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Temperature variance portends and indicates the extent of abrupt climate shifts

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Abstract

Here, we show a discernable increase in temperature variance before a glacial termination by both the Ansari-Bradley test and the moving variance methods plus introduce the idea that there is a correlation between the peak variance and peak temperature increase. The behavior of temperature variance shows potential as a useful tool in analyzing time series data of Earth systems to assess the risk and extent of an upcoming abrupt climate transition.

1. Abrupt climate shifts and signals

During the Quaternary period, ice core and sediment data show the Earth's climate fluctuated between two relatively stable states, long cold glaciations which are interrupted by shorter warm interglacials [1]. These shifts may occur when conditions change gradually until a critical threshold is reached called a bifurcation, beyond this point continued change will result in a rapid transition to an alternative stable state much faster than the rate of change of the underlying forcing [2].

One signal of a dynamical system approaching a threshold is critical slowing down [3] and refers to a decrease in the recovery rate to equilibrium conditions after a small perturbation [2, 4]. Previous studies confirm that a slowing of the recovery rate of a system after it is perturbed is a signal of an approaching climate shift to very different conditions [5]. Paleoclimate evidence of these recovery slowdowns was evidenced by increased autocorrelation prior to a transition for past abrupt climate change events [6] and experimental data obtained by exposing cyanobacteria to increasing amounts of sunlight until the population collapsed [5, 6].

2. Methods and data

We used similar methods [4, 6–9] and paleoclimate data of long-term time scales; the glacial-interglacial cycles and on a planetary level. Our hypothesis is that paleotemperature variance would change before the known abrupt climate transitions, thus forecasting the shift and that the magnitude of the preceding variance change can help estimate the magnitude of the shift. This is tested by analyzing the reconstructed paleotemperature time-series data to observe the changes in the behavior of temperature variance as a climate transition becomes imminent.

Here, we examine past abrupt climate transitions observed in the paleoclimate dataset as did previous studies [6, 9]. However, instead of looking at increased autocorrelation, we examined changes in temperature fluctuations to determine its usefulness as a predictor of imminent transitions. We also examined the relationship between the magnitude of the preceding variance and the extent of the climate transition. The paleotemperature data used in this study are published time series from five globally distributed sites (table 1). The reconstructed temperature-time series data used are the LR04 data stack, EPICA Dome C data, and from Ocean Drilling, Program (ODP) sites 1090, 882, and 982. These were available for download from NOAA

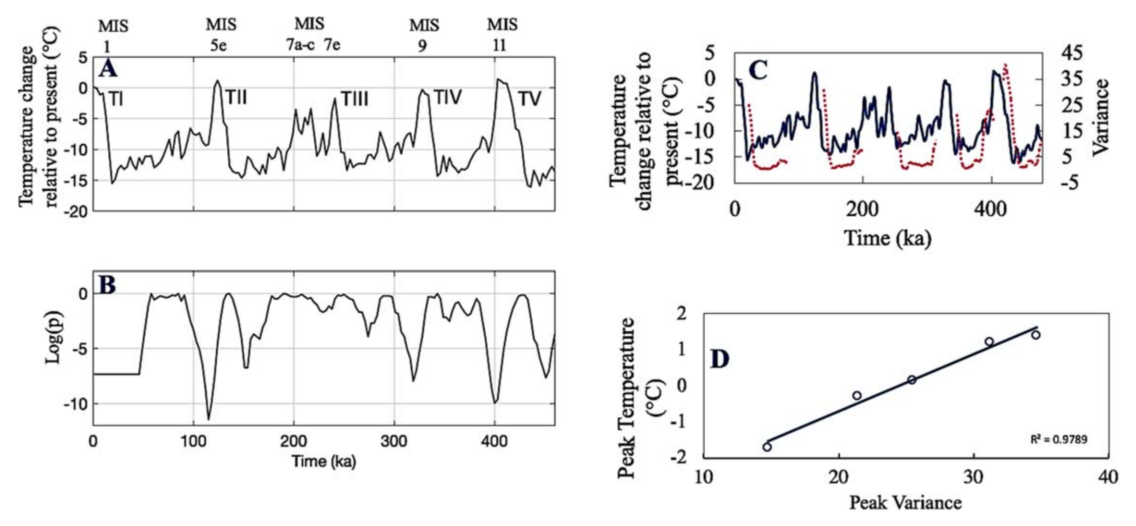

Figure 1. The LR04 stack paleo-temperature dataset.

Table 1. Paleo-temperature records used in this study.

No.	Site	Lat	Lon	Location	Proxy	References
1	LR04 stack	Land surface North of ~45 N		Subarctic-Arctic	Oxygen isotopes	[11]
2	EPICA Dome C	−75	123	Antarctica	Deuterium	[12]
3	ODP Site 1090	−43	8.9	Sub-Antarctic Atlantic	Alkenone SST	[13]
4	ODP Site 882	50	168	Subarctic Pacific	Alkenone	[14]
5	ODP site 982	57	−17	North Atlantic	Alkenone	[15]

National Centers for Environmental Information formerly known as the National Climatic Data Center (NCDC) database website [10]. Since the proxy temperature data is not on an evenly spaced time-period, we used linear interpolation to resample the temperature data on evenly spaced time intervals of 3 Ka running from 1 to 460 Ka.

2.1. Ansari-Bradley test

The Ansari-Bradley test is used to identify changes in the paleo-temperature variability. This test performs a two-sided rank-sum test of the null hypothesis that assumes both samples are from a distribution with similar shape and median but different dispersions [16]. The Ansari-Bradley test was employed similarly in an earlier study—to reassess dust flux records to detect major transitions in the dust variability [17]. It is an alternative to the F-test for comparing dispersions but does not require a normality assumption—a non-parametric test [16]. Here, this statistic is employed to detect significant shifts in the variability of temperature in the paleo records of the last 460 Ka. The length of the average glacial cycle is approximately 100 Ka [18]. Based on this the running Ansari-Bradley tests are computed using a paired sliding window size of 100 Ka.

2.2. Moving variance test

The moving variance with a moving window of 31 Ka was computed for each site just before each interglacial period begins during the last 460 Ka. Finally, the peak temperature and peak variance announcing the transition to higher temperatures are extracted and given in the Supplementary material tables S1–5 (available online at stacks.iop.org/IOPSN/2/014002/mmedia).

3. Results and discussion

The results from the Ansari-Bradley and moving variance tests are shown in figures 1–5 where the temperature record resampled on an evenly-spaced time scale running from 1 to 460 Ka in 3 Ka intervals are shown in panel **A**, the deviations in mean temperature variance from the Ansari-Bradley test is shown in **B.** Panel **C** shows the temperature (solid line) and moving variance (dotted line) for the last 460 Ka; **D**, shows the peak variance preceding glacial termination and the peak temperature of the interglacial that followed that variance increase. This is repeated for all data sites analyzed.

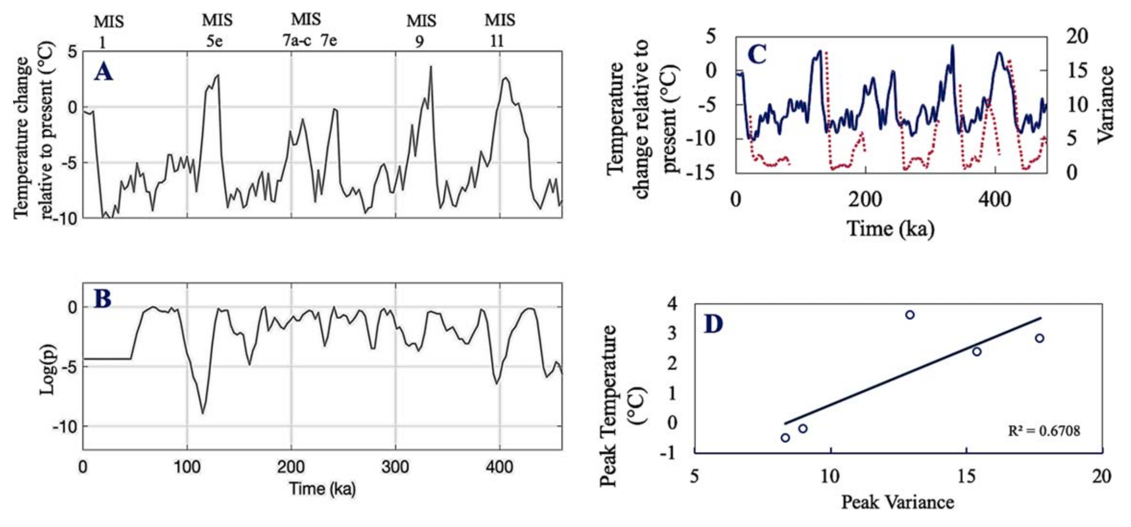

Figure 2. EPICA Dome C temperature dataset.

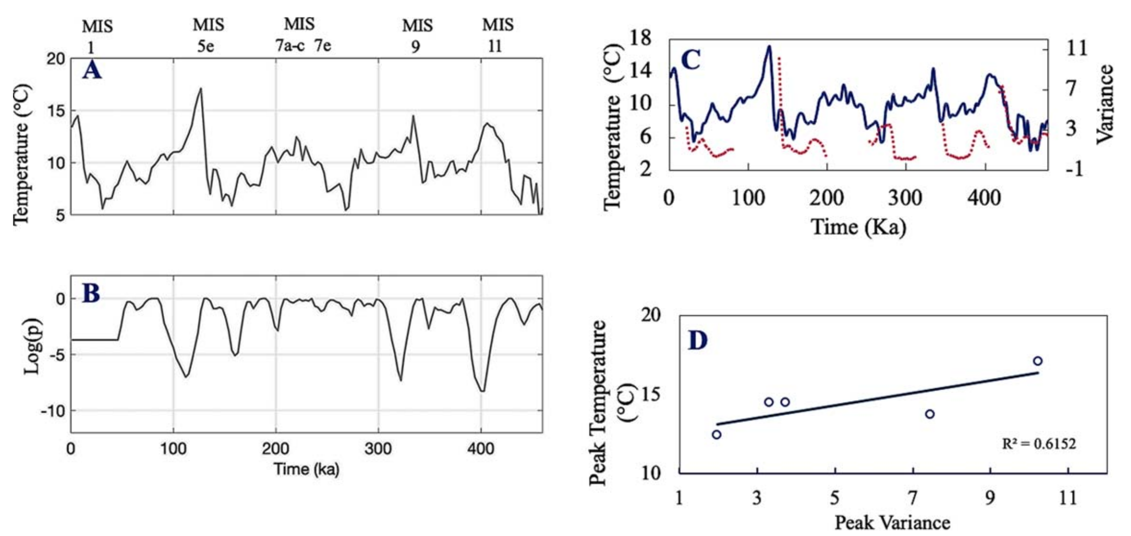

Figure 3. ODP Site 1090.

From the results, the running Ansari-Bradley test identified both major and minor changes in temperature variability revealing significant changes in temperature variance for abrupt climate changes. For example, looking at the entrance to MIS 5e (TII) around 145 Ka in figure 1, A where there is a sudden increase in temperature, the Ansari-Bradley test in B finds significant deviations in temperature variability just prior to it. The exit from MIS 5e (figure 1(A)) at around 130 Ka in figure 1(B), again the Ansari-Bradley test shows significant changes in the variability. Going over to MIS 7e, TIII occurring around 250 Ka (figure 1(A)), the Ansari-Bradley test (figure 1(B)) shows a small deviation in variability occurring just prior and similarly for the exit from MIS 7e, although here those deviations are smaller than those for MIS 5e. For the glacial termination to MIS 9, TIV (figure 1(A)), there is a minor deviation in variability while for the exit of this interglacial there is a larger deviation detected by the Ansari-Bradley test (figure 1(B)). For MIS 11 starting around 430 Ka, (figure 1(A)), there is a significant change in temperature variability (figure 1(B)) and similarly for the exit. Similarly, for the other sites shown in figures 2(B)–5(B), the Ansari-Bradley test shows significant increases in temperature variability identifying the major abrupt temperature shifts.

From the temperature and moving variance (figures 1(C)–5(C), an increase in variance is discernible before all the glacial terminations covered by this time-period. Since there is a distinct increase in variance before the glacial terminations, it seems intuitive that there is a relationship between the peak variance and the interglacial maximum temperature that follows. Figures 1(D)–5(D) shows there is a good correlation between the peak variance and maximum interglacial temperatures for the LR04 stack data.

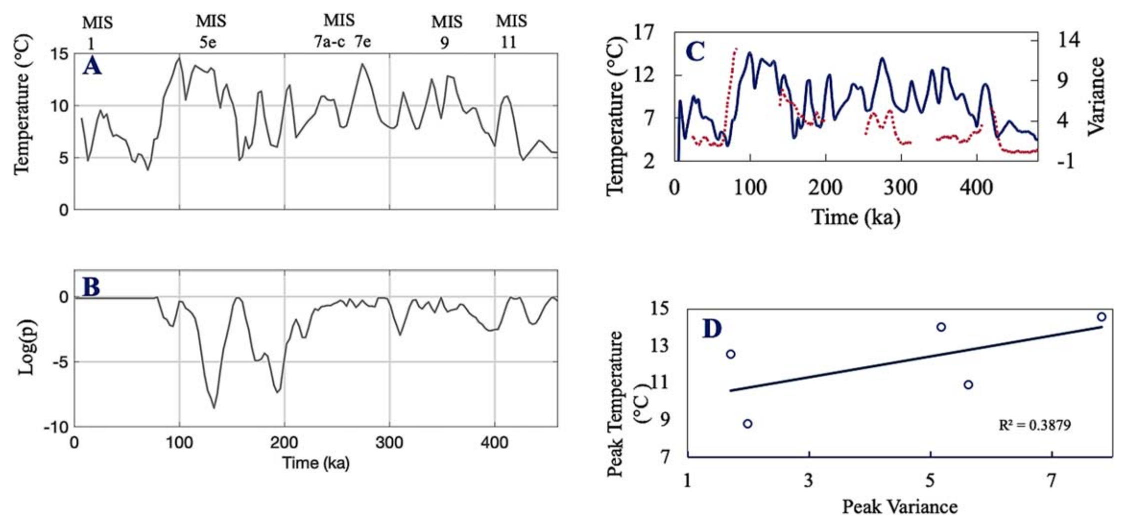

Figure 4. ODP Site 882.

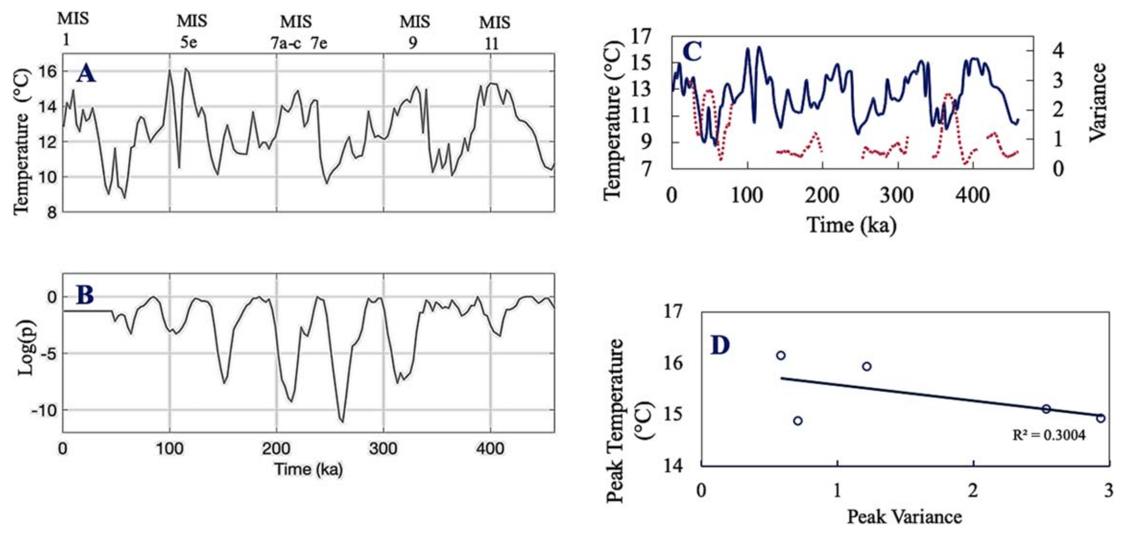

Figure 5. ODP Site 982.

An interesting trend emerged from both the Ansari-Bradley tests and the moving variance, where MIS 7e is announced by a small change in variance; this is consistent across the sites. Previous research has found MIS 7e to be a cooler, less intense interglacial in comparison with those found in the last 450 Ka [19]. It is quite intriguing that this is reflected in the quantity of variance change and shows there is promise in developing the use of peak variance forecasting a transition to estimate the intensity of that change. Here the use of this metric is explored with favorable results for the high latitude sites such as the LR04, the EPICA Dome C data, and ODP Site 1090, more research in this direction may help develop its use to a more robust metric.

The LR04 data stack (figure 1(D)) shows a strong positive relationship between peak variance and maximum temperature with an r-squared value of 0.9789 but with a p-value > 0.005 (0.001). The ice core dataset, EPICA Dome C and sediment data ODP Site 1090 (figures 2(D) and 3(D)) both have a moderately good relationship with an r-squared value of 0.6708 and 0.6152 respectively and p-values > 0.005 (0.09 and 0.116 respectively) indicating it may not be significant. ODP Site 882 and ODP Site 982 (figures 4(D) and 5(D)) exhibit r-squared values of 0.3879 and 0.3004 respective and p-value >0.005 (0.261 and 0.338 respectively). Overall, the r-squared values suggest that the model of greater variance prior to entering a warm period presages a greater maximum temperature of that interglacial. However, with low p-values, the significance suggests more analyses are needed to confirm if this will make a robust estimation tool. For now, these results are promising in the use of the magnitude of variance change prior to an interglacial as a forecaster of its intensity. Additional application to a wider range of datasets will determine its robustness.

Table 2. Prediction efficiency for each site analyzed and the resolution.

No.	Site	Location	Resolution (Ka)	Prediction efficiency
1	LR04 stack	Sub-Arctic Arctic	0.10	100
2	EPICA Dome C	Antarctica	0.14	100
3	ODP Site 1090	Sub-Antarctic Atlantic	2.3	80
4	ODP Site 882	Sub-Arctic Pacific	2.4	20
5	ODP Site 982	North Atlantic	3.0	40

Table 2 shows the percent efficiency of when the moving variance test predicted a termination and the data resolution for the dataset used. Based on this, it seems low-resolution data may explain why ODP Site 882 did not display a noticeable prediction. However, ODP Site 982 with a lower resolution of 3.0 Ka did a better job at predicting an impending transition suggesting there may be additional factors at work here such as ocean currents since this site is located in the Pacific versus the others are in the Atlantic. Studies show that a comparison of data from sites around the globe shows glacial termination patterns vary spatially [20] and may explain why the differing results obtain across sites here. Another explanation is that variance changes may also be affected by some environmental conditions and can be amplified or diminished [21]. Overall, these results suggest that there is an increased temperature variance before an abrupt climate change and that changes in the variance can be used as an early warning signal of impending transition regardless of the underlying mechanism causing the shift. They also demonstrate the effectiveness of the Ansari-Bradley test in detecting changes in variance in a time series as this test was able to forecast both glacial terminations and inceptions while the moving variance only predicted the terminations.

4. Conclusions

These findings can have important implications in improving our understanding of the climate system behavior and predicting nonlinear transitions in Earth systems. First, there is increased variance preceding each of the last five glacial terminations, this supports theoretical studies by providing empirical evidence that variance change is an important tool in estimating proximity to a critical transition. Second, by not isolating specific ancient climate transitions but looking at the entire time series we found a new emergent trend of decreasing variance as a significant signal for glacial inceptions, thus including decreased variance in the repertoire of early warning signals. Third, by exploring the potential novel tool of using the preceding peak variance to estimate the intensity of interglacials, the magnitude of transitions can be evaluated. Variance change could prove an essential metric in monitoring Earth systems amidst ongoing anthropogenic changes to determine stable state boundaries ofthe system and is worth further study.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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