Flickering body temperature anticipates criticality in hibernation dynamics

DANIEL ORO¹ AND LÍDIA FREIXAS²

¹ Theoretical and Computational Ecology Laboratory, CEAB – Center for Advanced Studies (CSIC), Acces Cala Sant Francesc 14, 17300 Blanes, Spain
² Granollers Natural Sciences Museum, Francesc Macià 51, 08402 Granollers, Spain

Corresponding author:
Daniel Oro
Theoretical and Computational Ecology Laboratory
CEAB – Center for Advanced Studies (CSIC)
Acces Cala Sant Francesc 14
17300 Blanes, Spain
e-mail : d.oro@csic.es

Running head: Critical transitions in hibernation
Table S1 Details about how metric-based indicators of EWS of temperatures were applied and pre-processed to avoid biased results. TS = time series; T = temperature; BT = body temperature

| Indicator                              | Statistical goal                                          | Procedure for considering sensitivity to set up choices                                      | Transformation                                      | Filtering                                                                 |
|----------------------------------------|-----------------------------------------------------------|---------------------------------------------------------------------------------------------|-----------------------------------------------------|--------------------------------------------------------------------------|
| BDS test                               | Detects non-linear serial dependence in the TS            | We ran the test under different set ups for data transformation and filtering-detrending, because the test is sensitive to these choices | We log-transformed data (using log(T+1)) because of the presence of very fluctuating values between active BT (around 38º) and dormancy BT (close to 0º). | We filtered extreme data by fitting linear AR models, and we also generated partial autocorrelation functions for setting the best choice of time lags for the linear models fitted to the TS |
| Conditional heteroskedasticity (CH)    | It measures whether variance at one time step is positively associated with variance at one or more previous steps; CH should increase when approaching a critical transition. | We used two lengths of rolling windows (10% and 30% of the total, the latter because of the slow timescale of varying temperatures in dormice). The significance threshold was set to 0.1 | Data was standardized because of the presence of extreme values of BT in the dataset. | We filtered by fitting linear AR models                                                                                   |
| Nonparametric Drift-Diffusion-Jump (DDJ)| Models yield: conditional variance or drift, diffusion, jumps, and total variance | BT was log-transformed (using log(T+1))                                                      |                                                      |                                                                          |
| Generic early warning signals          | EWS include: temporal autocorrelation of BT at lag-1, standard deviation SD and skewness | We used an overlapping moving window since indicators should be estimated as data become available | BT was log-transformed (using log(T+1)) and results were compared with raw BT | Data were filtered using Gaussian smoothing                                                                                   |
Table S2 Partitioning of the times series and number of temperature records for each of the analyses.

| Indicator                              | transition                        | Time series length (female/male) |
|----------------------------------------|------------------------------------|----------------------------------|
|                                        | To hibernation                     | To activity                      | To hibernation | To activity | After hibernation |
| BDS test                               | From start to first breaking point | From first to last breaking point | 1124/1717      | 4498/3930   |                 |
| Conditional heteroskedasticity         | From start to first breaking point | From first to last breaking point | 1124/1717      | 4498/3930   |                 |
| Nonparametric drift-diffusion-jump models | Whole time series                |                                 |                |             |                 |
| AR(1), standard deviation, skewness    | From start to first breaking point | From first to last breaking point | 1124/1717      | 4498/3930   |                 |
|                                        | Idem adding 15 days of hibernation | Idem adding 30 days of activity  | 1502/2054      | 4682/4673   |                 |
| Potential analysis                     | Whole time series                  |                                 |                |             |                 |
| AR(p) of body temperature with air temperature | The whole series was partitioned in three periods: pre-hibernation, hibernation and post-hibernation (see electronic supplementary material, table S4) | | 1124/1717 | 4498/3930 | 2570/2545 |
| Threshold AR(p) models                 | Whole time series                  |                                 |                |             |                 |
Table S3 BDS statistic on body temperature variability before the transition to hibernation (TH) and to activity (TA) for the male and female dormice for each model tested (first-difference, AR(1) and GARCH(0,1), three different values of $\varepsilon$ (.5, .75 and 1, which were used to scale the standard deviation of the time series) and two embedding dimensions, D, up to which the test was performed. All statistical tests for detrended data (using 1000 bootstrapping iterations) were significant ($P < 0.0001$).

| Model | D  | $\varepsilon$ value | 0.5 | 0.75 | 1 | 0.5 | 0.75 | 1 | 0.5 | 0.75 | 1 |
|-------|----|---------------------|-----|-----|---|-----|-----|---|-----|-----|---|
| Female | TH | 2                   | 15.40 | 17.18 | 18.74 | 18.62 | 18.85 | 19.31 | 27.40 | 29.26 | 26.46 |
|       |    | 3                   | 16.61 | 17.69 | 18.67 | 21.17 | 20.17 | 19.91 | 29.62 | 30.42 | 26.78 |
|       | TA | 2                   | 57.02 | 53.65 | 48.14 | 59.38 | 52.14 | 45.78 | 43.48 | 44.84 | 42.57 |
|       |    | 3                   | 64.12 | 54.41 | 47.60 | 66.12 | 53.47 | 45.32 | 52.45 | 48.66 | 42.94 |
| Male  | TH | 2                   | 24.06 | 24.26 | 23.73 | 33.89 | 21.53 | 16.28 | 44.16 | 41.23 | 34.88 |
|       |    | 3                   | 25.67 | 23.61 | 22.34 | 46.36 | 28.08 | 17.91 | 49.81 | 44.14 | 35.91 |
|       | TA | 2                   | 46.94 | 49.84 | 45.36 | 48.11 | 47.54 | 44.07 | 25.64 | 35.93 | 36.71 |
|       |    | 3                   | 50.23 | 49.36 | 44.70 | 52.09 | 47.62 | 43.28 | 32.36 | 39.23 | 36.16 |
Table S4 Coefficients of the parameters of regression AR($p$) models of body temperature $T$, in which air temperature was added (A), compared to AR($p$) models not including this covariate. All temperatures were standardized for each of the three periods considered: pre-hibernation, hibernation and post-hibernation (a, b and c respectively, see figure; note that periods a and b correspond to transition to hibernation (TH) and to activity (TA)). Models have the form: 

$$T(t) = \beta A_i + \phi_0 + \sum_{i=1}^{p} \phi_i (T(t-i) - \phi_0),$$

in which $p = 1$. Standard errors of the mean (SE) are shown in parentheses; $\Delta$AIC = difference in AIC value with the best model in each of the comparisons. All models including air temperature as a covariate showed lower AIC values.

| Dormice | Period             | Air T (ºC) | Parameters | $\Delta$AIC |
|---------|--------------------|------------|------------|-------------|
| female  | Pre-hibernation (a)| Included   | $-0.0320$  | $0.004$     | $0.958$     | $0$          |
|         |                    |            | ($0.043$)  | ($0.199$)   | ($0.001$)   |              |
|         |                    | Not included|           | $0.001$     | $0.999$     | $26.45$      |
|         |                    |            |            | ($0.810$)   | (NA)        |              |
|         | Hibernation (b)    | Included   | $0.069$    | $0.001$     | $0.964$     | $0$          |
|         |                    |            | ($0.012$)  | ($0.105$)   | ($0.004$)   |              |
|         |                    | Not included|          | $0.000$     | $0.966$     | $13.81$      |
|         |                    |            |            | ($0.114$)   | ($0.004$)   |              |
|         | Post-hibernation (c)| Included | $0.148$    | $-0.014$    | $0.923$     | $0$          |
|         |                    |            | ($0.031$)  | ($0.098$)   | ($0.008$)   |              |
|         |                    | Not included|         | $-0.011$    | $0.924$     | $20.91$      |
|         |                    |            |            | ($0.099$)   | ($0.008$)   |              |
| male    | Pre-hibernation (a)| Included   | $-0.116$   | $0.001$     | $0.949$     | $0$          |
|         |                    |            | ($0.045$)  | ($0.151$)   | ($0.001$)   |              |
|         |                    | Not included|         | $0.000$     | $0.945$     | $4.65$       |
|         |                    |            |            | ($0.142$)   | ($0.001$)   |              |
|         | Hibernation (b)    | Included   | $0.868$    | $-0.001$    | $0.477$     | $0$          |
|         |                    |            | ($0.012$)  | ($0.001$)   | ($0.021$)   |              |
|         |                    | Not included|         | $0.001$     | $0.952$     | $731.16$     |
|         |                    |            |            | ($0.101$)   | ($0.005$)   |              |
|         | Post-hibernation (c)| Included | $0.107$    | $-0.004$    | $0.915$     | $0$          |
|         |                    |            | ($0.032$)  | ($0.094$)   | ($0.008$)   |              |
|         |                    | Not included|         | $-0.011$    | $0.912$     | $9.28$       |
|         |                    |            |            | ($0.095$)   | ($0.008$)   |              |
**Figure S1** Partial autocorrelation functions for the body temperature time series partitioned for the period before the transition to hibernation (panels a and b for the female and the male, respectively) and before the transition to activity (panels c and d for the female and the male, respectively). Body temperature when dormice were active and prior to hibernation (panels a and b for the female and the male respectively) showed a circadian cyclicity, but not during hibernation.
Figure S2  Results from conditional heteroskedasticity (expressed as the R\textsuperscript{2} values of the regressed residuals) for the transitions to hibernation (panels (a) and (b) for female and male respectively) and transitions to activity (panels (c) and (d) for female and male respectively), considering two sizes of rolling windows (lengths 10% and 30% of the total). The red lines show the limit above which R\textsuperscript{2} values are statistically significant (P = 0.1). CH was sensitive to rolling window size.
**Figure S3** Nonparametric drift-diffusion-jump model-based indicators for body temperature dynamics of the female (panels a to e) and the male (panels f to j) edible dormouse. Left panels show (from top to bottom) how body temperature, conditional variance, diffusion, jump intensity and total variance vary with time, whereas right panels show how the same indicators vary with body temperature. Dashed lines show the two breaking points signalling transition to hibernation and activity. When plotted against body temperature, conditional variance peaked around value 3 (20.1°C), which was the temperature that separates the two states of hibernation and activity, and jump intensity peaked at value 2.5 (12.2°C), which measures the average jump in temperature from dormancy to $T_*$ and vice versa.
Figure S4  Metric-based rolling window indicators estimated for the body temperature time series for the two dormice and separated for each alternative state (activity and hibernation). For the transition to hibernation, we added 15 days of data once hibernation started (as marked by the first breaking point in the time series) and 30 days of data from the onset of activity (as marked by the last breaking point). (a and b): activity state and hibernation state for the female; (c and d): activity state and hibernation state for the male. Red lines show the Gaussian filtering of the time series. Panels 1, 2 and 3 show autocorrelation at lag-1 (AR(1)), standard deviation and skewness respectively, estimated within sliding windows of 20% the size of the time series. The Kendall $\tau$ indicates the strength of the trend in the indicators. Vertical dashed lines show the breaking points separating the two stable states.
**Figure S5**  Metric-based rolling window indicators estimated for the body temperature time series for the two dormice for the whole time series (a and b for female and male, respectively). Red lines show the Gaussian filtering of the time series. Panels 1, 2 and 3 show autocorrelation at lag-1 (AR(1)), standard deviation and skewness respectively, estimated within sliding windows of 20% the size of the time series. The Kendall $\tau$ indicates the strength of the trend in the indicators. Vertical dashed lines show the breaking points separating the two stable states.
Figure S6  Metric-based rolling window indicators estimated for the body temperature time series and air temperature time series (yellow lines) for the two dormice and separated for each alternative state (activity and hibernation). (a and b): activity state and hibernation state for the female; (c and d): activity state and hibernation state for the male. Red lines show the Gaussian filtering of the time series. Panels 1, 2 and 3 show autocorrelation at lag-1 (AR(1)), standard deviation and skewness respectively, estimated within sliding windows of 20% the size of the time series. The Kendall τ indicates the strength of the trend in the indicators. Vertical dashed lines show the breaking points separating the two stable states.
**Figure S7** Sensitivities of generic EWS (autocorrelation at lag-1 AR(1), standard deviation SD and skewness Sk) for testing the robustness of the rolling window metrics. For each of the two transitions and each dormouse, left panels are the contour plots showing the influence of the width of the rolling window and Gaussian filtering on the observed trend in the metrics as measured by Kendall’s τ; right panels are the histograms with the frequency distribution of the trend for τ. Small triangles show the parameter choice used in each of our analyses. Windows sizes ranged from 20% to 80% in increments of 10 points and bandwidths ranged from 5 to 200 in an increment of 20.

Transition to hibernation

Female

AR(1)

SD

Sk

Male

AR(1)

SD

Sk
Transition to activity

Female

AR(1)

SD

Sk

Male

AR(1)

SD

Sk