Characterizing the statistical properties and global distribution of Dansgaard-Oeschger events

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Ice core records from Greenland have shown times of rapid warming during the most recent glacial period, called Dansgaard-Oeschger (D-O) events. D-O events are important to our understanding of both past climate systems and modern climate volatility. In this paper, we present new approaches for statistically evaluating the existence of cyclicity in D-O events and the possible lagged correlation between the Greenland and Antarctica temperature records. Specifically, we consider permutation testing and bootstrapping methodologies for assessing the cyclicity of D-O events and the correlation between the Greenland and Antarctica records. We find that there is not enough evidence to conclude that D-O events are cyclical; however, the Antarctica record leads the Greenland record by 545 years with a statistically significant correlation of 0.455.

Greenland ice core records show times of rapid warming during glacial periods, called Dansgaard-Oeschger (D-O) events[1]. Some argue that a regular process paces D-O events and D-O events are therefore cyclical in nature[2,3,4]. In this manuscript, we assess this hypothesis to better understand the appearance of D-O events. It can be inferred that if D-O events are cyclical in nature, then they contain a deterministic component[5]. The possibility of cyclicity in D-O events may be further explored to better understand climate variability in general. If D-O events instead appear to be randomly distributed throughout time, then the timing of such extreme warming events is not easily characterized and is not likely to be associated with well-documented astronomical or geophysical cycles.

Another characteristic of D-O events that is uncertain relates to the manifestation of D-O events on a global scale. Some suggest that occurrences similar to D-O events are discernible in the Antarctica ice core records[1,6,7,8,9]. A connection of this sort between Antarctica and

Greenland fosters the hypothesis that the climate in the Northern and Southern Hemispheres is linked by some mechanism. Others speculate that the events seen in the Antarctica ice core records have no association with D-O events[10,11]. Under this theory, it is suggested that regional forces govern the climate in the Northern and Southern Hemispheres and that occasionally, climate events occur that are large enough to be recorded on a global scale[10].

The purpose of this paper is to evaluate the stochastic nature of D-O events and whether or not D-O events occur on a global scale. Specifically, we investigate if D-O events exhibit a statistically significant cyclical component or if they are randomly distributed events. In addition, we explore if D-O events are evident in the Antarctica ice core records or found only in Greenland.

Methods

An initial examination of GISP2 and Dome C revealed a quadratic trend in the data. To eliminate this problem, both records were detrended and the analysis was performed on the residuals of the detrended data. Because of the nature of ice cores, GISP2 and Dome C contain unevenly spaced observations. In addition to this, GISP2 is of a higher resolution than Dome C, presenting difficulties when comparing GISP2 to Dome C. In order to remedy these issues, GISP2 and Dome C were linearly interpolated to be of the same resolution with evenly spaced observations. For our analysis, two series were considered. The first series, referred to as the "short series," ranges from 47,245 to 20,000 year BP and contains D-O events 2 through 13. Because the first D-O event occurs during the beginning of the transition between the glacial and interglacial periods, there is not a general consensus as to if this really is a D-O event. To be thorough, we considered the time frame that included this event as well, which ranges from 47,245 to 12,500 years BP. This time frame will be called the "long series." The short series actually introduces a bias towards causing D-O events to appear cyclical because we consider this tight window in which D-O events are consistently appearing, excluding time periods where no D-O events are observed. Because the long

series includes D-O event 1, and thus a stretch of time when no D-O events are observed, this series does not contain the same bias towards making D-O events appear cyclical.

The occurrence of D-O events can be viewed from two perspectives, either non-overlapping or overlapping in nature. These two perspectives are referred to as the non-overlapping D-O events model (NOM) and the overlapping D-O events model (OM). The NOM implicitly assumes that a D-O event is characterized by a sharp increase in temperature followed by a sustained and gradual return to baseline temperature. Because of this rigid definition of a D-O event, a second D-O event cannot occur until the first has run its full course. The OM assumes that a D-O event is characterized by the initial sharp increase in temperature, with the gradual return to baseline temperature being a natural result of the initial change in temperature. Thus, the OM allows for a D-O event to occur before a previous D-O event has run its full course. We consider both characterizations of the D-O event.

Under the OM two perspectives can be taken: (1) D-O events 8 and 12 are not the result of overlapping D-O events but are simply longer than other D-O events, or (2) D-O events 8 and 12 may be considered to be periods in which more than one warming event occurs so closely in time that the temperature does not return to baseline between events. The second perspective implies that D-O events 8 and 12 should not be included in the data generation for the analysis. We explored the potential for cyclicity under both positions and found the conclusions to be the same. For the purposes of this manuscript, we discuss the findings of the first perspective when referencing the OM.

Cyclicity Detection

In order to assess the cyclicity of D-O events, permutation testing and bootstrapping methodologies were applied. Our end goal with these methods is to create a distribution of temperature records that represent the range of possible records under the hypothesis of no cyclicity. Specifically, the D-O events within each series were randomly shuffled (sampled without replacement) or resampled (sampled with replacement) to destroy any cyclicity among the

observed sequence of D-O events. Although the p-values associated with shuffling D-O events were typically lower, the conclusions reached when shuffling or resampling D-O events were the same. For simplicity, the results presented in this manuscript are derived from resampling D-O events only. D-O events were identified objectively using a piece-wise linear model algorithm. The observations between D-O events, referred to as the "filler," were randomized such that groups of sequential observations also remained together in the new series. It was important to allow the filler to be randomized such that continuous segments were retained in order to preserve some of the dependencies inherent to the time series. These resulting series will be referred to as pseudo-series, which act as possible realizations of temperature records under the assumption of the hypothesis of no cyclicity. These pseudo-series were linearly interpolated to contain 1,000 observations. As a result, comparisons can be made between the observed, linearly interpolated series and the pseudo-series without affecting statistical significance.

By the use of periodograms, the maximum periodogram peak of the pseudo-series was obtained and compared to the periodogram peaks associated with the observed series. The periodogram peak of the observed series is the test statistic. The filler of the observed series was also randomized using an approach that resembles the block bootstrap[12,13,14,15,16,17], but ensuring that we have removed any residual low-frequency cyclicity that may be associated with the filler. For the evaluation of each model (NOM and OM), periodogram peaks associated with very low-frequency cycles (i.e., cycles with periods exceeding 2,500 or 3,000 years) were treated as unrelated to D-O event-like phenomena. We refer to this upper bound for the length of a cycle of interest as the cycle length threshold. To evaluate the significance of the observed cyclicity, the test statistic was compared against the maximum periodogram peak of the pseudo-series and p-values were computed. An α level of 0.05 was used as the threshold of significance.

Correlation between GISP2 and Dome C

The correlation at various lags between GISP2 and Dome C was evaluated using similar methods. After generating pseudo-series from GISP2 using the methods previously described, these series were compared to Dome C and the maximum absolute value of the lagged correlations was computed, considering 27-year lags in the range of -2,500 to 2,500 years[6,7]. The inflated experiment-wise error rate associated with the simultaneous testing of multiple lagged correlations was corrected for by creating a distribution of the maximum absolute value of the lagged correlations in the spirit of Tukey's HSD[18]. The correlation of each lag between the original records was then compared against this null distribution to determine significance. Also considered was the correlation between GISP2 and Dome C at a lag of 0 using methods that did not correct for simultaneous testing. The results associated with this procedure should only be considered if we are interested in the correlation of GISP2 and Dome C at a lag of 0 and no other lags.

Results

To evaluate the existence of cyclicities in the manifestation of D-O events, the D-O events in the short and long series were considered under the NOM and OM. The corresponding p-values are summarized in Table (1). It appears that the OM consistently results in lower p-values when compared to the NOM, indicating that cyclicity is more plausible under the OM for D-O events. However, there is no combination of D-O event model, cycle length threshold, and data series length that yields a statistically significant p-value. Evidence for cyclicity is strongest when using the OM, the cycle length threshold of 2,500 years, and the shorter series with a p-value of 0.116. That is, in this setting, the pseudo-series (which randomly distribute D-O events throughout the 47 to 20 kyr BP time period) yield evidence of cyclicity that is more compelling than the original data in 11.6% of the replications.

Also evaluated was the number of D-O events that could have occurred during the short series. Essentially, each D-O event can be considered a Bernoulli trial in which the event

	Cycle Length Threshold	Short Series (47 to 20 kyr BP)	Long Series (47 to 12.5 kyr BP)
NOM	2,500 years	0.229	0.411
	3,000 years	0.284	0.502
OM	2,500 years	0.116	0.273
	3,000 years	0.154	0.355

Table 1: The p-values after considering the short and long series for the non-overlapping D-O events model (NOM) and the overlapping D-O events model (OM). Under these specifications and at an α level of 0.05, there are no significant cyclicities associated with the appearance of D-O events.

either appears or does not appear at a given time. D-O events have been hypothesized to occur every 1,470 years during glacial periods[19]. Based on this information, between 4 and 18 D-O events could have appeared in the short series with probability greater than 0. Under the NOM and OM, the number of D-O events in the pseudo-series was allowed to vary between 4 and 18. Even after varying the number of D-O events that could appear in the short series, at an α level of 0.05, there is no significant evidence of cyclicity in the appearance of D-O events, as summarized by Figure (1).

We explored the possibility that the duration of D-O events was a contributor to these events appearing somewhat cyclic in their manifestation. To test this hypothesis, a duration multiplier was applied to each D-O event in the short series to either shrink or expand the events. The scaled D-O events were randomized and cycles of less than 3,000 years were examined. Because the NOM does not allow D-O events to overlap, the duration multipliers considered under this model were $m_{NOM} = 0.25$, 0.50, 0.75, and 1.00; however, under the OM, the duration multipliers considered were $m_{OM} = 0.25$, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, and 2.00. Figure (2) confirms the suspicion that the observed D-O event durations are ideal for making this series appear cyclic. Because D-O events involve evaluated temperatures for a sustained period of time, the (possibly false) evidence of cyclicity in the time series will be affected by the duration of the events. These analyses indicate that any perception of cyclicity in D-O events is accentuated by event durations that are optimal for appearing
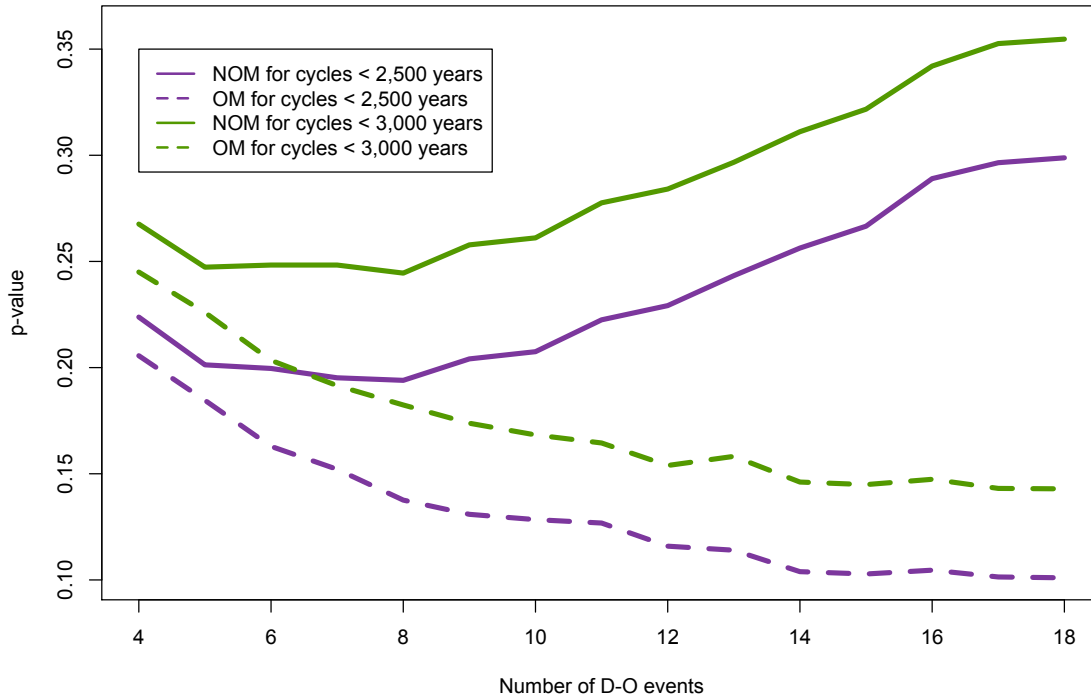
Figure 1: The *p*-values after allowing the number of D-O events in the series to vary from 4 to 18. Using the short series, the non-overlapping D-O events model (NOM) and overlapping D-O events model (OM) were considered. Regardless of the number of D-O events examined, at an α level of 0.05 there is not enough evidence to conclude that D-O events are cyclical in nature.

	NOM	OM
Short Series	0.258	0.140
Long Series	0.483	0.356

Table 2: The p-values after accounting for the possibility of skipping manifestations of D-O events, where the short series is 47 to 20 kyr BP and the long series is 47 to 12.5 kyr BP. Two models were employed: the non-overlapping D-O events model (NOM) and the overlapping D-O events model (OM). Under this paradigm and at an α level of 0.05, there is not enough evidence to conclude that D-O events are cyclical in nature.

cyclic—shorter D-O events with more filler or longer D-O events with less filler each yield less dramatic evidence of cyclicity.

D-O events have been suggested to occur every 1,470 years but may occasionally skip an appearance or two; that is to say, the duration between D-O events could occasionally be 3,000 or 4,500 years[4]. In order to assess this argument, we considered the periodograms of the pseudo-series differently than previously described. Instead of identifying the maximum peak of the periodograms, we found the sum of the two highest peaks within a certain distance of each other at different periodicities. The value that maximized this procedure was retained to represent the particular pseudo-series. The same was done to the observed series after randomizing the filler as previously discussed. This new test statistic was compared to the collection of maximum sums computed from the pseudo-series to evaluate if the cyclicity observed from this perspective was statistically significant. Under this scenario, both the short and long series were considered with the NOM and OM. Table (2) contains these p-values. Because these p-values do not exceed an α level of 0.05, there is not enough evidence to conclude D-O events are cyclical after accounting for the possibility of D-O events skipping an appearance.

The correlation between GISP2 and Dome C from 47 to 20 kyr BP was evaluated at various lags, as shown in Figure (3). The x-axis of this plot represents the lag in years. A positive value means that GISP2 leads Dome C, whereas a negative value indicates that Dome C leads GISP2. It appears that the correlation between these two records is greatest
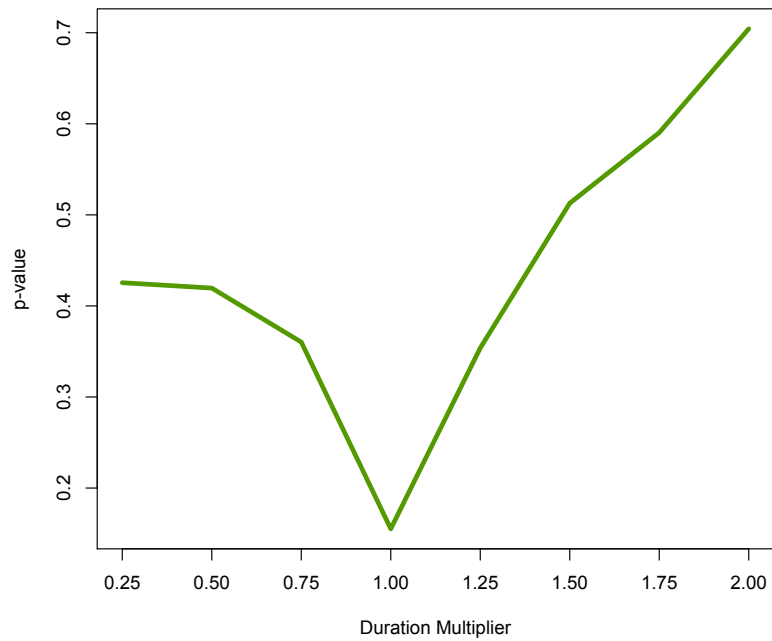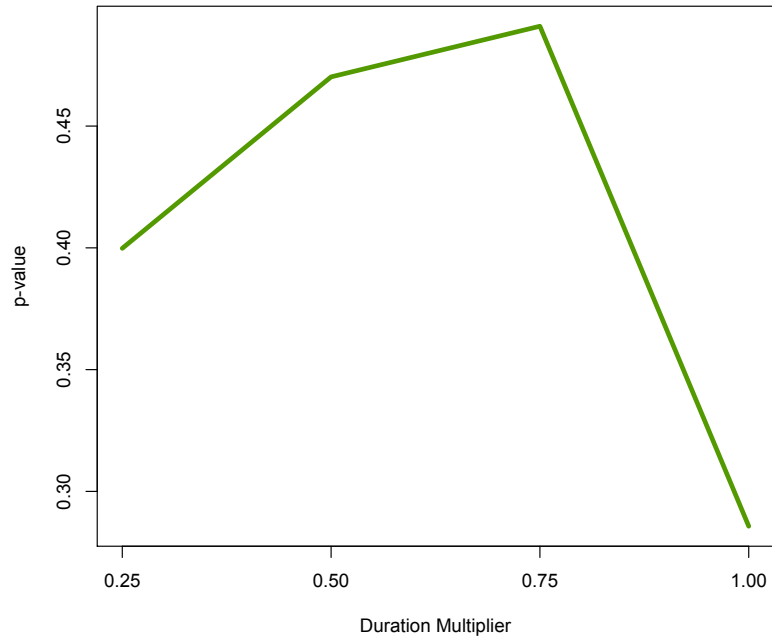
Figure 2: The *p*-values for the non-overlapping D-O events model (NOM, top plot) and the overlapping D-O events model (OM, bottom plot), where the duration multiplier is the amount the D-O events were retracted or expanded. The short series and cycles of less than 3,000 years were considered. The observed duration is ideal for this series appearing cyclic; however, at an α level of 0.05, there are no significant cyclicities.
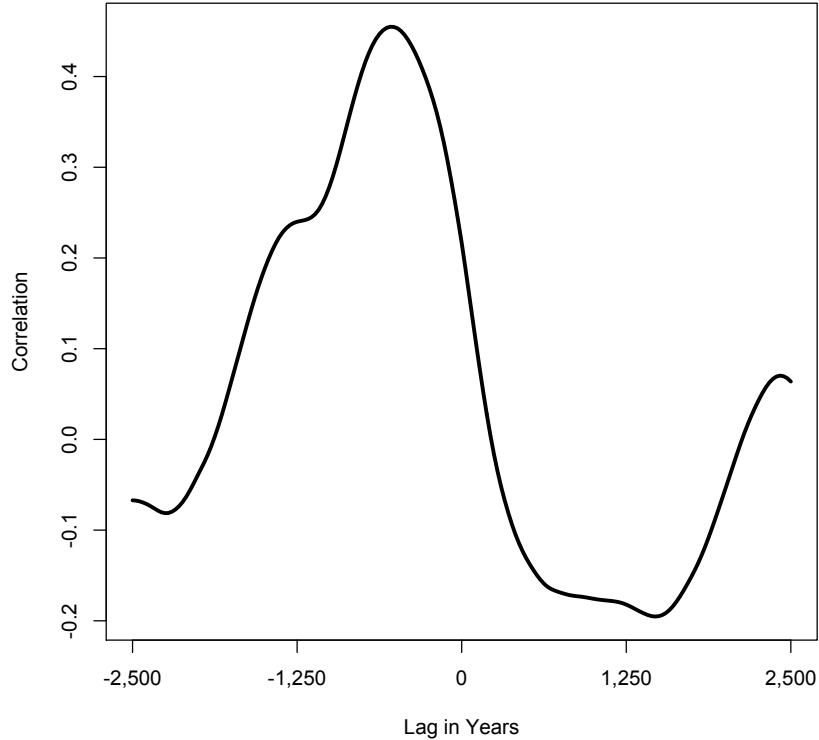
Figure 3: The correlation between the Greenland and Antarctica records at various lags. The records were considered from 47 to 20 kyr BP. A positive lag in years indicates that GISP2 leads Dome C, and a negative lag in years means that Dome C leads GISP2.

when Antarctica leads Greenland. The statistical significance of the correlation between GISP2 and Dome C was assessed under the NOM and OM. Figure (4) shows the resulting p-values at various lags under the NOM. The black line represents the p-values computed using an approach similar to Tukey's HSD and the black point is the p-value at a lag of 0 when we did not correct for simultaneous testing. The red dotted line represents an α level of 0.05. Any observations that fall below this line are significant. The plot similar to Figure (4) was examined for the OM and was almost identical to the plot included in this manuscript.

As Figure (4) demonstrates, under the NOM, the correlations between GISP2 and Dome C are significant when Dome C leads GISP2 by 382 to 682 years. Similarly, when the OM
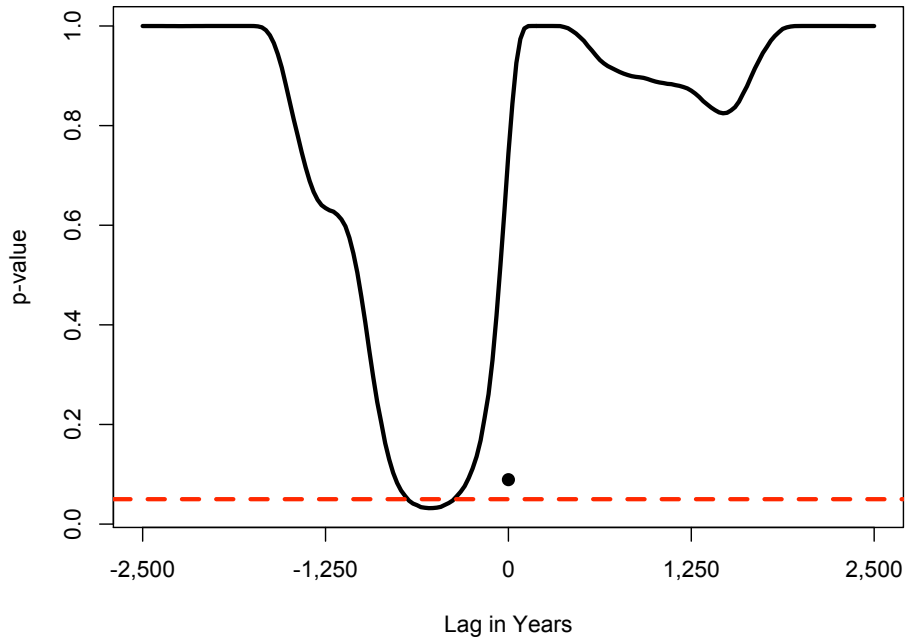
Figure 4: The black line represents the *p*-values, after correcting for simultaneous testing, associated with the correlation between GISP2 and Dome C at each lag. The black point shows the *p*-value at a lag of 0 that has not been corrected for simultaneous tests, and the red dotted line represents an α level of 0.05. The non-overlapping D-O events model (NOM) was considered. When Dome C leads GISP2 by 545 years, the correlation is 0.455, the maximum significant correlation.

is evaluated, significant correlations occur when Dome C leads GISP2 by 382 to 682 years. In each of these two scenarios, the maximum significant correlation between GISP2 and Dome C is 0.455 and occurs when Dome C leads GISP2 by 545 years. Thus, it appears that temperatures in Antarctica lead temperatures in Greenland by 545 years, roughly agreeing with an Antarctica lead of 1,000 to 2,500 years[6].

Discussion

The evidence for cyclicity in observed D-O events is not compelling enough to conclude that D-O events are cyclical, regardless of the D-O event model, cycle length threshold, and data series length imposed. This does not mean that D-O events are not cyclical; rather, there is a lack of evidence to prove they are cyclical. However, for there to be a cycle governing the appearance of D-O events, some external force would have to be involved that causes this regularity. As of yet, an external force that has the same time scale has not been identified. This, coupled with the lack of evidence for cyclicity in observed D-O events, may suggest that D-O events are not cyclical in manifestation. Non-cyclicity of D-O events implies that internal forces govern this climate variability and that the internal climate system is inherently unstable and sensitive.

With this research, we explored two definitions of D-O events. The first definition forces a cooling period between warming events, and thus D-O events are not allowed to overlap (NOM), whereas the second definition allows multiple warming events to occur before the previous warmings return to baseline, allowing D-O events to overlap (OM). Understanding which of these two definitions represents the appearance of D-O events will aid our understanding of the mechanism forcing their manifestation. Specifically, if the NOM describes D-O events, then the mechanism driving their appearance will have long time scale changes, such as ice sheet, whereas the OM representation of D-O events would point to mechanisms that can reorganize quickly.

The length of the lags that resulted in significant correlations between Greenland and

Antarctica suggest that temperature in the Northern and Southern Hemispheres are linked via oceanic teleconnection. In particular, because Antarctica leads Greenland, it appears that the temperature in the Southern Hemisphere changes first, and that change is communicated to the Northern Hemisphere through the ocean. Because of the long length of the lag, an atmospheric teleconnnection is unlikely[6]. Considering this South-North connection and the lack of evidence for cyclicity in the observed D-O events, small climate changes in the Southern Hemisphere may result in amplified changes in the Northern Hemisphere, as demonstrated through D-O events. The larger volume of land and ice in the Northern Hemisphere may cause the amplifications of climate variability in the North. The signal between hemispheres may be transferred through the ocean. In order to evaluate this possibility, further research in this area must be completed.

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