these results we applied our potential model. In the model we find transitions occur under direct solar insolation forcing when reaching the end of the stable branches, explaining the high degree of synchronicity between the transitions and solar forcing. The initial 100 realisations produced from our potential model appear broadly to follow the path of June insolation at 30°N with a small phase lag (Figure 9). The model simulations also follow the speleothem palaeodata for all but the monsoon transition at 129

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ka BP near Termination II, where the model simulations show no extended lag with respect to the insolation.

Figure 9 Probability range of 100 model simulations, with the June 30°N NHSI (in red), and the palaeodata from SB11 (in green)

No consistent early warning signals were found in the initial 100 model simulations during the period 224-128 ka BP. In order to detect critical slowing down on the approach to a bifurcation, the data must capture the gradual flattening of the potential well. We suggest that early warning signals were not detected due to a relatively fast rate of forcing compared to the sampling of the system; this comparatively poor sampling prevents the gradual flattening of the potential well from being recorded in the data; a feature common to many palaeoclimate datasets. Figure 10 illustrates the different flattening of the potential well over a normal transition cycle and over the transition cycle at the termination. There is more visible flattening in the potential at the termination, as seen in panel (c), which is thought to be due to the reduced amplitude of the solar forcing at the termination.

Figure 10 Potential analysis showing the changing shape of the potential well over (b) a normal transition cycle; and (c) the transition cycle at the termination. (Dotted lines show stages of the transition over high, medium, and low insolation values).

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To test the effect on the early warning signals of the sampling resolution of the model, we compared a range of different sampling time steps in the model (see section 2.4) measuring the Kendall tau values of autocorrelation and variance over each realisation of the model (one realisation displayed in Figure 11), which demonstrates the effects of increasing the sampling time step in the model. We found that whereas an increasing sampling time step produces a steady decrease in the Kendall tau values for autocorrelation (Figure 11b), Kendall tau values remain fairly constant for variance (Figure 11c), suggesting that the latter is not affected by time step changes. This supports the contention by Dakos et al. (2012b) that 'high resolution sampling has no effect on the estimate of variance'. In addition, we manipulated the noise level and found that decreasing the noise level by a factor of 2 was necessary to identify consistent early warning signals. This is illustrated in Figure 11a, where the grey line represents the noise level as determined by the model, which does not follow a step transition, and cannot be adequately detrended by the equation derived from the model. However, once the noise level is sufficiently reduced, early warning signals (displayed here as high Kendall tau values for autocorrelation and variance) can be detected.

Figure 11 a) Example of single realisation of the approach to a bifurcation over 4 noise levels (original noise = grey, 0.5 noise = black, 0.2 noise = blue, 0.1 noise = green), the red line is the detrending line and the grey dashed vertical line is the cut-off point where data is analysed up to; b) distribution of Kendall tau values for autocorrelation over increasing sample step; c) distribution of Kendall tau values for variance over increasing sample step.

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4. Discussion

It is important to note here that although the detection of early warning signals in time series data has been widely used for the detection of bifurcations in a range of systems (Dakos et al., 2008), there are instances when critical slowing down cannot be detected/recorded prior to a bifurcation. This can be due to external dynamics of the system, such as a high level of stochastic noise, or when there is an insufficient sampling resolution.

These results confirm that early warning signals may not be detected for bifurcations if the rate of forcing is too fast compared to the sampling rate, such that the flattening of the potential is poorly recorded in time series. 'Missed alarms' may therefore be common in palaeodata where there is an insufficient sampling resolution to detect the flattening of the potential; a high sampling resolution is thus recommended to avoid this issue. There is more flattening visible in the potential for the monsoon transition at 129 ka BP (Termination II) which is due to the reduced amplitude of the solar forcing at the termination, but it is unclear whether this is sufficient to explain the early warning signal detected in the palaeodata. We suggest that additional forcing mechanisms may be driving the termination e.g. (Caley et al., 2011) which cannot be captured by the potential model (as evidenced by the trajectory of the data falling outside the probability range of the potential model (Figure 9)).

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Deleted: bifurcations are not preceded by critical slowing down. To explore this further, we initially produced an ensemble of 100 realisations of the potential model, looking for early warning signals prior to each transition (see Methods). We chose the sampling resolution of the model outputs to be comparable to the speleothem data (10^2 years). These 100 realisations appear broadly to follow the path of June insolation at 30°N with a small phase lag (Figure 11

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Moved up [13]:). The model simulations also follow the speleothem palaeodata for all but the monsoon transition at 129 ka BP near Termination II, where the model simulations show no extended lag with respect to the insolation.

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Moved up [14]: In order to detect critical slowing down on the approach to a bifurcation, the data must capture the gradual flattening of the potential well.

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Moved up [15]: This supports the contention by Dakos et al.

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Moved up [16]: In addition, we manipulated the noise level and found that decreasing the noise level by a factor of 2 was necessary to identify consistent early warning signals.

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Moved up [17]: , where the grey line represents the noise level as determined by the model, which does not follow a step transition, and cannot be adequately detrended by the equation derived from the model. However, once the noise level is sufficiently reduced, early warning signals ... [25]

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One possible reason for the detection of a critical slowing down immediately prior to the termination (129 ka BP) is a change in the background state of the climate system. Termination II is preceded by a Weak Monsoon Interval (WMI) in the EASM at 135.5-129 ka BP (Cheng et al., 2009), characterised by the presence of a longer lag between the change in insolation and the monsoon transition. The WMI is thought to be linked to migrations in the Inter-tropical Convergence Zone (ITCZ) (Yancheva et al., 2007). Changes in the latitudinal temperature gradient (Rind, 1998) or planetary wave patterns (Wunsch, 2006) driven by continental ice volume (Cheng et al., 2009) and/or sea ice extent (Broccoli et al., 2006) have been suggested to play a role in causing this shift in the ITCZ. For instance, the cold anomaly associated with Heinrich event 11 (at 135 ka BP) has been invoked as a possible cause of the WMI, cooling the North Atlantic and shifting the Polar Front and Siberian High southwards, forcing an equatorward migration of westerly airflow across Asia (Broecker et al., 1985; Cai et al., 2015; Cheng et al., 2009). Such a scenario would have maintained a low thermal gradient between the land and sea, causing the Weak Monsoon Interval and potentially suppressing a simple insolation response. The implication is that during the earlier monsoon transitions in Stage 6, continental ice volume and/or sea-ice extent was less extensive than during the WMI, allowing the solar insolation response to dominate.

5. Conclusions

We analysed two speleothem $\delta^{18}O$ records from China over the penultimate glacial cycle as proxies for the past strength of the EASM to test whether we could detect early warning signals of the transitions between the strong and weak regimes. After determining that the data was bimodal, we derived a non-stationary potential model directly from this data

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featuring a fold bifurcation structure. We found evidence of critical slowing down before the abrupt monsoon shift at Termination II (129 ka BP) in the speleothem $\delta^{18}O$ data. However, we do not find consistent early warning signals of a bifurcation for the abrupt monsoon shifts in the period between 224-150 ka BP, which we term ‘missed alarms’. Exploration of sampling resolution from our model suggests that the absence of robust critical slowing down signals in the palaeodata is due to a combination of rapid forcing and the insufficient sampling resolution, preventing the detection of the steady flattening of the potential that occurs before a bifurcation. We also find that there is a noise threshold at which early warning signals can no longer be detected. We suggest that the early warning signal detected at Termination II in the palaeodata is likely due to the longer lag during the Weak Monsoon Interval, linked to cooling in the North Atlantic. This allows a steadier flattening of the potential associated with the stability of the EASM and thus enables the detection of critical slowing down. Our results have important implications for identifying early warning signals in other natural archives, including the importance of sampling resolution and the background state of the climate system (full glacial versus termination). In addition, it is advantageous to use archives which record multiple transitions, rather than a single shift, such as the speleothem records reported here; the detection of an early warning signal during one transition compared to previous events in the same record provides an insight into changing/additional forcing mechanisms.

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Acknowledgements

We thank Sue Rouillard from the drawing office in the Geography department at the University of Exeter for drawing Figure 2.

The data for this paper are available from the National Climate Data Centre, NOAA (SB11: http://hurricane.ncdc.noaa.gov/pls/paleox/f?p=519:1:::::P1_STUDY_ID:8641 and Hulu: http://hurricane.ncdc.noaa.gov/pls/paleox/f?p=519:1:::::P1_STUDY_ID:5426)

Competing financial interests

The authors declare no competing financial interests.

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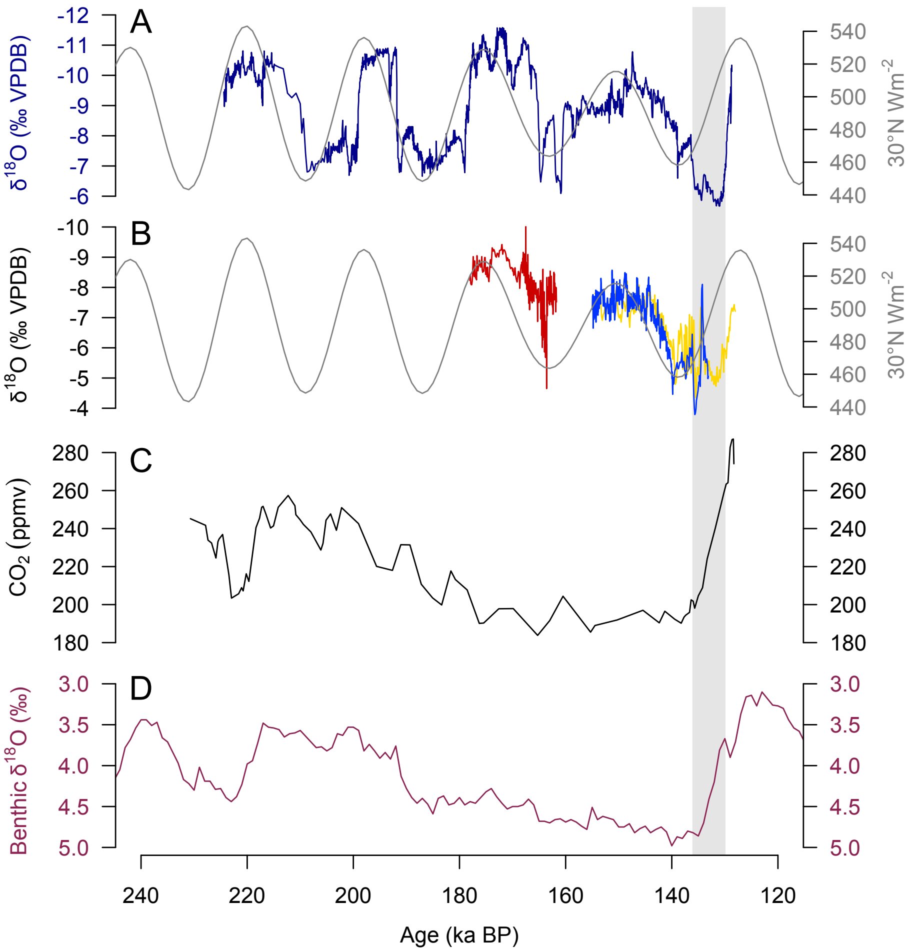

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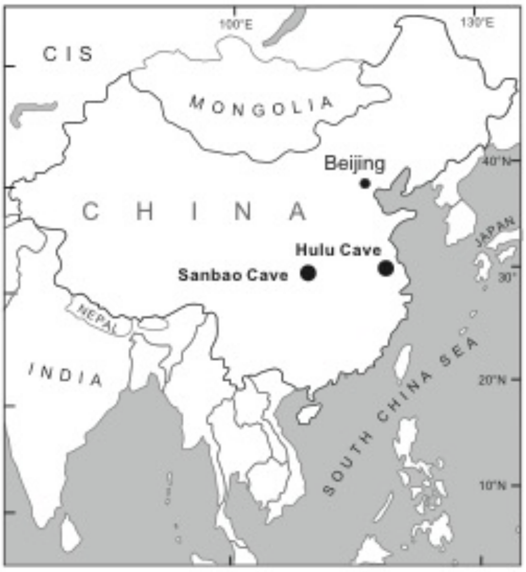

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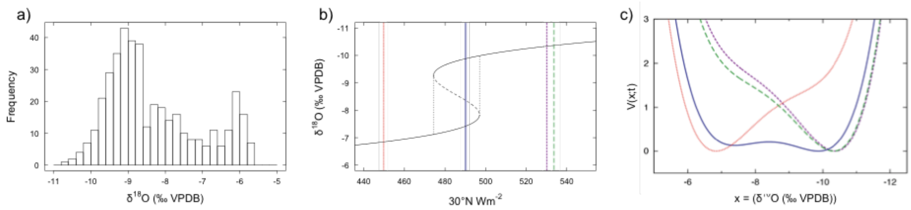

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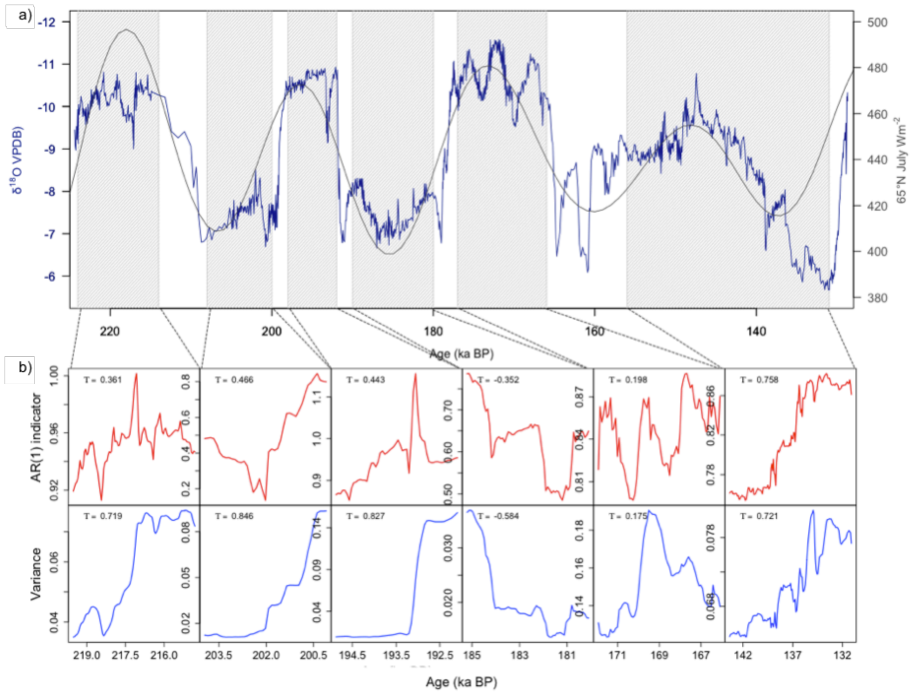

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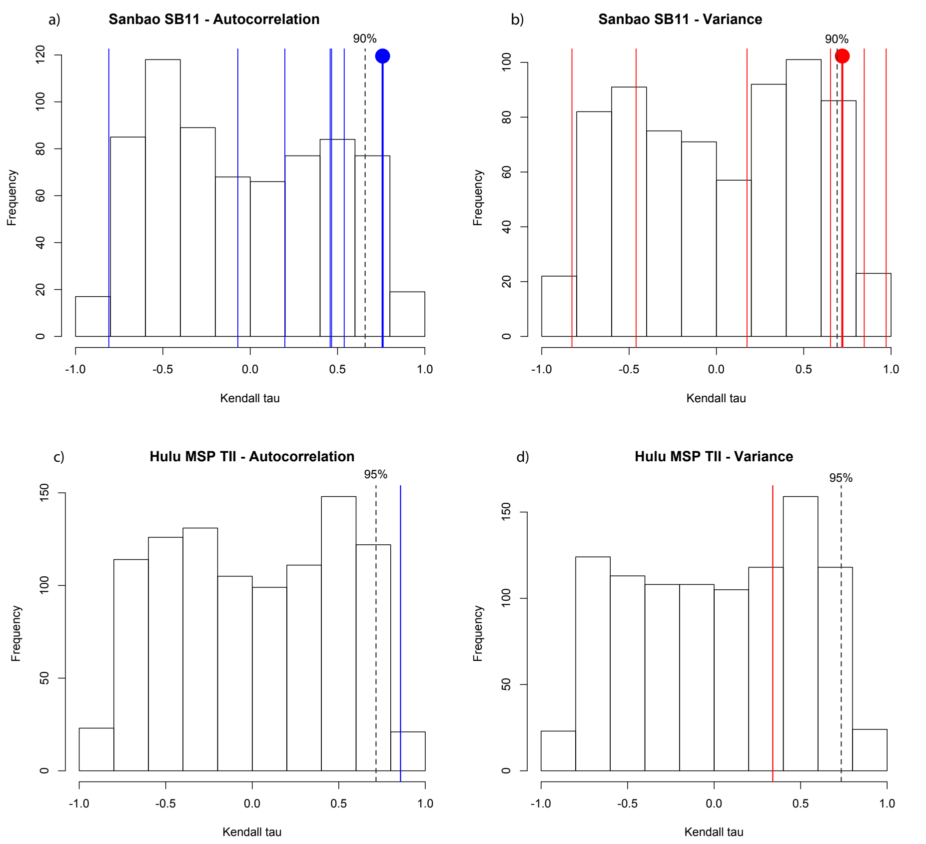

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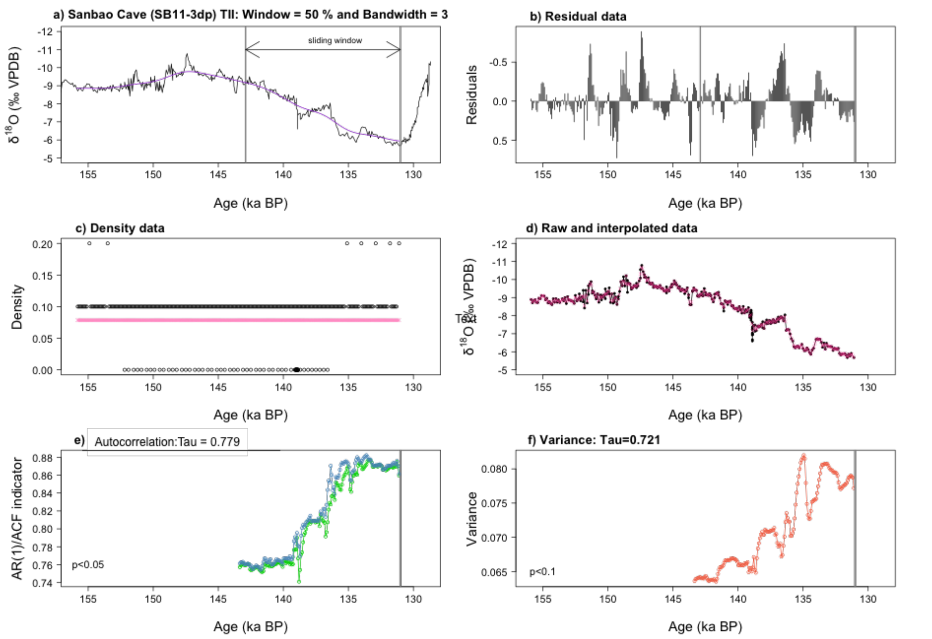

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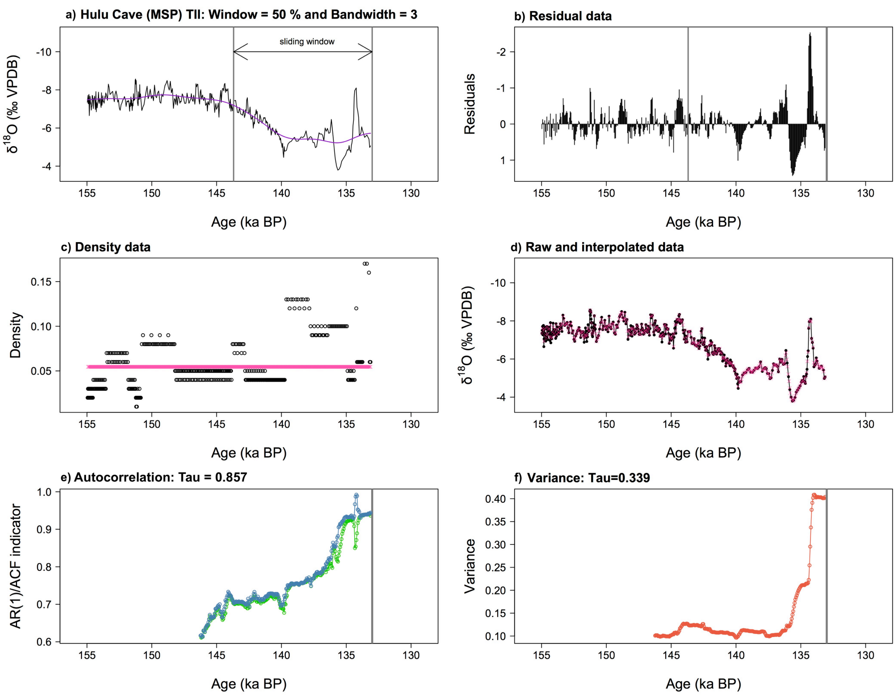
1203 

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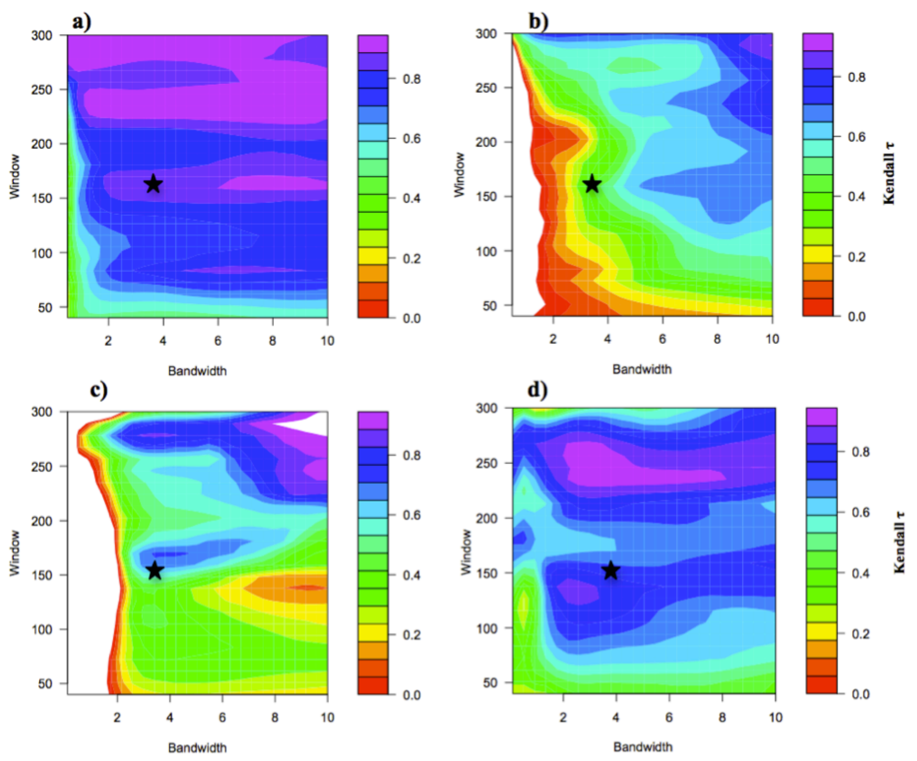

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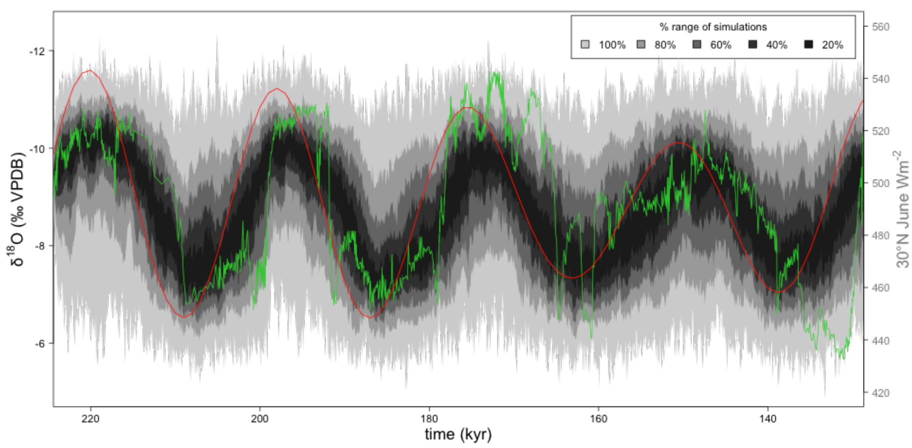

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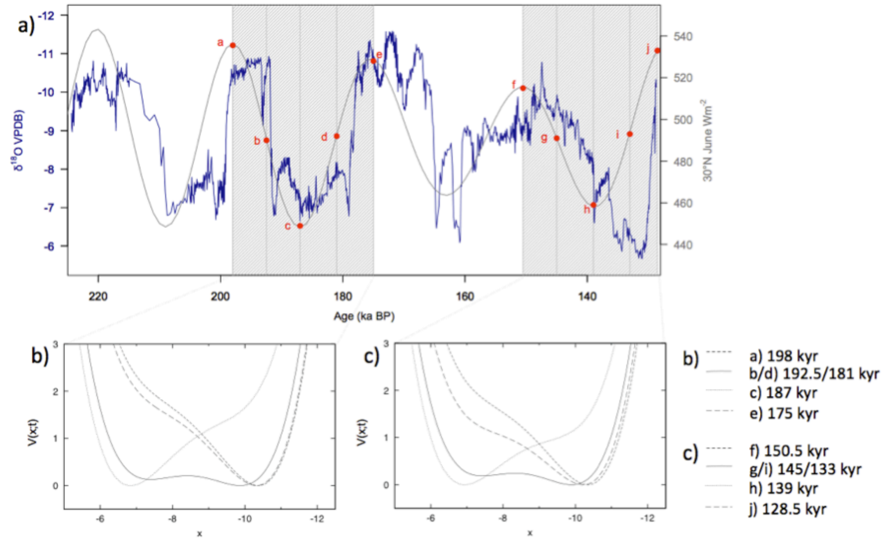

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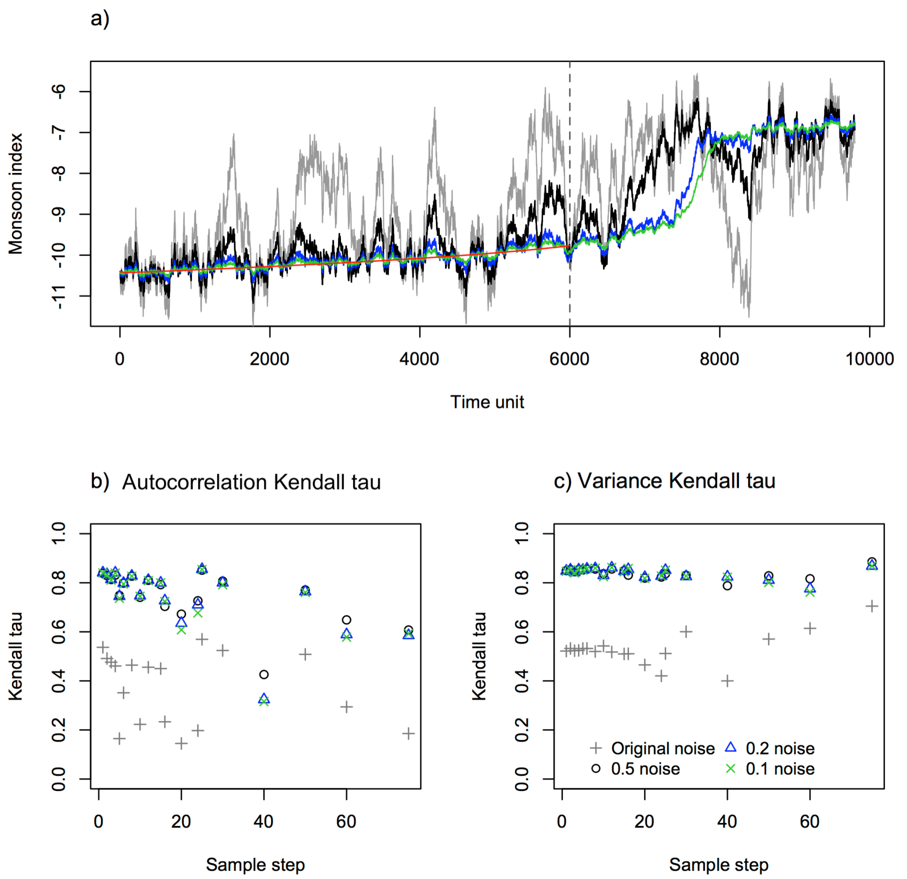

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(Dakos et al., 2014; Lenton et al., 2012; Scheffer, 2010).

Page 13: [3] Deleted **Zoe Thomas** **03/08/2015 21:59**

(Wang et al., 2001), considering both potential external and internal drivers. Some of the particular strengths of speleothem $\delta^{18}O$ as a record of past climate are their long duration (10^3-10^4 years), high-resolution and very precise and absolute-dated chronologies, making them ideal for tipping point analysis. Sanbao Cave in central China (speleothem SB11) and Hulu Cave in eastern China (speleothem MSP) have two of the highest resolution chronologies in the time period of interest, with a relatively constant density of data points, and provide some of the best records of Quaternary-scale monsoonal variation. Speleothem SB11 has one of the longest, continuous $\delta^{18}O$ records in China, with a very well constrained chronology and a temporal resolution of around 100 years (Wang et al., 2008) and is the only speleothem where analysis over an entire glacial cycle has been reported without using a spliced record.

Page 13: [4] Deleted **Zoe Thomas** **03/08/2015 21:59**

Tipping point analysis involves specific data requirements; not only does the data have to present a clear climate proxy, it also must be of an adequate length and resolution. In addition, since time series analysis methods require interpolation to equidistant data points, a relative constant density of data points is important. Figures 4 and 5 show that density of data points do not change significantly over either records, and thus the observed trends in autocorrelation are not an artefact of the data interpolation.

Page 13: [5] Deleted Zoe Thomas 03/08/2015 21:59

2.2 Tipping point analysis

A search for early warning signals of a bifurcation at each monsoon transition was carried out during each stable period (determined by deviation from the mean) between 230-128 ka BP of the Sanbao Cave speleothem record, and the shorter duration of the Hulu Cave speleothem record. Data pre-processing involved removal of long term trends using a Gaussian kernel smoothing filter and interpolation to ensure that the data is equidistant (a necessary assumption for time-series analysis), before the trends in autocorrelation and variance (using the R functions *acf()* and *var()* respectively) are measured over a sliding window of half the data length (Lenton et al., 2012).

Page 13: [6] Moved to page 8 (Move #8) Zoe Thomas 03/08/2015 21:59

The smoothing bandwidth was chosen such that long-term trends were removed, without overfitting the data. A sensitivity analysis was undertaken by varying the size of the smoothing bandwidth and sliding window to ensure the results were robust over a range of parameter choices.

Page 13: [7] Deleted Zoe Thomas 03/08/2015 21:59

Autocorrelation and variance are expected to increase on the approach to a bifurcation due to a gradual decrease in recovery rate to perturbations (Dakos et al., 2008; Lenton et al., 2012), based on the concept of critical slowing down. This phenomenon is fundamentally inherent to all bifurcational tipping points; when the system approaches a bifurcation point, the basin of attraction becomes wider and shallower, thus causing an increasingly slower characteristic return time to equilibrium (van Nes and Scheffer, 2007). This is measured through the autocorrelation or 'memory' of a time series, and variance, which tracks the distance travelled from equilibrium.

Page 13: [8] Moved to page 4 (Move #2) **Zoe Thomas** **03/08/2015 21:59**

While it has been theoretically established that autocorrelation and variance should both increase together (Ditlevsen and Johnsen, 2010; Thompson and Sieber, 2011), there are some factors which can negate this, discussed in detail in Dakos et al.

Page 13: [9] Deleted **Zoe Thomas** **03/08/2015 21:59**

(2012, 2014).

The nonparametric Kendall's tau rank correlation coefficient was applied (Dakos et al., 2008) to test for statistical dependence for a sequence of measurements against time, varying between +1 and -1, describing the sign and strength of any trends in autocorrelation and variance. In addition, the results were tested against surrogate time series to ascertain the significance level of the results found, based on the null hypothesis that the data are generated by a stationary Gaussian linear stochastic process. The surrogate time series were generated by randomising the original data over 1000 permutations, which is sufficient to adequately estimate the probability distribution of the null model, and destroys the linear correlation while retaining the amplitude distribution of the original time series. Tipping point analysis was undertaken on these permutations, and a histogram constructed from the Kendall Tau values of autocorrelation and variance. The 90^{th} and 95^{th} percentiles provided the 90% and 95% rejection thresholds respectively.

2.3 Non-stationary potential analysis

To supplement the analysis of the speleothem records and help interpret the results, a simple model derived directly from this data was constructed. Non-stationary potential analysis (Kwasniok, 2013) is a method for deriving from time series data a simple dynamical model which is modulated by external factors, here solar insolation. The dynamics of the monsoon system are conceptually described as motion in a time-dependent one-dimensional potential landscape; the influence of unresolved spatial and temporal scales is accounted for by stochastic noise. The shape of the potential as well as the noise level, are estimated from data in a maximum likelihood framework. The analysis allows for the detection of multi-stability in the system and helps pinpoint basic dynamical mechanisms, for example, directly forced versus noise-induced transitions.

Simple statistical-dynamical models modulated by external factors are derived from data according to the maximum likelihood principle. The method allows extraction of basic dynamical mechanisms and to distinguish between competing dynamical explanations. We assume here that the monsoon system is governed by the effective one-dimensional Langevin equation:

$$\dot{x} = -V'(x; t) + \sigma\eta$$

where η is a white Gaussian noise process with zero mean and unit variance, and σ is the amplitude of the stochastic forcing. The potential landscape $V(x; t)$ is time-dependent, linearly modulated by the solar insolation:

$$V(x; t) = U(x) + \alpha\, I(t)x$$

The time-independent part of the potential, U(x), is modelled by a fourth-order polynomial, allowing for possible bi-stability (Kwasniok and Lohmann, 2009). I(t) is the insolation forcing and α is a coupling parameter. The model variable x is identified with the speleothem record. The model incorporates the possibility of directly forced transitions between the two states as well as noise-induced switching, including the phenomenon of stochastic resonance. The deterministic model parameters are estimated using only the probability density of the data (Kwasniok, 2013) rather than transition probabilities. This more generic approach takes account of the fact that the model is rather crude and the degree of its validity is not known a priori. The noise level is then estimated from the residuals. Inspection of the estimated model parameters enables assessment of the significance of the different mechanisms.

Page 16: [10] Deleted	Zoe Thomas	03/08/2015 21:59

There is some visible flattening in the potential in Figure S8c, which is due to the reduced amplitude of the solar forcing at the termination.

Figure 5 Tipping Point analysis on data from Sanbao Cave (Speleothem SB11) (31°40'N, 110°26'E).

Page 16: [11] Deleted	Zoe Thomas	03/08/2015 21:59

c,d) Displays the data density, where the black points are the original data and the pink points are the data after interpolation. e) Displays the AR(1) values and associated Kendall tau value, and f) displays the variance and associated Kendall tau.

Figure 6 Tipping Point analysis on data from Hulu Cave (Speleothem MSP) (32°30'N, 119°10'E). Data was smoothed over an appropriate bandwidth to produce data residuals, and analysed over a sliding window (of size between the two grey vertical lines). The grey vertical line at 133 ka BP indicates the tipping point, and the point up to which the data is analysed.

Figure 7 Contour plots showing a range of Window and Bandwidth sizes for the analysis; (a) Sanbao SB11 autocorrelation, (b) Sanbao SB11 variance, (c) Hulu MSP autocorrelation, (d) Hulu MSP variance. Black stars indicate the parameters used for the analysis in Figures 5 and 6.

Figure 8

Page 16: [12] Deleted	Zoe Thomas	03/08/2015 21:59

from the original SB11 time series at Termination II for autocorrelation (A) and variance (B) respectively.

Page 16: [13] Formatted	Zoe Thomas	03/08/2015 21:59

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Page 16: [14] Deleted	Zoe Thomas	03/08/2015 21:59

Figure 9 Histogram showing frequency distribution

Page 16: [15] Formatted	Zoe Thomas	03/08/2015 21:59

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Page 16: [16] Formatted	Zoe Thomas	03/08/2015 21:59

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Page 16: [17] Formatted	Zoe Thomas	03/08/2015 21:59

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Page 16: [18] Deleted	Zoe Thomas	03/08/2015 21:59

a surrogate time series model. The grey dashed line indicate the 95% significance level and the blue and red vertical lines show the Kendall tau values from the original Hulu MSP time series at Termination II

Page 16: [19] Formatted	Zoe Thomas	03/08/2015 21:59

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Page 16: [20] Deleted	Zoe Thomas	03/08/2015 21:59

autocorrelation (A) and variance (B) respectively.

Importantly, we found a clear increasing trend

Page 19: [21] Deleted	Zoe Thomas	03/08/2015 21:59

To test whether the signal is present in other EASM records, we undertook the same analysis on a second speleothem sequence (Figure 6), covering the same time period. We find that Speleothem MSP from Hulu Cave (32°30'N, 119°10'E) (Wang et al., 2001) displays a comparable increase in autocorrelation and variance to speleothem SB11 from Sanbao Cave (though these display slightly lower p values; see Figure 9), suggesting our interpretation is robust. In contrast, the transitions during the earlier period 230-150 ka BP from Sanbao Cave have less consistent trends; although autocorrelation and variance do increase prior to some of the abrupt monsoon transitions, there is no clear evidence of critical slowing down across these transitions (see Figure 10).

Figure 10 (A

Page 19: [22] Deleted	Zoe Thomas	03/08/2015 21:59

(B) These panels show the corresponding autocorrelation and variance for each period prior to a transition. No values are annotated since it is the increasing trend, rather than the absolute values of the autocorrelation and variance that indicate critical slowing down. The colour legend shows the Kendall tau values (-1 to 1) from autocorrelation over a range of smoothing bandwidths (5-15%) and sliding windows (40-60% of data range).

To help interpret these results we applied the potential model.

Page 21: [23] Deleted	Zoe Thomas	03/08/2015 21:59

Figure 11 a) Probability range of 100 model simulations, with the June 30°N NHSI (in red), and the palaeodata from SB11 (in green); histograms showing the distribution of the Kendall tau values from running the AR(1) (b), ACF (c) and variance (d) over the

monsoon transitions for the period 230-128 ka BP. Note there is no significant skewness associated with trends towards increased autocorrelation and variance.

The results of the search for early warning signals in these 100 realisations of the model are plotted as histograms of the distribution of Kendall tau results for autocorrelation and variance (Figure 11).

Page 21: [24] Deleted **Zoe Thomas** **03/08/2015 21:59**

No consistent early warning signals were found in the period 230-129 ka BP, which we term 'missed alarms' (Lenton et al., 2012). We suggest that these missed alarms are caused by a relatively fast rate of forcing compared to the sampling of the system; this comparatively poor sampling prevents the gradual flattening of the potential well from being recorded in the data. To test our hypothesis, we compared a range of different sampling time steps in the model (see section 2.3) measuring the Kendall tau values of autocorrelation and variance over each realisation of the model (one realisation displayed in Figure 12), which demonstrates the effects of increasing the sampling time step in the model. We found that whereas an increasing sampling time step produces a steady decrease in the Kendall tau values for AR(1) (Figure 12b), Kendall tau values remain fairly constant for variance (Figure 12c), suggesting that the latter is not affected by time step changes.

Page 21: [25] Moved to page 20 (Move #17) **Zoe Thomas** **03/08/2015 21:59**

, where the grey line represents the noise level as determined by the model, which does not follow a step transition, and cannot be adequately detrended by the equation derived from the model. However, once the noise level is sufficiently reduced, early warning signals (displayed here as high Kendall tau values for autocorrelation and variance) can be detected.

Page 21: [26] Deleted	Zoe Thomas	03/08/2015 21:59

Figure 12 a) Example of single realisation of the approach to a bifurcation over 4 noise levels (original noise=grey, 0.5 noise=black, 0.2 noise=blue, 0.1 noise=green), red line is the detrending line and the grey dashed vertical line is the cut-off point where data is analysed up to; **b)** distribution of Kendall Tau values for AR(1) over increasing sample step; **c)** distribution of Kendall Tau values for variance over increasing sample step.

Page 21: [27] Deleted	Zoe Thomas	03/08/2015 21:59

, Figure 11). One possibility is continental ice volume effects may explain the presence of a longer lag between the change in insolation and the monsoon transition at glacial terminations (Cheng et al., 2009). Alternatively, reduced sea ice extent may have played a role (Wunch, 2006).

Page 22: [28] Deleted	Zoe Thomas	03/08/2015 21:59

and/or sea ice extent (Broccoli et al., 2006) may have played a role in causing this shift in the ITCZ. For instance, the cold anomaly associated with Heinrich event 11 (at 135 ka BP) has been invoked as a possible cause of the WMI, cooling the North Atlantic and shifting the Polar front and Siberian high southwards, forcing an equatorward migration of westerly airflow across Asia (Broecker et al., 1985; Cai et al., 2015; Cheng et al., 2009). Such a scenario would maintain a low thermal gradient between the land and sea, causing the Weak Monsoon Interval and potentially suppressing a simple insolation response.

4

Page 23: [29] Deleted	Zoe Thomas	03/08/2015 21:59