

Brief Report

Reduced Rainfall Variability Reduces Growth of *Nothofagus alessandrii* Espinosa (Nothofagaceae) in the Maule Region, Chile

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Abstract: *Nothofagus alessandrii* Espinosa is an endemic species of the coastal Maulino forest of central Chile that has historically been severely threatened by the reduction of its habitat and the isolation of its fragments. In addition, a gradual reduction in precipitation has been observed in recent years across its entire natural distribution area. Although the genus *Nothofagus* has been extensively analyzed in dendrochronological studies in the Southern Hemisphere, the dendrochronological potential of this species is unknown. In this study, we developed a novel tree-ring chronology of *N. alessandrii* in order to examine the climate sensitivity of the radial growth and to thus understand its response to climate change in central Chile. Our ring-width chronology showed a series intercorrelation value of 0.48 for the period of 1942–2016 (EPS < 0.85, with 10 trees), showing a strong common growth signal among the trees. *N. alessandrii* growth was strongly influenced by precipitation from May to November (the austral winter and spring seasons), while the temperature signal was weak. We observed that the radial growth patterns of *N. alessandrii* chronology showed upward growth trends, with a marked positive slope until the mid-1980s. However, a negative trend was observed for the period of 1985–2016, which was related to the increased drought conditions (rainfall and soil moisture reductions) in past decades and affected the entire natural distribution of the species. We suggest that drier winters and springs would slow the growth of this species. This information is of vital importance to understanding the growth dynamics of *N. alessandrii*, a critically endangered species, and to take on urgent adaptation and mitigation measures in the face of climate change.

Keywords: tree rings; coastal Maulino forest; climatic variability; wood anatomy



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1. Introduction

Nothofagus alessandrii Espinosa (ruil) is an endangered species [1] that is endemic to the Mediterranean area of Chile. Their condition is mainly due to the limited number of specimens and the fragmentation of their populations [2,3]. Since the beginning of the 20th century, its habitat has been reduced because of the expansion of the agricultural frontier with wheat crops [4] and, since the 1970s, the substitution of forest plantations with non-native species [5]. In addition, these forests have recently been affected by forest fires of great magnitude and intensity [6,7] and persistent drought conditions [8]. In 2008, the

total area of rui forest only covered 314 ha, having decreased by 11.8% over a period of 17 years [3]. Considering the factors described above, we find it is possible that, at present, the remaining area of these forests has been reduced even more. All *N. alessandrii* forests are second-growth forests whose origins are in the regeneration of coppice in forests that were logged and then abandoned [9]. In its natural distribution, forests of this species are only found in the Coastal Range along a linear extension that does not exceed 100 km and that has a discontinuous distribution; in shady exposures; and relatively close to the sea (i.e., between 7 and 30 km) [3]. *N. alessandrii* is a species that has taken refuge in sites that are characterized by higher humidity than other exposures; therefore, in addition to fragmentation, global warming has become another threat to the survival of this species.

One of the consequences of the recent warming of the Earth on a global scale has been the increase in and intensity of droughts [10], such as those in central Chile, a region encompassing the remnant populations of *N. alessandrii*. This region has been experiencing a historical, unprecedented megadrought since 2010 [8]. Forest ecosystems have had to adapt to these new climatic conditions, which has caused changes in the growth of large areas of trees and the composition of forests [11]. The impact of climate change on the radial growth of trees varies according to environmental differences. In humid areas, higher temperatures can promote tree growth by accelerating the appearance of xylem cells or the rate of photosynthesis [12]. Alternatively, warmer weather can trigger drought events, and in dry regions, trees have a reduced ability to absorb water because of reduced xylem carbohydrates, leading to reduced growth [13]. Understanding the spatial and temporal response patterns of forest ecosystems to climate change is of paramount importance to providing a scientific basis for future forest management [14], especially for endangered forest species.

Dendrochronology is a discipline that focuses on the variability of the radial growth of trees (i.e., tree rings) at different time scales [15]. Its scope is diverse, and it has been successfully used in ecological, paleoclimatic, hydric, and chemical studies in different forests in South America [16–18]. Tree rings tell the story of a tree's life and the environment in which it grew; they are natural archives that preserve evidence of past climatic changes and therefore allow paleoclimatic reconstructions [19]. Dendrochronological studies on angiosperms from the Southern Cone have focused on the genus *Nothofagus* because these species present easily distinguishable annual growth rings that have high hydroclimatic sensitivity [18]. Among the most studied species are *N. menziesii* (Hook. F.) Oerst. and *N. solandri* (Hook. F.) Oerst. in the subalpine forests of New Zealand [20,21]; *N. grandis* Steenis in Papua New Guinea [22]; *N. antartica* (Forster) Oerst., *N. betuloides* (Mirb.) Oerst., *N. dombeyi* (Mirb.) Oerst., and *N. pumilio* (Poepp. & Endl.) Krasser in the temperate forests of southern South America [23–26]; and, recently, *N. macrocarpa* in the Mediterranean ecosystems of Central Chile [27,28]. However, there are still unexplored species, such as *N. alessandrii*, which are relevant because they could serve as ecological indicators of a region that is highly vulnerable to global change.

Despite its conservation status, knowledge about the autoecology of *N. alessandrii* is limited [29], especially regarding the biological characteristics of its wood, and the relationship between local climate variability and its dynamics of growth requires further research. These aspects are key for the recovery, conservation, and restoration of a unique species. In 1995, this species was declared as a Natural Monument by the State of Chile, and, consequently, its felling was prohibited, with the exception of if the Chilean forestry service authorized it for research. However, in practice, the felling of any specimen is not authorized, which makes dendrochronological studies of the species difficult. In consideration of the serious fires in 2017 [7], the Chilean forestry service exceptionally authorized the extraction of the ringlets of trees damaged by fire and that were blown down by the wind from the storm. With this material, we seek to understand the climate sensitivity of *N. alessandrii* tree-ring growth. Therefore, we analyze its vulnerability to the increase in the recent drought conditions using a population located on the eastern limit of its range of distribution.

2. Materials and Methods

2.1. Study Area, Sampling and Characteristics of *N. alessandrii* Populations

The study area corresponds to the El Fin property of the Los Ruiles National Reserve, Maule Region, Chile ($35^{\circ}37'47''$ S– $72^{\circ}20'40''$ W) (Figure 1A). The soil of the study area is good for forestry, and according to CIREN [30], it is deep, well-evolved, and formed from metamorphic rocks, with a silty clay loam texture throughout the profile and good drainage. It rests on a substratum composed of highly weathered metamorphic rocks with a high content of micas and quartz. The soil is well-structured and friable, with good porosity that allows for good root development. The slope of the area is undulating and greater than 45% and has moderate erosion, which limits it to forest cultivation. The climate has Mediterranean characteristics; rainfall is concentrated in winter, and there are dry summer periods. Following the Köppen–Geiger classification, the climate is warm temperate with winter rainfall (Csb), with an average annual rainfall of 700 mm and average annual temperature of 11 °C [31].

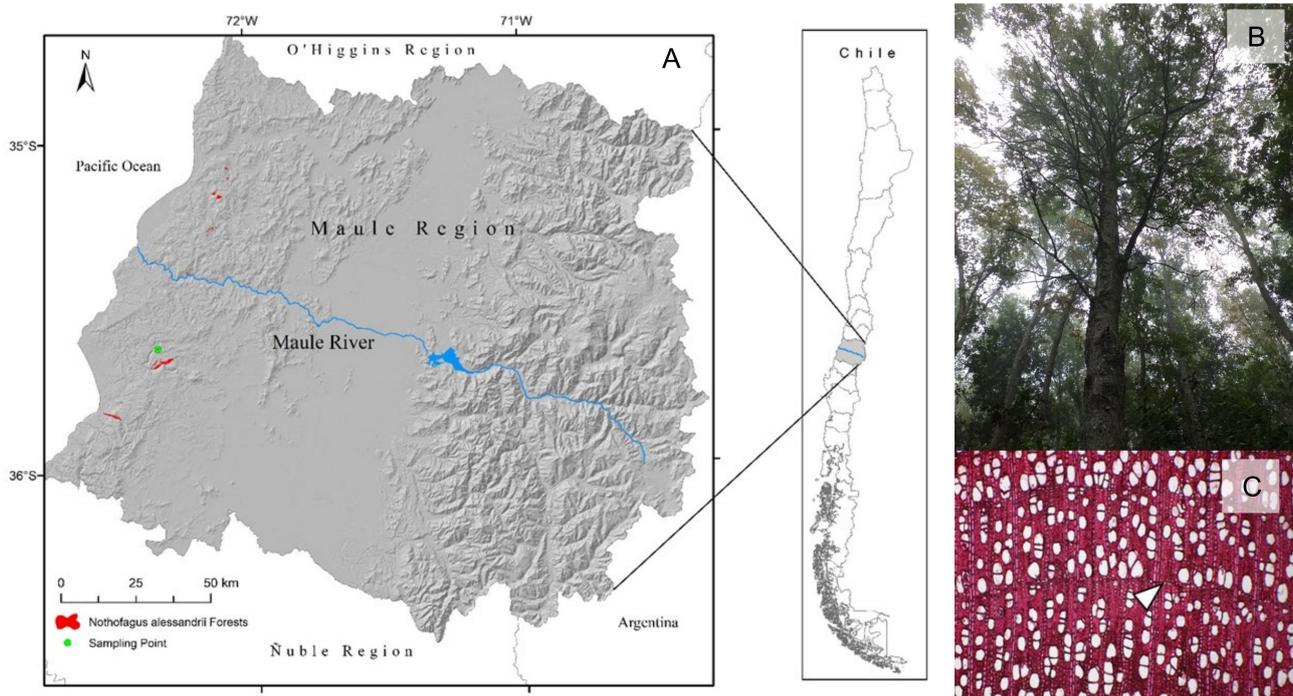


Figure 1. (A) Current distribution of *N. alessandrii* and location of studied population; (B,C) *N. alessandrii* trees and the anatomical structure of annual tree rings.

In August 2019, 10 dead tree stumps (20–32 cm of diameter) were collected from the study site. Each tree died in the 2017 fire and later fell due to a storm, so according to the Schulman convention [32] for the Southern Hemisphere, the last visible complete tree ring corresponds to the year 2016. The samples were obtained from a forest community composed of two heliophyte species (i.e., *N. alessandrii* and *N. glauca*) and from an intermediate layer mainly composed of a sclerophyllous tree species (i.e., *Cryptocarya alba* (Mol.) Looser). *N. alessandrii* represents 43% of the density (507 trees ha^{-1}) and has a site occupation value of 56% (18.7 m^2 ha^{-1} of basal area). *N. glauca* occupies 25% of the basal area (8.3 m^2 ha^{-1}) and only 9% of the density (107 trees ha^{-1}). *C. alba* covers 413 trees ha^{-1} (35% of the density) and 4.3 m^2 ha^{-1} of the basal area (13% site occupation). *N. alessandrii* had a diameter distribution that is concentrated in the intermediate classes, with a diameter equal to 22 cm.

2.2. *N. alessandrii* Tree-Ring Chronology

Core samples were air dried in the laboratory, mounted on wooden supports, and sanded with progressively finer sandpaper (80–12,000 grit cm^{-2}) to clearly delineate annual tree-ring boundaries (Figure 1C). Once the annual tree-ring boundaries could be clearly observed, two to three cores were selected for the delimitation and dating of the tree rings using a stereomicroscope (continuous zoom 7–45 \times). Subsequently, the tree-ring width series was measured using the Velmex measuring system (Velmex Inc., Bloomfield NY, USA, EE.UU.) with a precision of 0.001 mm. We used COFECHA software to statistically validate the cross dating and measurement quality of each core and to find potential errors during the dating stage [33]. We then removed the non-climatic and age-related trends by fitting a regression function and built the tree-ring width chronology using Arstan [34] and the DplR package [35,36] in Rstudio [37]. We used a cubic spline with a 50% frequency response cutoff equal to 67% of the series length, thus isolating the high-frequency variability. The common signal in the temporal variability of tree growth was evaluated using the expressed population signal (EPS) and the series of average correlations (R_{bar}) [15]. In addition, we converted the ring width series to the Basal Area Increment (BAI), which depends less on the size of the tree and is a more representative variable of the growth trends [38]. Later, piecewise regression models of the tree-ring BAI were used to analyze the significant changes in the temporal trends using years as the independent variable, which detected the most significant break years between two consecutive segments of the variable length in the time series [39].

2.3. Relationships between Local Climatic Variability and Radial Growth

We obtained instrumental precipitation records from the closet meteorological station, “embalse Tutuven”, located <30 km away from the study area. We used data for the monthly mean and minimum and maximum temperatures from CRU TS.404, which were extracted from the KNMI Climate Explorer (<https://climexp.knmi.nl/> (accessed on 03 March 2022)). In addition, we analyzed the relationship of the soil moisture and ring width chronology using the gridded data for the soil moisture obtained from the Climate Data Store of Copernicus (<https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-soil-moisture> (accessed on 30 March 2022)). To study the climate–growth relationship, the Pearson correlation analysis function was used to determine the monthly values of the climatic variables and the tree-ring width chronology for the common period of both time series (1942–2016) using the TreeClim package [40]. Because the radial growth in any specific year is influenced by the climate of the current year (t) and the previous year ($t - 1$) [15], correlation analyses were performed for a period of 21 months: from the August before the ring formation through May of the current growing season. The study area has four well-differentiated seasons, so the analyses were performed seasonally (i.e., winter (June to August), spring (September to November), summer (December to February), and autumn (March to May)). This allowed us to identify the climatic seasons with a significant influence on tree growth.

3. Results

3.1. Ring Width Chronology

Of the total samples collected, crossdating was achieved for 100% of them, with a series intercorrelation of 0.48 and R_{bar} of 0.29, indicating that a significant percentage of the trees involved in the analysis have a common growth signal. The age of the trees varied between 75 and 129 years. In addition, we found an EPS value > 0.85 for the period of 1942–2016. All of the trees were crossdated in this period, confirming an optimal common signal for the past 75 years of analysis (Table 1).

Table 1. Descriptive statistics of the residual chronology of the studied *Nothofagus alessandrii* forest.

Chronology	Ruiles National Reserve
Number of samples	18
Number of trees	10
Correlation among series	0.48
Total length	1888–2016
Age Min–Average–Max. (years)	75–95–129
EPS > 0.85	1942–2016 (with 10 trees during whole period)
Mean Rbar	0.25

3.2. Relationship of Radial Growth to the Local Climate

The radial growth of *N. alessandrii* showed a directly proportional relationship with local climate variability and especially with precipitation, which seems to be the main limiting factor. We found that winter and spring precipitation during the growing season had a strong influence on tree growth during the period of 1942–2016 ($r = 0.37$ and $r = 0.50$, respectively, both with $p < 0.001$; Figure 2B). On the contrary, all of the temperature variables that were studied did not show a strong relationship with tree growth, achieving lower r values ($0.27 < r > -0.27$; Figure 2C–E).

The significant values of the growth–precipitation relationship did not change during the entire analyzed period, although it should be noted that the correlation coefficient has increased in recent decades (Figure S1). In this sense, the chronology of the basal area increment (BAI) showed a significant breakpoint in 1985, revealing a negative growth trend for the period of 1985–2016. This linear trend seems to be related to a decrease in winter–spring precipitation and in the spring soil moisture during this period, with $r > 0.60$ and $p < 0.001$ (Figure 2G,H).

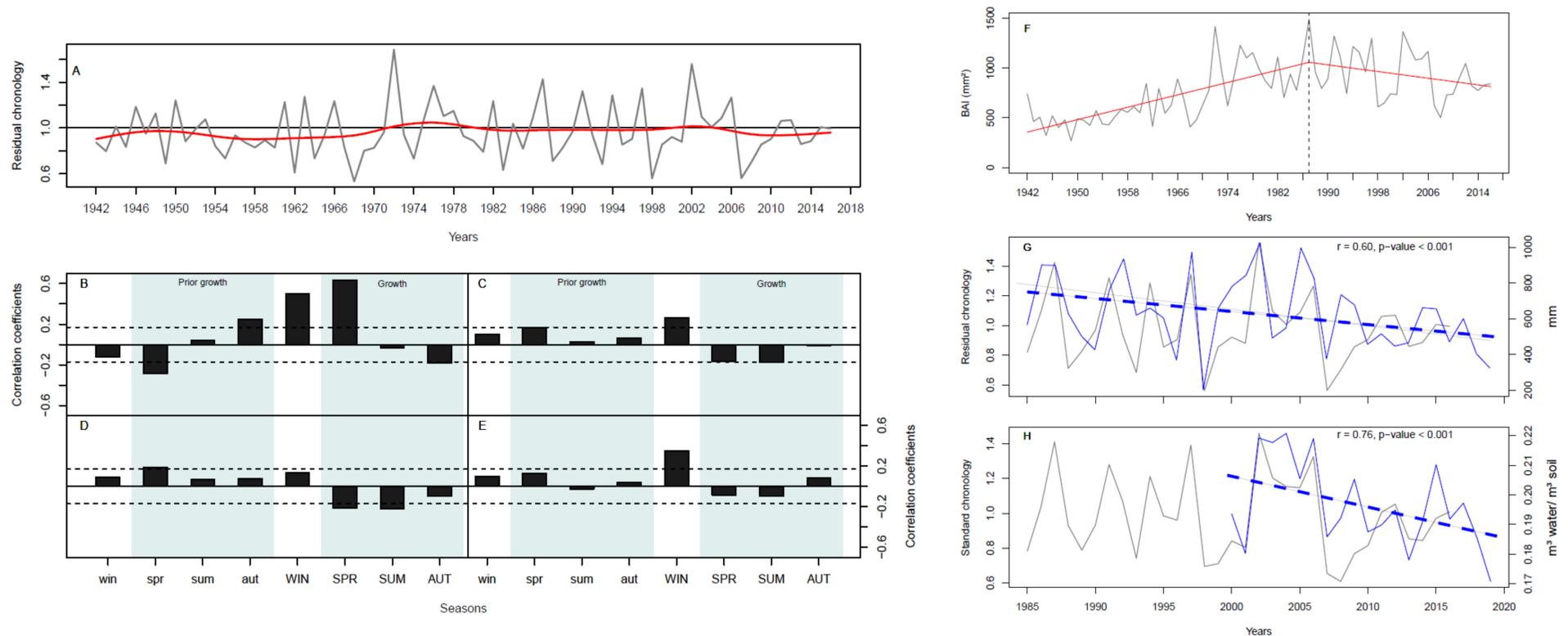


Figure 2. (A) Residual chronology of *Nothofagus alessandrii* (gray curve) with a smoothed filter of 20 years (red curve) and the number of trees per year (gray background) for the period of 1942–2016 (EPS > 0.85, with 10 trees). (B–E) Correlation coefficients between residual chronology (A) and local climatic variables: precipitation (B), mean temperature (C), and maximum (D) and minimum (E) temperature. On the abscissa axis, the lower-case (upper-case) letters represent the seasons of the year: winter (win), spring (spr), summer (sum), and autumn (aut), and the shaded area (light blue) represents the previous ($t - 1$) and current (t) growing seasons. The segmented lines indicate a significant correlation coefficient ($p < 0.05$) with a 95% confidence interval. (F) Average basal area increment series (BAI) and linear trends with detected breakpoint in 1985. (G,H) Correlations between the tree-ring chronology and precipitation (May to November) and surface soil moisture (September to November) for the period with significant negative decreasing trends (1980–2014).

4. Discussion

The suitability of the species *N. alessandrii* for dendrochronological studies was demonstrated due to its clear and well-defined boundaries of annual rings that are similar to the other species of the genus *Nothofagus* [20–22,24–28]. Therefore, we were able to study the environmental and anthropogenic factors that affect the growth dynamics of this species. It was possible to identify key dry years (1924, 1968, and 1998) as indicators of the quality of the measurements, allowing the identification of reliable growth patterns with an intercorrelation between a series of 0.48 (Table 1). For example, *N. pumilio*, a species widely used in dendrochronological studies, has shown correlations in the range between 0.40 and 0.55 [23,24]. Furthermore, the chronology has an EPS value > 0.85 from 1942 to 2016 for all trees during the whole period, indicating a strong common signal between the series and suggesting adequate sample replication with the ten trees studied (i.e., the chronology of *N. alessandrii* is consistent and appropriate for climatic and ecological investigations).

The radial growth patterns (BAI chronology) of *N. alessandrii* chronology showed upward growth trends with a markedly positive slope until the mid-1980s. Then, it stabilized around the mean for approximately the next 10 years, and we observed negative growth until 2016. This last growth period coincided with the megadrought detected for the Mediterranean zone of Chile [8]. This is consistent with our climate–growth analysis, which suggests that sensitivity to drought is expressed in a direct relationship with winter and spring precipitation (Figure 2B). In addition, we found that precipitation and soil moisture strongly influence radial growth after the breakpoint (Figure 2F–H). That is, drier and colder winters would counteract the radial growth of *N. alessandrii* in the study area. The radial growth patterns of *N. alessandrii* and its relationships with the climate coincide with what has been found in other species of its genus in the Maule region and in the Mediterranean zone of Chile [16]. Corvalán and Hernández [41] found that in the Maule region, a deficit in precipitation during the dry period 2007–2012 explains 57.3% of the decrease in the radial growth of *N. obliqua* for that period. The annual reconstruction of the flow of the Maule River based on the ring-width chronology of *Austrocedrus chilensis* (D. Don) Pic.Serm. & Bizzarri shows that water availability is influenced by tropical and high-latitude forcings, such as the El Niño Southern Oscillation and the Antarctic Oscillation. In addition, it reveals a higher proportion of below-average flows in the last century when compared to the previous three centuries [42]. Therefore, the current conditions and climate predictions for the Mediterranean zone of Chile, which indicate an increase in extreme drought events [43], show an increase in the risk of *N. alessandrii* extinction across its entire natural distribution area. In addition, *N. alessandrii*'s limited distribution [3] and anthropic pressures such as plantations [5] and forest fires [6,7] make the conservation of this species critical for future generations.

It is well known that climate change can alter the frequency and intensity of forest disturbances and that drought conditions contribute to an increase in the extent, intensity, and severity of forest fires and the lower water table levels that make tree roots unable to absorb moisture and weaken their natural defenses against pests and pathogens [19]. Taking into account everything described above, we note the information provided in this study is of vital importance to understand the growth dynamics of *N. alessandrii* in relation to climate change, which can guide decision making to conserve this species in the Maule region.

5. Conclusions

Our results show that the radial growth of *N. alessandrii* is sensitive to the rainfall variability of the austral winter and spring seasons, mainly in the period of 1985–2016, where we reported a significant decrease in tree growth. Our research suggests that the current drought conditions, i.e., drier winters and springs and decreased soil moisture in recent decades, are slowing tree growth in this tree species. This information is important to understand the growth dynamics of *N. alessandrii*, a critically endangered species, and to

take urgent adaptation and mitigation measures in the face of climate change, especially considering the climatic current situation in its natural distribution.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/f13081184/s1>, Figure S1: 25-year moving correlation functions for the significant months of Figure 2 of main manuscript text.

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