

Slowing down of North Pacific climate variability and its implications for abrupt ecosystem change

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Marine ecosystems are sensitive to stochastic environmental variability, with higher-amplitude, lower-frequency—i.e., “redder”—variability posing a greater threat of triggering large ecosystem changes. Here we show that fluctuations in the Pacific Decadal Oscillation (PDO) index have slowed down markedly over the observational record (1900–present), as indicated by a robust increase in autocorrelation. This “reddening” of the spectrum of climate variability is also found in regionally averaged North Pacific sea surface temperatures (SSTs), and can be at least partly explained by observed deepening of the ocean mixed layer. The progressive reddening of North Pacific climate variability has important implications for marine ecosystems. Ecosystem variables that respond linearly to climate forcing will have become prone to much larger variations over the observational record, whereas ecosystem variables that respond nonlinearly to climate forcing will have become prone to more frequent “regime shifts.” Thus, slowing down of North Pacific climate variability can help explain the large magnitude and potentially the quick succession of well-known abrupt changes in North Pacific ecosystems in 1977 and 1989. When looking ahead, despite model limitations in simulating mixed layer depth (MLD) in the North Pacific, global warming is robustly expected to decrease MLD. This could potentially reverse the observed trend of slowing down of North Pacific climate variability and its effects on marine ecosystems.

regime shifts | North Pacific | marine ecosystems | abrupt change | climate change

Sea surface temperature (SST) fluctuations are well known to exhibit “red” spectra—with increased power at lower frequencies—even when forced by purely “white” noise from the atmosphere (1, 2). Individual realizations of a stationary red noise process will typically drift one side of the mean and later switch over, resembling an irregular oscillation. One such “oscillation,” the Pacific Decadal Oscillation (PDO) index (3, 4), is described by the variation of the dominant spatial pattern of SSTs >20°N in the Pacific over time, having removed the seasonal cycle and an overall warming trend. Shifts in the PDO between its positive and negative phases—especially around 1977 and 1989—have been linked to abrupt changes in salmon productivity (3, 5), drought regimes in the United States (6), changes in Indian summer monsoon rainfall (7), and a host of other ecological and climatic time series (4). Whereas some early work described the PDO itself as exhibiting regime shifts (4, 8), implying the existence of alternative climate attractors, subsequent work has found no evidence for nonlinearity in the PDO or other North Pacific climate indices (9). Instead, North Pacific climate variability can be characterized as a linear, stochastic, red noise process (10). North Pacific marine ecosystems have also been widely described as exhibiting regime shifts between alternative attractors in response to stochastic fluctuations in the physical climate system (9). Whereas there is evidence for nonlinearity in some North Pacific ecosystem time series (9, 11), other populations appear to linearly track the climate forcing, especially if their generation time matches the damping timescale of the forcing (11). Thus, one “double-integration” model for the overall behavior is that SSTs (and

indices derived from them such as the PDO) integrate white noise forcing from the atmosphere to produce red noise (1), and ecosystems further integrate this red noise to create time series that are even redder (12). The redder the ocean climate variability, the more closely a marine ecosystem will track it (13), making the ecosystem more prone to large changes driven by the climate variability (13).

Here we consider whether North Pacific climate variability has changed over the observational record. A simple generic model for SST fluctuations (10) is the first-order linear autoregressive process:

$$x_t = \alpha x_{t-1} + \sigma \eta_t \quad [1]$$

where the subscript t denotes time, x is the time series, α is the lag-1 autocorrelation [AR(1)] coefficient ($0 < \alpha < 1$, for red noise), and η_t is Gaussian white noise of amplitude σ . Existing work has used a constant value of $\alpha = 0.95$ (corresponding to a decorrelation timescale of 20 mo) to mimic the PDO index (10). If, however, there has been a change in the spectrum of SST variability we expect this to manifest as a change in α , with an accompanying change in variance (14, 15). Hence, for each of a series of North Pacific datasets [the PDO index (3), HadISST (16), ERSST v3 (17), and HadSST3 (18) detailed below], we estimated the AR(1) coefficient (α) and calculated the variance, in a sliding window moved through the dataset, to look for any trends (*Methods*). In each case, the results were tested against a null model for North Pacific SST fluctuations, with fixed $\alpha = 0.95$ (10), which was used to generate 10,000 realizations of a series of the same length as the time series being tested (*Methods*)—the idea being that a relatively short realization of such a stationary red noise process can display a wide range in trends of lag-1 autocorrelation and variance.

Significance

Sea surface temperature (SST) variations in the North Pacific have triggered past abrupt changes in fisheries and other ecosystems. We have discovered that over the last century, fluctuations of North Pacific SSTs have become less frequent and longer-lived. This “reddening” behavior can also be seen in the dominant pattern of climate variability in the region, known as the Pacific Decadal Oscillation index. This fundamental change in climate variability has important implications for ecosystems in the region. It implies that over the last century, ecosystems have become prone to undergoing larger climate-triggered abrupt shifts. Hence our discovery of changing climate variability could have contributed to the large magnitude of well-known abrupt changes in North Pacific ecosystems in 1977 and 1989.

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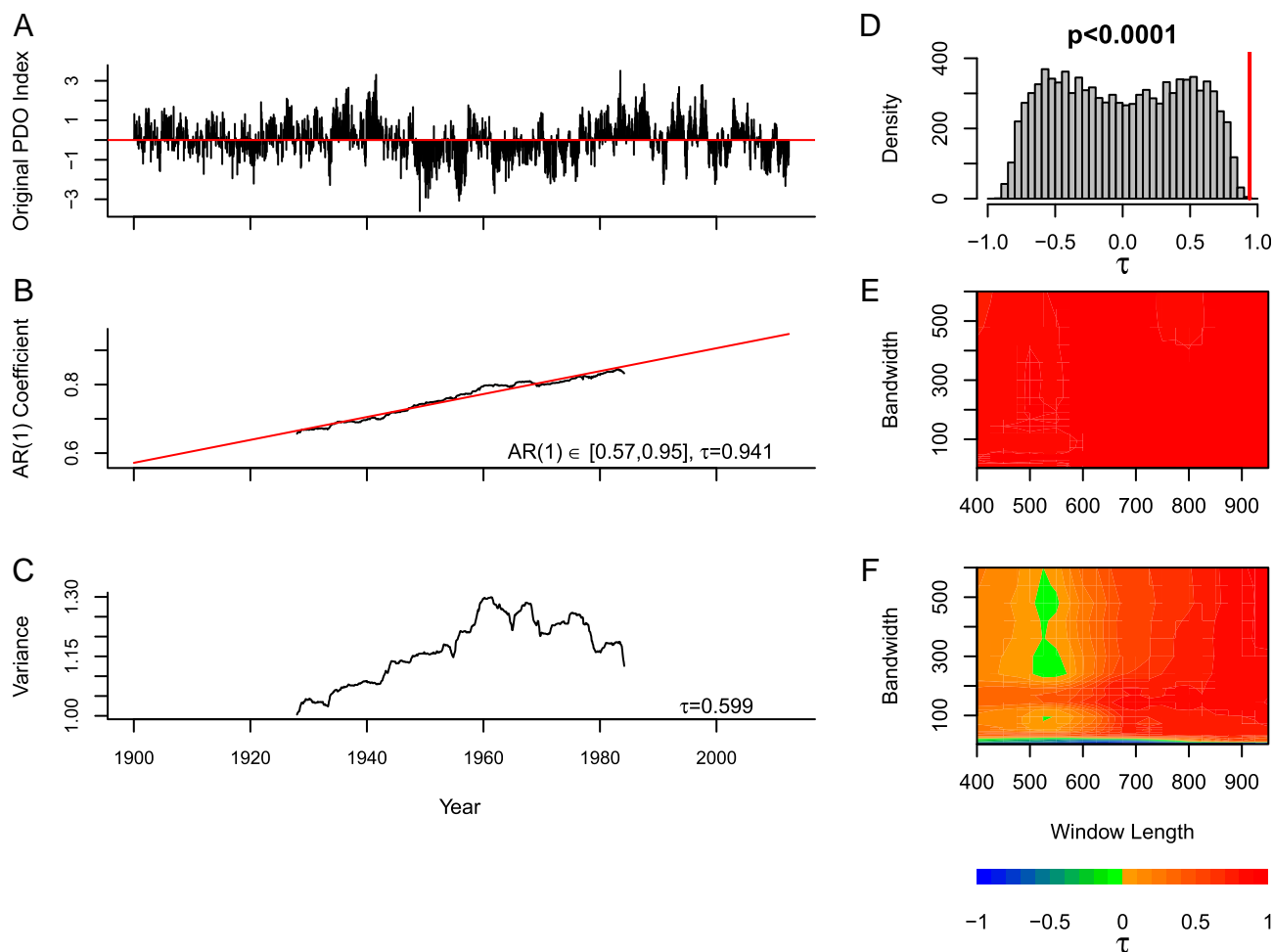


Fig. 1. Slowing down observed in the PDO index, 1900–2012. (A) The original PDO index. (B) Estimated increase in AR(1) coefficient, using a window length of 675 points (half the series), without detrending (*Methods*), results plotted in the middle of the sliding window. (C) Estimated increase in variance. Trends in the indicators are expressed as Kendall τ -values. (D) Range in τ -values expected from ensembles of 10,000 realizations of a null model with fixed $\alpha = 0.95$. Red vertical line denotes the τ -value found in the PDO index A ($P < 0.0001$). (E and F) Sensitivity analyses of the AR(1) coefficient estimate and variance respectively by testing the value of τ for a variety of window lengths and bandwidths.

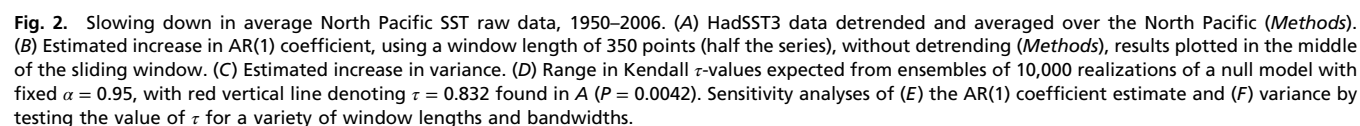
Slowing down of fluctuations is visible in the original PDO index (Fig. 1A), with a strongly increasing trend in the AR(1) coefficient (Kendall $\tau = 0.941$, *Methods*), from an estimated $\alpha = 0.57$ to $\alpha = 0.95$ over the 112.5-y record (Fig. 1B, *Methods*). Variance also generally increases (Fig. 1C), but not as strongly across the whole record ($\tau = 0.599$), due to a downturn in recent decades. The observed trend in AR(1) in the PDO index lies outside the distribution resulting from 10,000 realizations of the null model (Fig. 1D). Hence we can reject with high confidence ($P < 0.0001$) the null hypothesis that the observed trend in autocorrelation in the PDO index is the result of a red noise process with fixed α . The increasing trend in variance in the PDO index ($\tau = 0.599$) is less significant and could occur by chance with $P = 0.1411$ (Fig. S14). However, other aspects of North Pacific climate are showing increases in variance (19), and if we just consider the data up to 1989 the PDO index shows a strong increase in variance ($\tau = 0.909$), noting that the decrease in variance appears to begin in 1960 in Fig. 1C because the indicators are plotted at the midpoint of the window used to calculate them and at this point data from 1989 enter the sliding window.

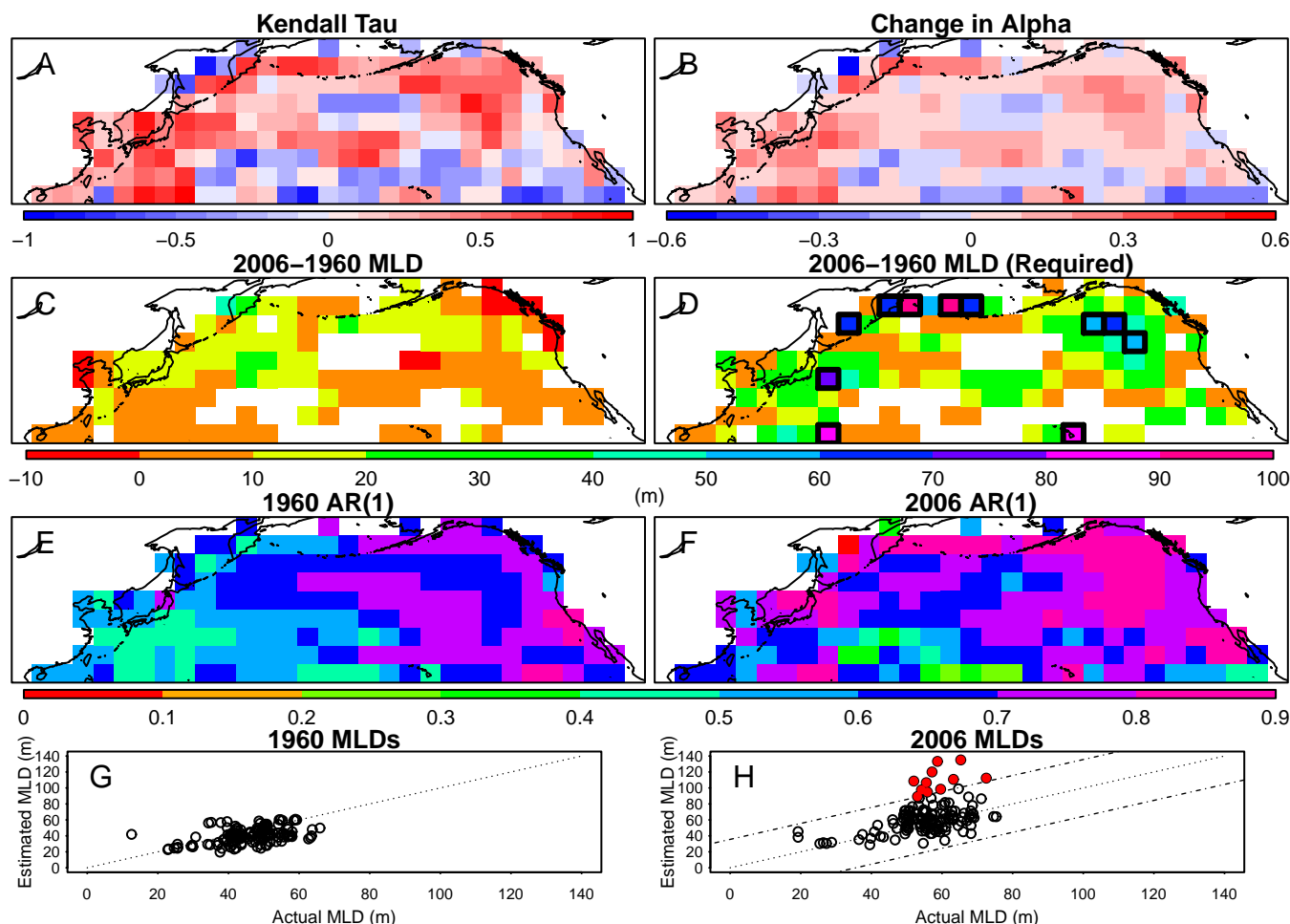
Nonstationary behavior can cause autocorrelation to increase; hence we examined the effect of further detrending the data before analysis. As the bandwidth is decreased, the lowest frequencies, including the (multi-) decadal “oscillation” itself, are

the first to be removed and the results are limited to ever shorter timescale fluctuations. As a further sensitivity analysis, we also varied the sliding window length in which the indicators are calculated. The positive trend in AR(1) is robust to varying sliding window length and filtering bandwidth (Kendall $\tau = 0.77$ – 0.98 , Fig. 1E). The positive trend in variance is also fairly robust (Fig. 1F), except when using a very short filtering bandwidth for detrending. This leaves only the highest frequency variability in the index and its variance decreases (e.g., $\tau = -0.903$ with the shortest filtering bandwidth). This is consistent with a shift in power from high to low frequencies, which can also be seen in the changing power spectrum of the data (Fig. S2A). Comparing to the null model (also filtered with the shortest bandwidth before analysis), the decline in variance at high frequencies has $P = 0.0006$ and we can reject the null model at 5% significance (Fig. S1B).

To establish whether slowing down has anything to do with the spatial pattern of the PDO we examined the HadISST (16) dataset. Removing seasonal and overall warming trends and then simply averaging HadISST over the North Pacific domain 20–60°N (*Methods*), slowing down is again visible by eye (Fig. S3A) and confirmed by a strongly increasing trend in the AR(1) coefficient ($\tau = 0.938$, Fig. S3B) with estimated change in α from 0.68 to 0.92 (the 95% confidence interval on the change in α hardly alters these results, given to two significant figures). There

A grid-point by grid-point analysis of HadSST3 data was conducted to determine where the slowing down of SST fluctuations is occurring, revealing that it is widespread but not universal across the North Pacific domain (Fig. 3 *A* and *B*). Strong slowing down occurs around the basin edge, e.g., off the West Coast of North America. To try and explain this slowing down we consider a simple physical mechanism consistent with known climatic trends, namely deepening of the mixed layer (20). In the original model of Frankignoul and Hasselmann (2) the key





system. It is set up to have no bias toward either state and to allow shifts between states to occur when $\alpha = 0.55$ in the forcing time series (the lowest value considered). The second model is a double-integration model which represents the concept that some ecosystem variables have only one state and linearly track climate forcing, integrating it with their own characteristic timescale (11). The model is based on one used elsewhere to simulate *Nyctiphanes simplex* (a species of krill) which has a damping timescale of ~ 20 mo (12) (*Methods*). For forcing these ecosystem models, we note that although there is an increase in variance in the climate indices we have analyzed, the increase in amplitude of variability is very modest compared with that generated by increasing α in our AR(1) model. Hence, we normalize (dividing by SD) the amplitude of the different levels of red noise (generated by different α) used to force the two idealized ecosystem models. This means that the resulting changes in the ecosystem models are due to the changing memory in climate forcing alone. The range of values of α we explore corresponds to damping timescales from ~ 2.2 mo when $\alpha = 0.55$, to 20 mo when $\alpha = 0.95$, there being an exponential relationship between α and the timescale, and noting that $\alpha = 0.95$ is often used to mimic PDO variability (10).

Increasing the autocorrelation in the climate forcing causes both the nonlinear and linear ecosystem models to become more correlated with the forcing (Fig. 4 *A* and *B*). When forcing the models with the PDO index, the correlation also increases as α increases (red lines). This is expected as the timescale of the ocean is increasing toward the assumed timescale of the ecosystems. As autocorrelation in driving SSTs increases, the SD of variations in both the nonlinear and linear ecosystem models generally increases (Fig. 4 *C* and *D*) and this is much more pronounced in the linear model (Fig. 4*D*). When using the PDO index to force the simple models, we again find that increases in α are generally linked to increases in SD in both ecosystem models (red lines). Examining some specific instances (Fig. S7), as autocorrelation in driving SSTs increases (Fig. S7 *A–C*), regime shifts in the nonlinear system become more frequent (Fig. S7 *D–F*), and the linear system shows increasing deviations from its single equilibrium (Fig. S7 *G–I*). Thus, larger ecosystem changes are associated with increasing memory in the climate forcing, especially in the linear ecosystem model, and if the ecosystem response is nonlinear, then shifts between different regimes become more frequent.

In summary, we detect strong slowing down (reddening) of North Pacific SST fluctuations, and of the PDO index constructed from them, over the observational record. Slowing down since 1960 can be at least partly explained by observed deepening of the ocean mixed layer. It represents a systematic change toward lower frequency, somewhat higher amplitude, North Pacific climate variability. Two of the resulting transitions in the PDO index, around 1977 and 1989, are well-known to have had significant impacts on a diverse range of ecological and climate systems (3, 4). Marine ecosystems, both those that have nonlinear dynamics (9) and those that linearly track climate forcing (11, 12), are vulnerable to large and sometimes abrupt changes in response to the low-frequency variability in the physical ocean (13). Our results suggest that ecosystem variables that respond linearly to climate variability became prone to larger changes over the observational record, as fluctuations in North Pacific SSTs slowed down. Furthermore, those ecosystem variables that respond nonlinearly to climate variability became prone to more frequent abrupt regime shifts. These results may help explain the well-known abrupt changes that occurred in North Pacific ecosystems in 1977 and 1989 (3, 4). The large size, especially of the 1977 shift, could be seen as a linear response to slowing down in climate variability, whereas the two events in relatively quick succession could be interpreted as a nonlinear response to slowing down in climate variability that was less likely to have occurred earlier in the twentieth century.

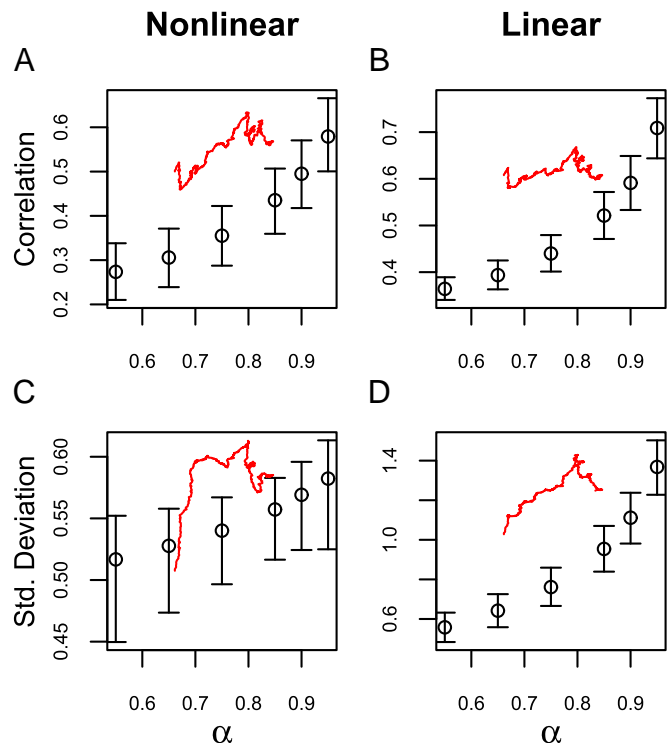


Fig. 4. Effect of reddening climate forcing on two simple models representing marine ecosystems (*Methods*). Correlations between the (A) nonlinear and (B) linear model time series and the forcing time series for different values of α are shown with the 5th and 95th percentiles from 1,000 simulations at each value of α . The mean SDs of the ensemble for the (C) nonlinear and (D) linear model time series are shown with the 5th and 95th percentiles. In all four plots, the red lines show the same analysis when the original PDO index is used to force the simple models and plotting the α -value from this against the other statistics when using a moving window (*Methods*).

It is tempting to extrapolate forward and infer that if the trend toward increasing autocorrelation in the North Pacific ocean were to continue, the propensity for large ecosystem changes would increase. Models are generally poor at simulating observed MLD in the North Pacific (24). However, global warming is robustly expected to drive ocean stratification and a decrease in MLD over the North Pacific (25), which could potentially reverse the historical trend of slowing down.

Methods

The PDO index (3) is the time variation of the first empirical orthogonal function of Pacific SSTs $>20^{\circ}\text{N}$, derived from the UK MO Historical SST dataset (26) and Reynolds' OI SST datasets (27, 28) (V1 and V2) (January 1900–May 2012). We created further indices from the HadISST (16) (January 1870–July 2011), HadSST3 (18) (January 1950–December 2006), and ERSST v3 (17) (January 1900–December 2011) datasets using North Pacific grid points (20° – 60°N) that are complete over the corresponding time spans. The average annual cycle of each grid point was removed, along with a quadratic warming trend (calculated by a regression model fit). Any further detrending using a kernel smoother of fixed bandwidth, with the bandwidth varied as a sensitivity analysis.

For each resulting series, within a sliding window of half the series, the variance was calculated and the AR(1) coefficient (α) estimated by fitting an autoregressive model (Eq. 1). The sliding window length was also varied as a sensitivity analysis. The tendency of an indicator to increase or decrease was measured with Kendall's τ -rank correlation coefficient (ranging from 1 to -1). A positive value indicates an increasing trend in an indicator; the larger the value, the more robust is that trend. Sensitivity analysis results are given as contour plots of Kendall's τ -values.

To determine the significance of our results, we ran bootstrap ensembles of 10,000 runs of a null model, using Eq. 1 with fixed $\alpha = 0.95$, to produce series of identical length to each index. Resulting trends in the null model of AR(1) coefficient were calculated using the same window length (half the

