

## Reviewer 1 Comments

5 **General comments:** The present study examines the variability of surface water temperatures at Long Island Sound (LIS) and how cold and warm events in this region are related to a dipole of atmospheric ridge and trough in the North Pacific, and to sea surface temperatures (SST) in the tropical Pacific Ocean.

10 The article addresses a relevant topic with important implications for the climate forecast and impacts community and overall appears to be technically sound. It makes interesting use of quite novel methods (e.g. statistical significance testing of event decomposition or wavelet analyses) to  
15 examine the variability and potential predictability of the LIS thermal system. However, the authors do not discuss any possible physical mechanism that could be responsible for these statistical associations (as stated in the Abstract). The choice of season for each analysis is not always clear and well justified which makes it quite difficult for the reader to understand the (lagged) relationship between LIS water temperatures, the atmospheric dipole and tropical SST  
variability. I think the overall structure of the manuscript could be improved, by being more succinct, by being careful not to over interpret results but rather highlighting how these results are new compared to the previous literature.

### Specific comments:

#### Abstract:

20 **The physical mechanisms are not (or poorly) discussed in the text. The 2012 ocean heat wave across the mid-Atlantic Bight to my knowledge has not been discussed in detail either.**

The authors agree that a physical mechanism is needed to explain the relationships identified in this study. To address the issue, we have included a discussion about how our dipole pattern is linked to LIS temperature variability using well-known ideas in meteorology.

#### 25 **1. Introduction:**

**It would be useful to explain why the LIS is an important region to study (in terms of impacts), and perhaps to describe in more detail previous results on the importance of the EP/NP pattern. If possible, please also add a reference discussing the lack of relationship with the Gulf Stream and NAO.**

30 The authors agree that the reason for studying the LIS needs to be better motivated. As such, a discussion describing the relevance of the LIS to fisheries was included in the revised manuscript. The discussion can be found on Page 3, Lines 7-16 of the revised manuscript. The authors also agree more background material is needed. We now highlight previous work examining EP/NP pattern impacts and use those

studies to motivate the construction of our dipole index on Page 2, Lines 20-28 of the revised manuscript (please see also Page 4, Lines 1-17). A reference to the Gulf Stream and NAO linkages with LIS temperature has also been included on Page 3, Line 21-22.

### 3. Methods:

#### 5 **Page 5 line 7: How many adjacent points are required to be considered an event?**

According to the definition of an event, there is no number of adjacent points required for an event. This lack of length restriction is now made more explicit in the methods section for clarity.

### 4. Results:

#### 10 **Fig. 2: Where are the vertical dotted lines representing the occurrence of canonical and East Pacific El Nino? Perhaps it would be useful to highlight the most intense warm and cold LIS events in red and blue (just a suggestion).**

The authors appreciate the suggestion regarding the clarity of the figure. The most intense LIS events are now highlighted with color; the CP and EP EL Ninos are now indicated with acronyms in the Figure 2a of the revised manuscript.

#### 15 **Section 4.1: It would be nice to clearly explain the added value of the event spectrum compared to the simple time series. The paragraph could also be shortened here. In what seasons are these extreme temperature anomalies more likely to occur? How long do they last? More discussion of Table 1 would be helpful here.**

20 The authors agree that the added value of the event spectrum has not been clearly explained. One reason for choosing the event spectrum approach is that we can treat time periods in which LIS temperature anomalies are of similar sign as individual events, which helps account for autocorrelation in the time series. Accounting for autocorrelation makes our results more statistically robust. Also, by separately looking at negative and positive events we are better able to uncover differences in the intensity of negative and positive events. The event spectrum also provides an easy way to objectively calculate the persistence of events, contrasting with lag-1 autocorrelation coefficients that need to be calculated over  
25 some predetermined time interval. Thus, persistence as measured using autocorrelation would be a function of the time window used. The motivation for the event spectrum can be found on Lines 7-13, Page 7 of the revised manuscript.

30 We found that intense LIS temperature events tend to occur most frequently during the cool season (November-March), presumably because atmospheric forcing is stronger during the cool season. On average, LIS temperature events last about 3 months, but the most intense LIS temperature events can span several seasons. A discussion to this effect was added on Page 10, Lines 1-7 of the revised manuscript.

**Section 4.2: Fig 3: How different do patterns look in each season? How coherent is this atmospheric dipole on different vertical levels? It would be worth detailing the possible physical mechanisms operating behind this forcing from the atmospheric dipole onto LIS water temperature variability. Fig. 4: I wonder how useful this figure is. It is very noisy and difficult to discern the 2012 event.**

5 The atmospheric pattern related to LIS temperature variability is generally the same for each season, but the relationships are strongest in the winter. We now note this seasonality in the revised manuscript. The authors note that the LIS is well-mixed (especially during the winter) so that the atmospheric pattern related to LIS water temperature at one vertical level is the same as those at other vertical levels. This is now mention in the text in Section 4.2. The authors agree that a physical mechanism  
10 behind the dipole pattern relationship with LIS temperature is needed. We now describe the physical mechanism in terms of the jet stream and surface pressure systems. For example, we now describe how the ridge over Alaska induces a downstream anticyclone that can be inferred to advect Arctic air from northern portions of North America into the LIS region. The discussion about the physical mechanism can be found on Page 11, Lines 3-17 of the revised manuscript.

15 The authors have replaced Figure 4 of the original manuscript with a new figure (now Figure 6) showing a less noisy 3-month running mean of the dipole index. The authors feel that it is important to show the time series.

**Section 4.3: The composite analyses are interesting (particularly the discussion of specific LIS events and El Nino years), with potentially important implications for the forecasting of LIS temperatures. However it is not clear how many events compose each of the LIS composites (counted in months, seasons?), which makes it difficult to really interpret in the context of ENSO and predictability. Perhaps it would be useful to show the correlation between the dipole index and SST anomalies (page 12, line 21). It might also be important to discuss the overall added value of the dipole index compared to the EP/NP index used in previous work.**

25 The authors agree that more information regarding the number of events is needed. The authors note that the events are not counted in seasons or months. Rather, the events are an arbitrary length. However, many of the events used in the composites have associated peaks in the winter. Thus, the composites shown in the composite figures generally reflect winter conditions. This information is now provided in Section 4.3 to help guide the reader.

30 Although the authors agree that it would be useful to show the correlation between the dipole index and SST, the authors feel that the number of figures is large already. Instead, we show the correlation between LIS temperature anomalies and SSTs which is similar (Figure 3c of revised manuscript).

We also now include a discussion highlighting the value of our dipole index. We now point out, for example, that the dipole index is optimized to explain the variance of LIS temperature, whereas the  
35 EP/NP index is constructed such that it explains a relatively large fraction of geopotential height variability. Also, the EP/NP index is curiously not defined in December, further complicating its use in a

forecasting setting. We now mention that the dipole index is needed because patterns extracted from an EOF analysis are unable to capture LIS temperature variability in December. An in-depth discussion about the advantages of the dipole index can be found on Page 13, Lines 7-27 of the revised manuscript.

5 **Finally, while the references to extreme LIS events are insightful, I think it might be helpful to consider the 2012 warm event more clearly as a case study throughout the text. It would help with the readability of the text and our understanding of the climate teleconnections mentioned.**

The authors agree that the inclusion of a case study will help readability of the manuscript. Thus, we included composite plots of the March 2012 event, which is now Figure 4 of the revised manuscript. We discuss in more detail the atmospheric and ocean features present during that event as well (please see  
10 Pages 10 and 12 of the revised manuscript).

## Reviewer 2 Comments

**In this paper, the authors performed a statistical analysis to show that Long Island Sound (LIS) surface temperature is linked to mid-tropospheric geopotential height difference between the US east coast and Alaska, which is referred to as ridge-trough dipole in this study. By performing composite analysis, they further argue that the dipole is forced by sea surface temperature anomalies in the central equatorial Pacific. From Figure 2, it is quite clear that LIS surface temperature is determined by the meridional shift of the atmospheric jet and the associated winter storm track across the US east coast. For instance, a northward shift of the storm track will warm up the subtropical North Atlantic and the mid-Atlantic bight, and cool the subpolar North Atlantic. The associated increase in the subtropical high will further increase the trade wind cooling the tropical North Atlantic. This is a well-known process, also known as North Atlantic tripole SST mode, which can be well observed in Figures 7 and 8. The North Atlantic tripole SST mode can be triggered by NAO, ENSO teleconnection and PNA, which is also very well known (e.g., Deser & Blackmon, 1993). Therefore, it is difficult for me to justify the publication of this manuscript in Ocean Science.**

Although the authors do see some evidence for the tripole mode in Figures 7 and 8, the signal is not particularly robust because the composite means are mainly statistically significant along the east coast of the United States. The lack of relationship with the tripole mode is consistent with how LIS temperature anomalies are not strongly linked to the NAO and PNA patterns that have been identified in previous work as excitation mechanisms for the tripole mode. That lack of relationship between LIS temperature anomalies and the tripole SST mode were confirmed by correlating LIS temperature anomalies with SSTs across the North Atlantic. It was found that LIS temperature anomalies are only significantly correlated with Atlantic SSTs along the east coast US and not across other regions where the tripole mode centers are locate (please see Figure 3c in the revised manuscript). Thus, the LIS mode is new and largely different from the tripole mode identified in previous work.

**I also feel that it is not well justified in the introduction why we need to study LIS surface temperature variability. Additionally, I am not convinced that the geopotential anomaly over Alaska is anything to do with LIS surface temperature.**

The authors agree that the physical mechanism behind the dipole pattern-LIS temperature relationship is not well-described in the original manuscript. As such, in the revised manuscript, a physical mechanism behind the connection between the Alaskan height anomaly and LIS temperature anomalies is now described (Page 11, Lines 11-26). We have also included a schematic and references elucidating the connection between the amplified wave pattern and Northeast U.S temperature variability. The importance of the geopotential height anomaly over Alaska is now described using fundamental principles in meteorology. During a negative phase of the dipole pattern (ridge over Alaska and trough over the

eastern US), the ridge over Alaska supports a surface anticyclone just upstream from the upper-level trough over the eastern US. The surface anticyclonic flow then is responsible for the advection of cold continental air across the Northeast US region, amplifying the trough over the eastern US.

5 **The atmospheric circulation anomalies linked to LIS surface temperature anomalies shown in Figure 3 does not appear to be one of the leading modes of NH atmospheric variability (Wallace & Gutzler, 1981) or typical ENSO teleconnection patterns. The East Pacific - North Pacific (EP- NP) pattern, which is inactive in boreal winter, does not look like Figure 3 either.**

10 While the authors agree that the dipole pattern does not resemble many of the well-known leading modes of variability (e.g NAO, PNA, and WP patterns), the dipole pattern is very important to LIS temperature variability. EOF patterns are modes that are extracted from an analysis that seeks patterns that explain the most variance within a data set. These patterns need not be relevant to climate variability across a given region. In fact, Schulte et al. (2016), Schulte et al. (2017a,b) and Schulte et al. (2018) found that the common leading modes do not explain much of the temperature and precipitation variability across the Northeast US. Thus, new patterns must be identified, and corresponding indices need to be constructed  
15 that can explain the temperature and precipitation variability. One alternative approach to EOF analysis is the continuum approach (Frankze and Feldstein, 2005; Johnson et al. 2008) in which atmospheric patterns are viewed as falling on a continuum, contrasting with EOF analysis that statistically partitions the atmosphere into a discrete finite set of patterns. Each location of the globe has a teleconnection pattern associated with it and the pattern may or may not resemble the leading modes extracted from an EOF  
20 analysis, much like how an arbitrary vector may not resemble any of the standard Cartesian basis vectors. To find a relevant teleconnection in the continuum, we adopted a one point correlation map approach, which resulted in our dipole pattern explaining 64% LIS temperature variability. This pattern is very similar to the EP/NP pattern, which we found to be a leading mode of variability, as determined by an EOF analysis (Table 4). In the introduction section of the revised manuscript, we motivate our  
25 construction of the dipole pattern by explaining how EOF patterns cannot capture precipitation and temperature variability across the Northeast US very well (Page 3, Lines 15-28 and Page 4, Lines 1-14). We then discuss the added value of using the dipole index on Pages 3 (Lines 16-28) and 4 (Lines 1-10) of the revised manuscript.

30 The authors disagree with the idea that the EP/NP is inactive in winter. The January and February EP/NP pattern very closely look like our dipole pattern for the same months, as can be confirmed by correlating indices for the EP/NP and dipole patterns during those months (Table 3). In fact, we found that correlation between the dipole index and the EP/NP index is strongest during the months of November, January, and February. These correlations are shown in Table 3 of the original manuscript and confirm that the EP/NP resembles the dipole pattern. Moreover, the relationship strength between the EP/NP and dipole indices  
35 increases from summer to winter, suggesting that the December dipole pattern is the EP/NP pattern and that the EOF analysis is unable to capture the EP/NP pattern in December. In fact, a comparison of the November and January EP/NP patterns with the December dipole pattern reveals a strong similarity

among the patterns, providing more evidence that the EP/NP pattern is active in winter and that the dipole pattern is an important driver of LIS temperature variability. In the revised manuscript, we use these findings to motivate the construction of our dipole index that can be unambiguously defined for all calendar months.

- 5 **I am also confused why the authors use a numerical model data instead of observations for the LIS surface temperature. And, it is not clear what depth is at “the first vertical level”.**

The authors agree that it is important to mention why numerical model data are used. For the Long Island Sound, observations are temporally and spatially sparse so that the output from a numerical model is better suited for the event spectrum analysis that requires continuous data (Please see Page 5, Lines 10-12). The data quality has been evaluated and shown to agree well with observations in previous work (Georgas et al., 2016).

**There are also many statements that do not match with the corresponding figures.**

In the revised manuscript, inconsistencies between the text and figures have been remedied throughout.

15 Franzke, C., and S. B. Feldstein, 2005: The continuum and dynamics of Northern Hemisphere teleconnection patterns. *J. Atmos. Sci.*, 62, 3250–3267.

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20 Johnson, N. C., S. B. Feldstein, and B. Tremblay, 2008: The continuum of Northern Hemisphere teleconnection patterns and a description of the NAO shift with the use of self-organizing maps. *J. Climate*, 21, 6354–6371.

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# Long Island Sound Temperature Variability and its Associations with the Ridge-trough Dipole and Tropical Modes of Sea Surface Temperature Variability

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**Abstract.** Possible mechanisms behind the longevity of intense Long Island Sound (LIS) water temperature events are examined using an event-based approach. By decomposing an LIS surface water temperature time series into negative and positive events, it is revealed that the most intense LIS water temperature event in the 1979-2013 period occurred around 2012, coinciding with the 2012 ocean heat wave across the mid-Atlantic Bight. The LIS events are related to a ridge-trough dipole pattern whose strength and evolution can be measured using a dipole index. The dipole index was shown to be strongly correlated with LIS water temperature anomalies, explaining close to 64% of cool-season LIS water temperature variability. Consistently, a major dipole pattern event coincided with the intense 2012 LIS warm event. A composite analysis revealed that long-lived intense LIS water temperature events are associated with tropical sea surface temperature (SST) patterns. The onset and mature phases of LIS cold events were shown to coincide with central Pacific El Niño events, whereas the termination of LIS cold events was shown to coincide possibly with canonical El Niño events or El Niño events that are a mixture of eastern and central Pacific El Niño flavors. The mature phase of LIS warm events was shown to be associated with negative SST anomalies across the central equatorial Pacific, though the results were not found to be robust. The dipole pattern was also shown to be related to tropical SST patterns and fluctuations in central Pacific SST anomalies were shown to evolve coherently with the dipole pattern and the strongly related East Pacific/North Pacific pattern on decadal time scales. The results from this study have important implications for seasonal and decadal prediction of the LIS thermal system.

## 1 Introduction

Fluctuations in sea-surface temperature (SST) across coastal portions of the United States (U.S.) are driven by changes in oceanic and atmospheric circulation patterns. Changes in water temperature along the U.S. west coast are related to the Pacific Decadal Oscillation (PDO) and the North Pacific Gyre Oscillation, as well-documented (Mantua et al., 1997, Mantua and Hare, 2002, Di Lorenzo, 2008). For the U.S east coast, water temperature fluctuations are related to changes in the Gulf Stream position and variations in the Atlantic Multidecadal Oscillation, PDO, and East Pacific/North Pacific (EP/NP) pattern (Pershing et al., 2015, Schulte et al., 2017). Superimposed on the water temperature changes driven by natural modes of variability is background warming associated with anthropogenic climate change (Pershing et al., 2015).

Although the mechanisms behind SST variability along the U.S. west coast are well-documented, comparatively fewer studies have focused on understanding SST variability across the mid-Atlantic Bight in the context of large-scale climate modes. Two recent studies put water temperature variability across the Gulf of Maine and the Long Island Sound (LIS) in a climate-mode context. The first study by Pershing et al. (2015) showed that the combination of Gulf Stream and PDO influences led to rapid warming of the Gulf of Maine that resulted in the collapse of the cod fishery.

More recently, a second study by Schulte et al. (2018) found the EP/NP pattern to be a dominant pattern governing LIS water temperature variability. The EP/NP pattern was shown to be strongly correlated to LIS water temperature unlike the well-known North Atlantic Oscillation (NAO; Hurrell, 1995), Pacific North American (PNA; Wallace and Gutzler, 1981, Svoma, 2011), Arctic Oscillation (AO; Thompson and Wallace, 1998), and West Pacific (WP; Barston and Livezey, 1987; Linkin and Nigam, 2008) patterns. In fact, Schulte and Lee (2017) found that the EP/NP pattern is more strongly related to temperature variability across the Northeast U.S than the AO, which is often associated with colder-than-normal conditions across the region (Wettstein and Mearns, 2002). Those results suggest that the EP/NP pattern is an important component to seasonal prediction of air and water temperature across the LIS region. Another important aspect of the EP/NP pattern is its strong decadal variability, which could enable decadal prediction of LIS water temperature. Schulte et al. (2018) termed the decadal component of the EP/NP pattern the quasi-decadal mode and showed that it fluctuates coherently with LIS water

temperature anomalies. The physical mechanism contributing to the EP/NP decadal variability was not identified, underscoring the need for an additional study to identify a possible source of the EP/NP decadal variability. Understanding the mechanisms behind the EP/NP decadal variability has implications for seasonal and decadal prediction of LIS water temperature.

5           Improving the current understanding of the climatic mechanisms governing LIS water temperature variability also has important implications for managing fisheries. For example, Howell and Auster (2012), using finfish abundance indices, found shifts in spring community structures that are related to water temperature. The LIS American lobster, which is sensitive to water temperature, dramatically declined around 1997 (Pearce and Balcom, 2005), but managing the lobster harvests has failed to recover  
10 the lobster fishery. For the nearby Rhode Island Sound, biological communities are related to spring-summer water temperature (Collie et al. 2008), suggesting that predicting spring-summer water temperature could aid the setting of fish harvest quotas. These studies underscore the need to better understand water temperature variability across the LIS region so that changes in biological communities can be better monitored and used to better manage fish harvests.

15           Another reason that the LIS is important to study is that it is in a region where air temperature and precipitation are not strongly influenced by well-known climate modes such as the NAO, AO, PNA, and WP that are extracted from the widely used classical empirical orthogonal function analysis (EOF) method (Barston and Livezey, 1987). Schulte et al. (2016) found weak relationships between well-known climate indices and variability of precipitation and temperature across the Northeast U.S. As shown by  
20 Schulte et al. (2018), LIS water temperature variability is strongly related to neither changes in the Gulf Stream position nor fluctuations in the NAO despite being located adjacent to the Atlantic Ocean. The weak Gulf Stream influence is likely the result of the LIS being a semi-enclosed water basin, whereas the general movement of weather systems from west to east may reflect the weak NAO influences because the NAO's centers of action are located downstream of the LIS.

25           Recognizing that well-known climate indices are weakly related to the salinity variability of Northeast U.S. estuaries, Schulte et al. (2017a) adopted a continuum approach (Franzke and Feldstein, 2005; Johnson and Feldstein, 2010; Johnson et al., 2008) to teleconnection pattern extraction and identified an Eastern North American Sea Level Dipole (ENA) pattern that is more strongly correlated

with streamflow than the PNA and NAO indices. In a subsequent study, Schulte et al. (2017b) found the ENA pattern to be strongly related to Northeast U.S. precipitation and LIS salinity. Those results suggest that a continuum approach is better suited for understanding climate variability and associated LIS water temperature impacts than an EOF-based analysis. Although Schulte et al. (2018) did show that the EOF-based EP/NP pattern is strongly correlated with LIS water temperature, the EP/NP pattern for December cannot be unambiguously extracted using the Rotated Principal Component analysis (RPCA) conducted by the Climate Prediction Center (CPC). Furthermore, EOF analysis assumes atmospheric patterns are orthogonal even though orthogonality does not hold for the real atmosphere. This orthogonality assumption can lead to the generation of unphysical modes (Temblay, 2001). In contrast, clustering methods such as Self-Organizing Maps (SOMS) that view the atmospheric as a continuum more accurately produce patterns that are actually observed than EOF analysis (Liu et al., 2006; Johnson et al., 2008, Yuan et al., 2015). Therefore, an additional study is needed to construct an atmospheric circulation index that is strongly related to LIS water temperature variability, physically based, and unambiguously defined for all months.

In this paper, we use an event-based approach to identify LIS water temperature relationships with atmospheric and oceanic patterns. More specifically, the main objectives of the study are the following: (1) identify the atmospheric circulation patterns associated with LIS water temperature events; (2) create a simple atmospheric index that is strongly correlated with LIS water temperature variability; and (3) use the simple atmospheric index to better understand LIS water temperature variability. Because tropical Pacific SST patterns are often used in seasonal forecasting over North America, in this study we also explore if there is a SST-pattern precursor to LIS temperature events.

## 2 Data

In this paper, SST fields from 1870 to 2013 are based on the Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST1) data set (Rayner et al., 2016). Atmospheric fields were analyzed using 500-hPa geopotential height and sea-level pressure (SLP) fields based on the National Oceanic Atmospheric Administration's 20<sup>th</sup> century Reanalysis (Compo et al., 2011) and the National Center for Atmospheric Prediction (NCEP; Kalnay et al., 1996) Reanalysis. The 20<sup>th</sup> century Reanalysis product

was used because the product extends back to 1851, whereas the NCEP Reanalysis product only extends back to 1948. Mean monthly air temperature data from 1979 to 2013 were based on the observed U.S climate divisional data set (Guttman and Quayle, 1996). The data set comprises average monthly temperature data for 344 climate regions (Figure 1a) that partition the U.S into homogeneous climate zones. The annual cycles were removed from the data by subtracting the mean monthly values for each month from the monthly values of the corresponding month for each grid point or climate division.

LIS surface water temperature data used in this study were generated from the New York Harbor Observing Prediction System (NYOPS; Georgas et al., 2016) model. Model generated data were preferred to observational data in this study because observations are temporally sparse and continuous data are needed for the methods adopted in this study. The NYHOPS model is a three-dimensional hydrodynamic model with 11 vertical levels. Following Schulte et al. (2018), water temperature computed on the 1<sup>st</sup> vertical level was considered surface water temperature. The LIS is a well-mixed estuary, so the choice of vertical level is not critical to the results presented in this study. To obtain a single time series representing LIS surface water temperature (for brevity, referred to as LIS temperature, hereafter), water temperature was averaged over the gray-shaded region shown in Figure 1b. The annual cycle in the resulting LIS temperature time series was removed using 1979-2013 monthly means.

The LIS temperature time series and the SST fields were detrended to remove the long-term trend. The time series were detrended by fitting a least-square fit of a line to the time series and subtracting the line from the time series. To check the sensitivity of results to detrending, the analyses were conducted using both the detrended and non-detrended data. Results for the detrended analysis are shown unless otherwise specified. The reason for showing the detrended results is that the study is focused on interannual variability rather than long-term trends.

Indices for the NAO, AO, EP/NP, PNA and the WP were obtained from the CPC and were based on the 1979-2013 period. The NAO, WP, PNA, and EP/NP indices obtained from the CPC were calculated from a RPCA of 500-hPa geopotential height anomalies poleward of 20°N. The AO index was calculated from a rotated RPCA analysis of 1000-hPa geopotential height anomalies. Data for the 1950-2013 period were also used for the EP/NP index.

The Niño 3 and Niño 4 indices from 1870 to 2013 (available at [https://www.esrl.noaa.gov/psd/gcos\\_wgsp/Timeseries/](https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/)) were used to measure the strength and evolution of the El-Niño/Southern Oscillation (ENSO). Whereas the Niño 3 index better describes the evolution of canonical ENSO, the Niño 4 index better describes the evolution of central Pacific ENSO events (Kao and Yu, 2009; Lee and McPhaden, 2010) Thus, using these two indices, we accounted for two different flavors of ENSO. The annual cycles from these ENSO metrics were removed using the long-term (1870-2013) monthly means.

### 3 Methods

#### 3.1 Event Decomposition

10 To better understand the characteristics of climate time series, time series were decomposed into negative and positive events. More specifically, let a time series  $X$  be a sequence of  $N$  data points  $x_1, x_2, \dots, x_N$  at the time points  $t_1, t_2, \dots, t_N$ , where the data points were assumed to be equally spaced. Data points were based on monthly anomalies so that they were both positively and negatively valued. Thus, a complete sequence  $x_1, x_2, \dots, x_N$  was partitioned into subsequences comprising adjacent data  
 15 points whose values are of similar sign. Such subsequences were termed positive or negative events depending on the values of the data points.

The onset and decay of events were defined as follows. A negative event  $E_{neg}$  was said to begin at  $t_j$  if  $x_j < 0$  and  $x_{j-1} > 0$ . A negative event beginning at  $t_j$  was said to terminate at  $t_k \geq t_j$  if  $x_k < 0$ ,  $x_{k+1} > 0$ , and  $x_i < 0$  for all  $i$  such that  $j \leq i \leq k$ . A similar definition was used to define positive events,  
 20 but the sign conventions were reversed. The time point  $t_j$  was termed the onset phase and the time point  $t_k$  was termed the decay phase. The peak intensity of a negative (positive) event was deemed the minimum (maximum) value obtained by a data point within the event period  $[t_j t_k]$ . If the peak intensity of an event occurred at  $t_p$ , then  $t_p$  was termed the mature phase.

Given this definition of an event, an event occurring over the time period  $[t_j t_k]$  contained  $M =$   
 25  $t_k - t_j + 1$  data points, where the integer  $M$  was regarded as the persistence of the event. The cumulative intensity (referred to as the intensity, hereafter) of an event  $E$  was defined as

$$I = \sum_{i=1}^M y_i, \quad (1)$$

where the  $y_i$  are data points composing the event  $E$ . The absolute value of intensity was deemed the magnitude of an event. The duration and intensity of events were depicted using an event spectrum. The event spectrum was comprised of line segments beginning at the onset phases and ending at the termination phases of the events. That is, for each event, a line segment was drawn from the point  $(t_j, I)$  to the point  $(t_k, I)$  so that the length of the line segment represented the event duration.

There are several advantages to using the event decomposition approach. The first advantage is that the autocorrelation of the data is accounted for by grouping the data into events. The second advantage is that persistence of individual events can be readily defined, whereas the lag-1 autocorrelation coefficient measure of persistence needs to be calculated using a data interval so that the lag-1 autocorrelation coefficient may not reflect the persistence of an individual event. A third advantage is that potential nonlinearities are accounted for by analyzing negative and positive events separately.

### 3.2 Wavelet Analysis

To extract time-frequency information from a time series  $X$ , a wavelet analysis (Torrence and Compo, 1998) was implemented. The wavelet transform of  $X$  is given by

$$W_n^X(s) = \sqrt{\frac{2\delta t}{s}} \sum_{n'=1}^N x_{n'} \psi^* \left[ \frac{(n'-n)\delta t}{s} \right], \quad (2)$$

where  $\psi$  is the Morlet wavelet given by

$$\psi(\eta) = \pi^{-1/4} e^{i\omega_0\eta} e^{-\frac{1}{2}\eta^2}, \quad (3)$$

$\omega_0 = 6$  is the dimensionless frequency,  $t$  is time,  $s$  is wavelet scale,  $\delta t$  is a time step (1 month in this study),  $\eta = s \cdot t$ , and the asterisk denotes the complex conjugate (Torrence and Compo, 1998).

To quantify the relationships between climate modes and water temperature as a function of frequency and time, a wavelet coherence analysis was conducted. Following Grinsted et al. (2004), the (local) wavelet squared coherence between two time series  $X$  and  $Y$  is given by

$$R_n^2(s) = \frac{|S(s^{-1}W_n^{XY}(s))|^2}{S(s^{-1}|W_n^X(s)|^2) \cdot S(s^{-1}|W_n^Y(s)|^2)}, \quad (4)$$

where  $W_n^{XY}(s)$  is the cross-wavelet transform defined as the product of the wavelet transform of  $X$  and the complex conjugate of the wavelet transform of  $Y$ . In Eq. (4),  $S$  is a smoothing operator that smooths

coherence in time and in wavelet scale (Grinsted et al., 2004). Using Monte Carlo methods, the statistical significance of wavelet squared coherence was assessed by generating 10000 pairs of surrogate red-noise time series with the same lag-1 autocorrelation coefficients as the input time series and computing the wavelet squared coherence between each pair (Grinsted et al., 2004).

5 To reduce the number of false positive results arising from the simultaneous testing of multiple hypotheses (Maraun and Kurths, 2004; Maraun et al., 2007, Schulte et al., 2015; Schulte, 2016), the cumulative area-wise test developed by Schulte (2016) was applied. The test tracked how the areas of contiguous regions of pointwise significance (significance patches) changed as the pointwise significance level was altered. The test was applied by computing the normalized areas of pointwise significance  
10 patches over a discrete set of pointwise significance levels. The normalized area of a patch was defined as the patch area divided by the square of its centroid's scale coordinate (Schulte et al., 2015; Schulte, 2016). In this study, the normalized areas were computed using pointwise significance levels ranging from  $\alpha = 0.02$  to  $\alpha = 0.18$ . The spacing between adjacent pointwise significance levels was set to 0.02.

The strength of coherence was also measured using global coherence (Schulte et al., 2016), the  
15 time-averaged representation of local wavelet squared coherence. Global coherence is given by

$$G_C(s) = \frac{|W^{XY}(s)|^2}{\left(\sum_{n=1}^N |W_n^X(s)|^2\right)\left(\sum_{n=1}^N |W_n^Y(s)|^2\right)}, \quad (6)$$

where

$$W^{XY}(s) = \sum_{n=1}^N W_n^X(s)W_n^{Y*}(s). \quad (7)$$

(Schulte et al., 2016). The statistical pointwise significance of  $G_C(s)$  was computed using Monte Carlo  
20 methods in a similar manner to local wavelet squared coherence.

A lower dimensional version of the cumulative area-wise test was applied to the global coherence spectra to reduce the number of false positive results (Schulte et al., 2018). The test assessed the statistical significance of one-dimensional arcs using arc length, which is an integrated metric accounting for the width of the peak in wavelet scale (frequency) and the extent to which the peak is above the critical level  
25 of the pointwise test. To track how the arc length of a given pointwise significance peak changed as the pointwise significance level was altered, the arc length of the pointwise significance peak was computed at pointwise significance levels ranging from 0.02 to 0.18. The test statistic in this case is cumulative arc

length. Normalized arc lengths were used to account for how peaks widen with wavelet scale. This normalization was achieved by computing the logarithm (base 2) of the wavelet scales. To further normalize, global coherence values at each wavelet scale were divided by the critical level of the test associated with the pointwise significance level 0.02 at each wavelet scale. The null distribution for the cumulative arcwise test was obtained by generating surrogate red-noise timeseries in the same manner as the cumulative area-wise test. For reference, we also plotted the traditional 5% pointwise significance bounds on all global spectra plots in this study. The reader is referred to Schulte et al. (2018) for more details regarding the cumulative arcwise test.

## 4 Results

### 10 4.1 LIS Temperature Time Series

The time series of detrended LIS temperature anomalies is shown in Figure 2a. Some notable features are the cool periods around 1982, 1996, 2003 (thick blue lines) and the warm events around 1991, 2001, and 2012. The 1982 cool period is rather intense, with LIS temperature anomalies approaching -2°C. In contrast, the 2012 event is associated with a maximum temperature anomaly of approximately 15 3°C, making this water temperature anomaly the largest in the 1979-2013 period.

Unlike the simple time series shown in Figure 2a, the event spectrum shown in Figure 2b clearly distinguishes the intense LIS events from the weak short-lived events. For example, both the cool period around 1982 and the warm episode around 2012 emerge as the most intense cool and warm events in the 1979-2013 period. The 1996, 2003, and 2011 cold events are nearly as intense as the 1982 event (Table 1). It is interesting to note that the most intense negative events shown in Table 1 peak in winter (December-February). This tendency for negative events to peak in winter was confirmed by computing the number of times a negative event peaked in a given month for a larger set of events (32 events) whose intensities fall below the median of all negative event intensities. A similar but weaker tendency was found for positive events, with a majority of the most intense (greater than 50<sup>th</sup> percentile) positive events 25 peaking in January and February.

The event spectrum also allows for the clear comparison of event persistence. An inspection of Figure 2b shows that the intense events are generally more persistent than less intense events. In fact,

Table 1 shows that all the most intense events have persistence of at least 5 months, exceeding the average persistence of 3 months calculated using all events. Negative and positive events were found to have similar average persistence. Given that the average persistence is 3 months, the 1982, 1991, 1996, 2003, and 2012 LIS temperature events are unusually persistent compared to other events in the study period. Moreover, not only is the 2012 event among the most persistent, but also its magnitude far exceeds that of any other event even with the removal of the long-term trend. This result suggests that atmospheric variability may have contributed strongly to that event.

#### 4.2 LIS Events and Atmospheric Patterns

To diagnose a possible mechanism behind the occurrence of the intense LIS events, the correlation between 500-hPa geopotential height anomalies and detrended LIS temperature anomalies was computed. We used this one-point correlation approach to extract a relevant teleconnection pattern from a continuum of patterns, much like how the PNA pattern was originally derived (Wallace and Gutzler, 1981). For this analysis, we focused on the December-February (DJF) season because atmospheric circulation anomalies are generally most pronounced during the DJF season and because the peak of events tends to occur in the winter.

Shown in Figure 3a is the correlation between DJF LIS temperature anomalies and 500-hPa geopotential height anomalies. The positive correlation between LIS temperature anomalies and 500-hPa geopotential height anomalies over the eastern U.S. suggest that warmer-than-normal LIS temperature conditions are associated with a jet stream ridge, which is consistent with how jet stream configurations can influence the temperature in the coastal ocean off the northeastern U.S. (Chen et al., 2014). Similarly, the negative correlations with 500-hPa geopotential height anomalies across Alaska indicate that LIS warm events are associated with an anomalous trough over Alaska. Thus, it appears that LIS temperature events are related to a ridge-trough dipole pattern, an anomalously amplified wave pattern across the U.S.

For comparison, the 500-hPa geopotential height anomaly field for the March 2012 event is shown in Figure 4a. Negative 500-hPa geopotential height anomalies are seen across Alaska, and positive 500-hPa geopotential height anomalies are seen across the eastern U.S. and across the central North Pacific. This 500-hPa geopotential height anomaly configuration is consistent with the results presented in Figure

3a, suggesting that the ridge-trough dipole pattern was an important contributor to the March 2012 LIS temperature event.

A physical mechanism behind the ridge-trough dipole-LIS temperature association perhaps can be better diagnosed by examining the relationship between DJF SLP anomalies and LIS temperature anomalies. As shown in Figure 3b, DJF LIS temperature anomalies are negatively correlated with DJF SLP anomalies across north western Canada. Thus, positive LIS temperature anomalies are associated with anomalous cyclonic flow, whereas negative LIS temperature anomalies are associated with anomalous anticyclonic flow. These relationships are physically consistent with findings from previous works showing how upstream (relative to the LIS) surface anti-cyclones play a crucial in occurrence of cold temperature extremes across the Northeast U.S. (Konrad, 1996, Konrad, 1998). Such surface anti-cyclones have been shown to be dynamically supported by a ridge-trough wave pattern in the middle troposphere (Konrad, 1998; Jones and Cohen 2011), in agreement with the results shown in Figure 3a. At the surface, the anti-cyclone results in cold advection from a high latitude source region into the LIS region (Figure 5a). Cyclones are also typically present along the East Coast U.S. during cold temperature events (Konrad, 1998), which could explain the positive correlation between LIS temperature anomalies and SLP anomalies along the East Coast U.S. Features associated with positive LIS temperature anomalies are opposite to those found for negative LIS temperature anomalies (Figure 5b).

As a specific example, consider the SLP anomaly pattern for March 2012 (Figure 4b). Negative SLP anomalies are seen to extend from western Alaska to central Canada, indicative of anomalously strong cyclonic flow and warm air advection across the eastern U.S. The location of the negative SLP anomalies generally coincide where SLP anomalies are correlated to LIS temperature anomalies (Figure 3b), again suggesting that the ridge-trough pattern played an important role in the March 2012 LIS temperature event.

To better understand LIS water temperature variability, a ridge-trough dipole index was created based on the pattern identified in Figure 3a. The dipole index was constructed by first locating the grid point for which the correlation between LIS temperature and 500-hPa geopotential height anomalies is minimum. This grid point is located at 70°N and 157.5°W and is marked by a cyan cross in Figure 3a. Next, the grid point for which the correlation between LIS temperature and 500-hPa geopotential height

anomalies is maximum was located. This grid point is located at 42.5°N and 75°W and is marked with a magenta cross in Figure 3a. Following Wang et al. (2014), the dipole index for a given month was defined as the 500-hPa geopotential height anomaly at 42.5°N and 75°W minus the 500-hPa geopotential height anomaly at 70°N and 157.5°W. Thus, the dipole index measures the intensity of the ridge-trough dipole pattern such that positive phases generally indicate that an anomalously strong ridge over the eastern U.S is accompanied by an anomalous trough over Alaska. Correlating the dipole index with SLP anomalies (not shown) reveals that negative (positive) phases of the dipole pattern are associated with positive (negative) SLP anomalies across north western Canada and cold (warm) air advection to the east of the anomaly center (Figure 5).

10 The time series for the 3-month running mean of the dipole index is shown in Figure 6. The time series is rather noisy, but notable features can still be identified. The dipole pattern, as indicated by positive dipole indices, is seen to be in a persistent positive phase around the 2012 LIS warm event. The positive dipole event around 2012 is quite intense but not as intense as the 1882 positive dipole event that persists for 11 months (Table 2). The most intense negative dipole event occurs around 1977. A comparison of Tables 1 and 2 shows that the second most intense negative dipole event calculated using the raw monthly dipole index time series coincides with the second most intense LIS cold event that occurred around 2003 (Table 1).

Although a comparison of Tables 1 and 2 shows that the 2012 LIS warm event coincides with the third most intense positive dipole event, the relationship strength between LIS temperature anomalies and the dipole pattern cannot be inferred. How strongly related is the dipole index to LIS water temperature anomalies? To assess the strength of the dipole index relationship with LIS water temperature anomalies, seasonally averaged detrended LIS temperature anomalies were correlated with the seasonally averaged dipole index. As shown in Figure 7, the dipole index is strongly correlated with LIS temperature anomalies for the October-December (OND), November-January (NDJ), DJF, and January-March (JFM) seasons. The relationships are generally stronger if the dipole index leads by 1 month, as indicated by the dotted line in Figure 7. The lagged correlation coefficients approach 0.8 for the DJF season, suggesting that DJF LIS temperature anomalies are strongly influenced by the dipole pattern in the NDJ season. Lagged correlations are also strong ( $r > 0.6$ ) for the OND, NDJ, and JFM seasons. The relationships are

generally weaker in the warm seasons possibly because teleconnection patterns are generally of the weakest amplitude in the warm season. Another reason is that LIS temperature anomalies in the winter can persist into the summer (Schulte et al., 2018), weakening the simultaneous relationships between LIS temperature anomalies and the dipole pattern for non-winter seasons. However, the weaker relationships between air temperature and the dipole index in the summer (not shown) likely contribute to the seasonal cycle in relationship strength shown in Figure 7.

The relationship strength found between the dipole index and LIS temperature anomalies is consistent with results found in prior work because the dipole index is strongly correlated with the EP/NP index for most months (Table 3) and because the EP/NP index is strongly correlated with LIS temperature anomalies (Schulte et al., 2018). However, Schulte et al. (2018) used an ad hoc approach to construct the December EP/NP index using linear regression. Thus, one may ask: is the EP/NP pattern a wintertime pattern? To answer the question, it is first noted that the relationship strength between EP/NP and dipole indices increases nearly monotonically from August to November, decreases almost monotonically from January to August, and peaks in January. With a such clear seasonal cycle, it is natural to infer that the December dipole pattern is largely the December EP/NP pattern despite how the CPC suggests that the EP/NP pattern is inactive in winter. Because the 500-hPa geopotential height anomaly structure associated with the dipole pattern is the same from November to March (not shown), one can deduce that December ridge-trough pattern is largely the December EP/NP pattern given the strong relationship between EP/NP and dipole indices during those months. More specifically, we compared the December dipole pattern to the January dipole pattern (Figure 8) and found them to be similar in terms of 500-hPa geopotential height anomalies. Thus, because the January dipole and EP/NP indices are strongly correlated, the December dipole pattern must also be EP/NP like. The strong relationships ( $r > 0.8$ ) between air temperature and the dipole pattern in winter suggests that the dipole pattern (or EP/NP pattern) is particularly active in the winter. It also has a strong physical basis because negative phases are associated with 500-hPa western North America and Arctic ridging, and eastern U.S. 500-hPa troughing (Figure 8), all features associated with eastern U.S. cold temperature events (Konrad, 1998). Although Schulte et al. (2018) used the EP/NP index to diagnose historical LIS temperature variability, our dipole index is defined in all months and is easy to calculate, making it more practical in an operational forecasting setting.

While the December dipole index is well-correlated with December indices for the AO, NAO, and WP, a close examination of the 500-hPa geopotential height anomaly fields (not shown) associated with those patterns reveals that those patterns are quite different from the dipole pattern found in this study. For example, the NAO and AO indices are correlated 500-hPa geopotential height around the dipole pattern's eastern center of action (green cross in Figure 3a) but are practically uncorrelated with 500-hPa geopotential height anomalies around the western center of action. The NAO and AO are also much more strongly correlated with 500-hPa geopotential height anomalies across the North Atlantic than the dipole pattern. The WP index is only weakly correlated with 500-hPa geopotential height around both dipole pattern's centers of actions and much more strongly correlated with 500-hPa geopotential height anomalies across the western North Pacific Ocean. Our results suggest that the reason why the wintertime AO, NAO, and WP patterns are not strongly related with wintertime LIS temperature anomalies as shown by Schulte et al. (2018) is that these patterns are not related to northern Alaskan jet-stream ridging that is important to LIS temperature variability (Figure 3a).

The fact that the dipole index is correlated with multiple large-scale indices (Table 3) suggests that the dipole pattern falls on a continuum of teleconnection patterns (Franzke and Feldstein, 2005) such that the dipole pattern is strongly EP/NP-like. Although we found by conducting our own EOF analysis of 500-hPa geopotential height anomalies that the AO pattern is the leading mode of variability, the EP/NP pattern appears to be consistently the 5<sup>th</sup> to 7<sup>th</sup> leading mode of variability. Thus, although the EP/NP pattern is not as dominant as the AO pattern, the dipole pattern tends to more closely resemble it than the AO pattern. Furthermore, the continuum-based extraction of a dipole pattern with a strong relationship to LIS temperature anomalies supports the idea that the continuum approach is useful for understanding climate variability across the Northeast U.S., a finding like that found in previous work focusing on precipitation in the Northeast U.S. (Schulte et al. 2017a, b). In particular, our results show that the one-point correlation map approach used by Wallace and Gutzler (1981) is a powerful but simple tool for understanding regional climate variability.

Given that LIS water temperature is strongly correlated with air temperature (Schulte et al., 2018), it is hypothesized that the dipole index is related to air temperature across the U.S., especially around the LIS. To confirm a dipole index-air temperature relationship, the dipole index was correlated with average

monthly air temperature anomalies for the 1979-2013 period (Figure 9). The results for the NDJ season are only displayed because the strongest correlation found in Figure 7 is between the NDJ dipole index DJF LIS water temperature anomalies.

As shown in Figure 9, the dipole index is, indeed, strongly correlated with air temperature anomalies across a large region of the U.S. Correlation coefficients exceed 0.8 and approach 0.9 across the Northeast U.S. and LIS region. The strong relationships extend to the southern U.S., and the relationships generally weaken equatorward. The relationships displayed in Figure 9 are generally stronger than those associated with the AO and NAO (not shown) whose influence on eastern U.S. temperature has been well-studied (Hurrell and van Loon 1997, Wettstein and Mearns, 2002). Thus, our dipole index is useful for diagnostic studies of cold outbreaks across the eastern U.S. The results for the other seasons are similar, but the relationships for seasons not comprising November, December, January, February (e.g. June-August) are generally weaker than those identified for the NDJ season. This result suggests that the dipole pattern is rather dominant in the winter. The strong relationship between the dipole index and U.S. air temperature anomalies is consistent with how the intense 2012 dipole event coincides with the record warm March 2012 (Dole et al., 2014), which resulted in a so-called false spring in which plants bloomed prematurely making them susceptible to drought and freezes (Ault, 2013). The results shown in Figure 9 suggest that the dipole pattern's impact on LIS temperature is related to the dipole pattern's influence on air temperature.

#### 4.3 Intense LIS Events and SST Patterns

SST patterns are often used in seasonal forecasting and, thus, identifying an SST pattern precursor to LIS temperature events has implications for seasonal prediction of LIS temperature anomalies. To identify SST patterns associated with LIS temperature events, a lagged SST composite analysis was conducted using detrended LIS warm and cool events separately. The SST composite plots for the warm events were constructed using the LIS warm events whose intensities are greater than or equal to the 50<sup>th</sup> percentile of all warm event intensities (32 events). Similarly, the SST composite plots for the cold events were constructed using LIS cold events whose intensities are less than or equal to the 50<sup>th</sup> percentile of all LIS cold event intensities (32 events). The composite mean SST patterns were computed at the onset,

mature, and decay phases of the LIS events. Because intense LIS events tend to peak in winter, the composite plots for mature phases mainly reflect wintertime conditions.

The results for the LIS cold events are shown in Figure 10. The composite plot shown in Figure 10a indicates that the onset of LIS cold events is associated with positive SST anomalies across the central equatorial Pacific. The results suggest that LIS cold events could be initiated by central Pacific El Niño events (Lee and McPhaden, 2010). A few examples of central Pacific El Niño events (based on the December-March season) are the 1991–92, 1994–95, 2002–03, 2004–05, and 2009–2010 events (Table 5), but a more complete list can be found in Johnson and Kosaka (2016). The 2002–2003, 2004–2005, and 2009–2010 events all appear to occur around LIS cold periods (Figure 2a). Note that there could be lags between the onset of central Pacific El Niños and LIS temperature anomalies because of the lagged response of water temperature to atmospheric forcing (Schulte et al., 2018). In addition, pre-existing positive water temperature anomalies may need time to degrade.

The SST anomaly pattern for the mature phases of LIS cold events features positive SST anomalies across the central equatorial Pacific (Figure 10b). However, the mature-phase composite mean SST anomaly pattern is more pronounced across the North Pacific Ocean than it is for the onset phase. A region of positive SST anomalies is seen to be horseshoe-shaped, with positive SST anomalies extending from the central equatorial Pacific to the U.S. west coast. Although Hartmann (2015) found an SST pattern resembling that shown in Figure 9b to be a contributor to the February 2015 eastern U.S. cold event, only a single event was considered. In this study, we show that the pattern is associated with numerous LIS negative temperature events (and thus eastern U.S. air temperature events), many of which persist for more than 5 months. Thus, we show here that the SST pattern influences both the intensity and persistence of events. It is noted that the pattern shown in Figure 10b resembles the DJF SST pattern of 1996, which is consistent with how 1996 was a cooler-than-normal period for much of the U.S. (Haplert and Bell, 1997) and the LIS (Table 1).

Unlike the composite mean SST pattern corresponding to the onset phase, negative SST anomalies are present along the U.S. east coast and across the Gulf of Mexico during mature phases. These results are consistent with how LIS temperature anomalies are strongly associated with the dipole pattern that influences air temperature across regions adjacent to the Gulf of Mexico and U.S. east coast. This

relationship between the dipole index and SST anomalies was confirmed by correlating the dipole index with SST anomalies for different seasons (not shown).

The tropical SST pattern associated with the decay phase of LIS cold events is different from those associated with the onset and mature phases (Figure 10c). The composite mean SST anomaly pattern most closely resembles the first leading mode of SST variability called the canonical ENSO pattern (Hartmann, 2015), though the most intense positive SST anomalies are still confined to the central equatorial Pacific. This result suggests that there may be a tendency for the decay of LIS cold events to coincide with canonical ENSO patterns or an SST pattern that is a mixture of central and eastern Pacific El Niños lying on a continuum of ENSO flavors (Johnson, 2013).

The tendency for the decay of LIS cold events to coincide with canonical ENSO patterns is more evident when constructing SST composites using the 10<sup>th</sup> percentile (Figure 11) instead of the 50<sup>th</sup> percentile used to construct the composite shown in Figure 10. However, possibly because of small sample sizes (7 events), the results generally lack statistical significance. Nonetheless, the event spectrum depicted in Figure 2b indicates that the major cool period around 1982 and 1997, for example, terminate around the major 1982/83 (Ramusson and Wallace, 1983; Quiroz, 1983) and 1997/1998 (McPhaden, 1999) El Niño events. Although Schulte et al. (2018) showed that LIS temperature anomalies are associated with a single SST pattern, we show in this study that predicting the evolution of LIS temperature events may require knowledge of several ENSO flavors.

The composite analysis was also conducted for LIS warm events, and the results revealed that LIS warm events are also associated with SST modes of variability (Figure 12). The onset of LIS warm events appears not to be associated with any coherent SST pattern. For the mature phase, statistically significant negative SST anomalies are seen across the central equatorial Pacific and positive SST anomalies are seen across the eastern equatorial Pacific. Like the SST anomaly pattern associated with mature phases of LIS cold events (Figures 10b and 11b), the pattern shown in Figure 12b generally resembles the 3<sup>rd</sup> leading mode of SST variability (Hartman, 2015). The SST pattern corresponds well with the SST anomaly pattern associated with March 2012 (Figure 4c), a month in which record warmth was experienced across the central and eastern U.S. (Dole et al., 2014). Mature phases are also associated with positive SST anomalies along the U.S. east coast and across the Gulf of Mexico like March 2012 (Figure 4c). Decay

phases (Figure 12c) appear to be associated with negative SST anomalies across the eastern and central equatorial Pacific, but the results were not found to be statistically significant.

The findings for the warm LIS events were found to be sensitive to the threshold used to construct the composites. For example, if we only considered the LIS warm events whose intensities were greater than or equal to the 90<sup>th</sup> percentile of LIS warm event intensities, then all phases of LIS warm events would resemble the pattern shown in Figure 12b. In general, the positive SST anomalies across the eastern Pacific were found to become more intense as the percentile used to establish the threshold was increased from 50 to 90. Despite the lack of statistical significance in the composite plots, statistically relationships with SST anomalies were found when correlating DJF LIS temperature anomalies with DJF SST anomalies (Figure 3c). The identified correlation pattern was found to resemble the pattern shown in Figures 10b and 11b.

The SST composite analyses were also conducted using the dipole events for the 1979-2013, 1950-2013, and 1870-2013 periods. The resulting SST patterns were found to be like those shown in Figures 10, 11, and 12, which is not surprising given the strong correlation between the dipole index and LIS temperature anomalies. Thus, intense long-lived dipole patterns seem to have a tropical origin, suggesting that a key to better understanding LIS temperature events rests in a firmer understanding of tropical processes.

#### 4.4 Decadal Variability

The results of the composite analyses suggest that dipole events may be associated with tropical SST patterns, but the time scale at which the SST patterns are most strongly associated with the dipole pattern cannot be inferred from the analysis. Thus, a wavelet coherence analysis was conducted to determine if the SST modes fluctuate coherently with the dipole pattern at a preferred time scale. The wavelet squared coherence was computed between the dipole index and indices for Niño 3 and Niño 4 metrics, but the results using the Niño 4 index were found to be most robust. As such, the results for the Niño 4 index analysis are only shown.

The results shown in Figure 13a indicate that the dipole and Niño 4 indices fluctuate coherently in the 64- to 256-month period band after 1930. The results suggest that stronger decadal-scale fluctuations in central equatorial Pacific SSTs are associated with larger decadal fluctuations in the dipole

pattern. Given that the decadal-scale fluctuations in the dipole pattern contribute to the overall variance of the dipole index around 2012, the decadal-scale fluctuations must contribute to some extent to the intense dipole event of 2012. The results from the coherence analysis thus suggest that central equatorial Pacific SST fluctuations may have contributed to that intense dipole event.

5           The strong correlation between the EP/NP and dipole indices (Table 3) suggests that the coherence between the EP/NP and Niño 4 indices is also strong. The strong coherence was confirmed by computing the wavelet squared coherence between the EP/NP and Niño 4 indices for the 1950-2013 period. To perform the analysis, the missing values for the EP/NP index in December were filled by establishing a linear relationship between the EP/NP and dipole indices for all months but December. The linear  
10 relationship was obtained using a least-squares fit of a line, and it was used to fill missing EP/NP values based on the available December dipole index values.

As shown in **Figure 14**, the EP/NP index does, indeed, fluctuate coherently with the Niño 4 index. The coherence appears to be strong, and the global coherence spectrum shows arcwise significant global wavelet coherence in the 64-256 month period band. As shown by Schulte et al. (2018), the EP/NP pattern  
15 fluctuates strongly on quasi-decadal time scales, but no possible source of the variability was identified. We show in **Figure 14** that the EP/NP variability on quasi-decadal time scales may be related to quasi-decadal fluctuations in central equatorial Pacific SSTs. Because the EP/NP pattern fluctuates coherently with LIS water temperature on decadal time scales (Schulte et al. 2018), LIS water temperature should also fluctuate coherently with the Niño 4 index, though the LIS temperature time series is too short to  
20 draw strong conclusions.

## 5 Conclusion and Discussion

This paper revealed that LIS events are associated with modes of tropical Pacific and North Pacific SST variability. The spatial characteristics of the SST patterns was demonstrated to depend on the phase of the LIS events. The onset of LIS cold events was shown to be associated with central equatorial Pacific  
25 SST anomalies, whereas the decay phase of such events was shown to coincide with canonical ENSO events. These results suggest that central Pacific El Niño events can be used to construct outlooks for the onset of major LIS cold events. Similarly, information regarding the formation of canonical ENSO events

could prove useful as guidance for assessing how likely a LIS cold event will end. Conversely, major LIS cold events could be used to anticipate the formation of El Niño events.

The strong relationships identified between the dipole index and LIS temperature anomalies suggest that the dipole index should be incorporated into LIS temperature outlooks and possibly temperature outlooks for other regions of the U.S. as well. The forecast skill associated with such outlooks will depend on the ability to predict the phase and intensity of the dipole pattern. The association between tropical SST patterns and the dipole pattern could prove useful in extended dipole pattern outlooks, contrasting with the AO index whose predictability is limited (Jung et al., 2011). The coherence between the Niño 4 index and indices for the EP/NP and dipole patterns supports the idea that extended dipole pattern outlooks based on tropical SST patterns may be possible. More research, however, is needed to quantify the ability of dynamical weather and seasonal forecasting models to predict the pattern.

Although not the focus of this paper, the dipole pattern may be an important temperature indicator for other estuaries across the Northeast U.S. The correlation pattern shown in Figure 9 suggests that the dipole pattern could be an important temperature indicator for the Delaware Bay and Chesapeake Bay estuaries. The strong correlation between air temperature and the dipole index across Maine also suggests that the dipole pattern may contribute significantly to the variability of water temperature across the Gulf of Maine. The Gulf of Maine has experienced rapid warming during the past decade (Pershing et al., 2015) and understanding the causes of the rapid warming has important implications for fisheries. Future work could therefore include understanding how the dipole pattern may have contributed to the rapid Gulf of Maine warming.

The results from the present analysis are consistent with temperature events that occurred after the study period considered in this study. For example, the cold period around February 2015 transitioned into a record warm period for most of the U.S. The record warm period lasting from September 2015 to December 2015 coincided with an extreme El Niño event (Hu and Federov, 2017). In agreement with our results, the February 2015 SST pattern strongly resembled the SST pattern shown in Figure 10b, which our results suggest occurs at the peak of LIS cold events. Furthermore, the SST pattern and extreme cold across the eastern U.S. occurred before the El Niño formation, which is also in agreement with the results from the present study. These recent events support the results from our study that indicate extended LIS

temperature outlooks may be possible if information regarding ENSO flavors are incorporated into such outlooks.

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### Data availability

The 20<sup>th</sup> century reanalysis data is available at [https://www.esrl.noaa.gov/psd/data/20thC\\_Rean/](https://www.esrl.noaa.gov/psd/data/20thC_Rean/) and  
5 NCEP reanalysis data are available at  
<https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html>. The Hadley SST data are  
available at <https://www.metoffice.gov.uk/hadobs/hadisst/data/download.html>. Monthly indices for the  
atmospheric climate modes can be found at <https://www.esrl.noaa.gov/psd/data/climateindices/list/>, while  
the long-term Nino 3.4 and Nino 4 indices are available at  
10 [https://www.esrl.noaa.gov/psd/gcos\\_wgsp/Timeseries/](https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/). The Long Island Sound data is available at  
[https://www.researchgate.net/publication/306256135\\_LIS\\_tmp\\_8113](https://www.researchgate.net/publication/306256135_LIS_tmp_8113). The dipole index and forecasting  
tools are available at <http://justinschulte.com/forecasting/dipole.html>.

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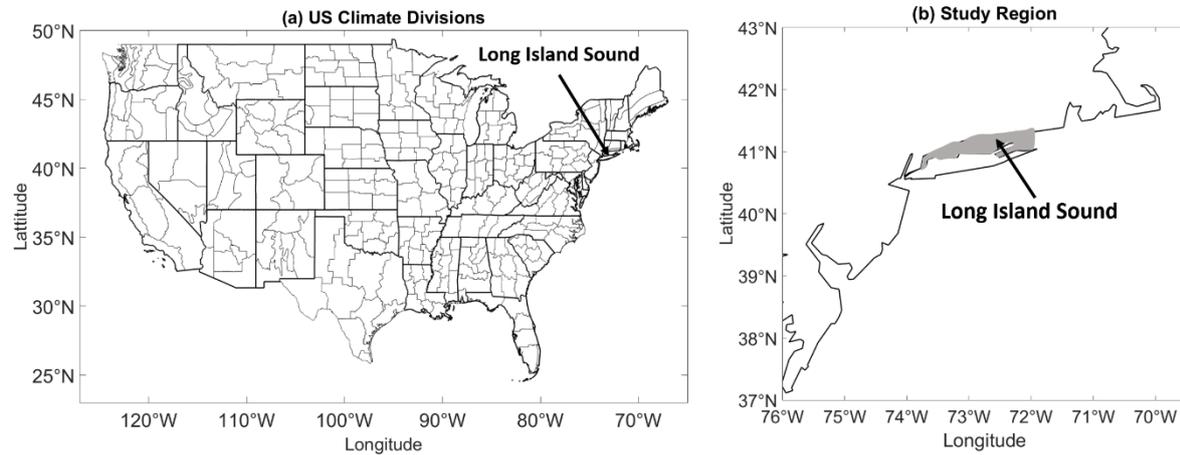
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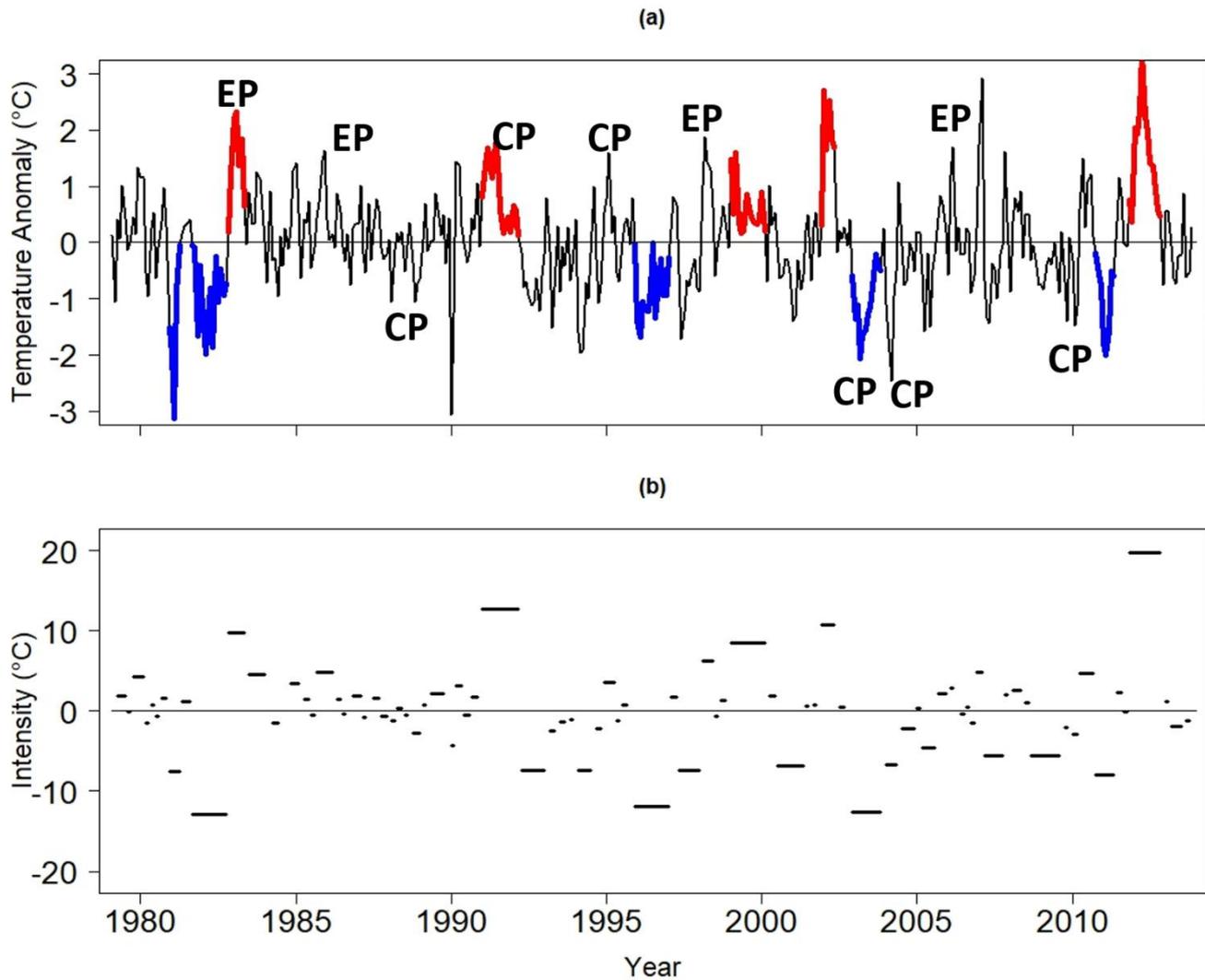
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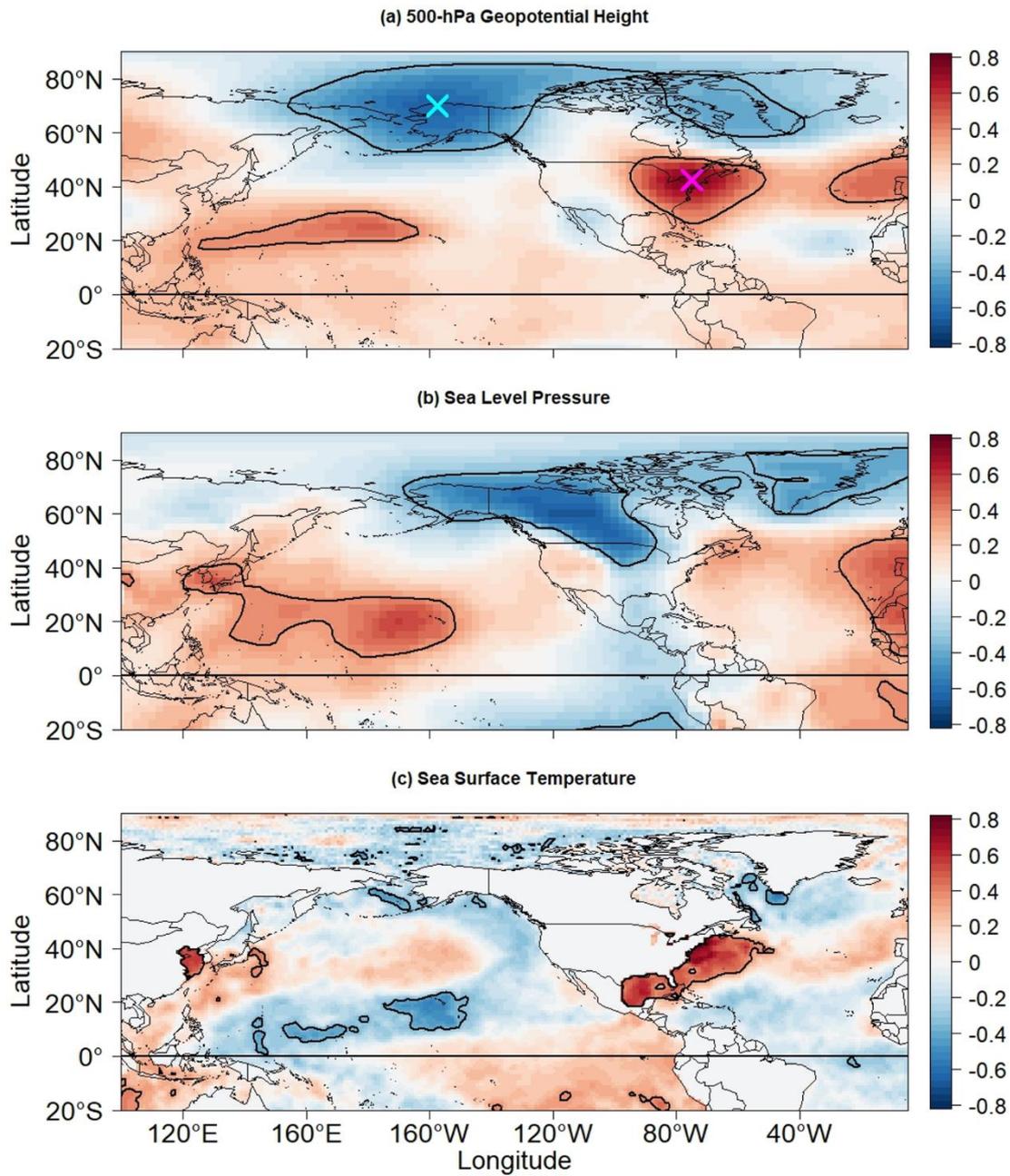
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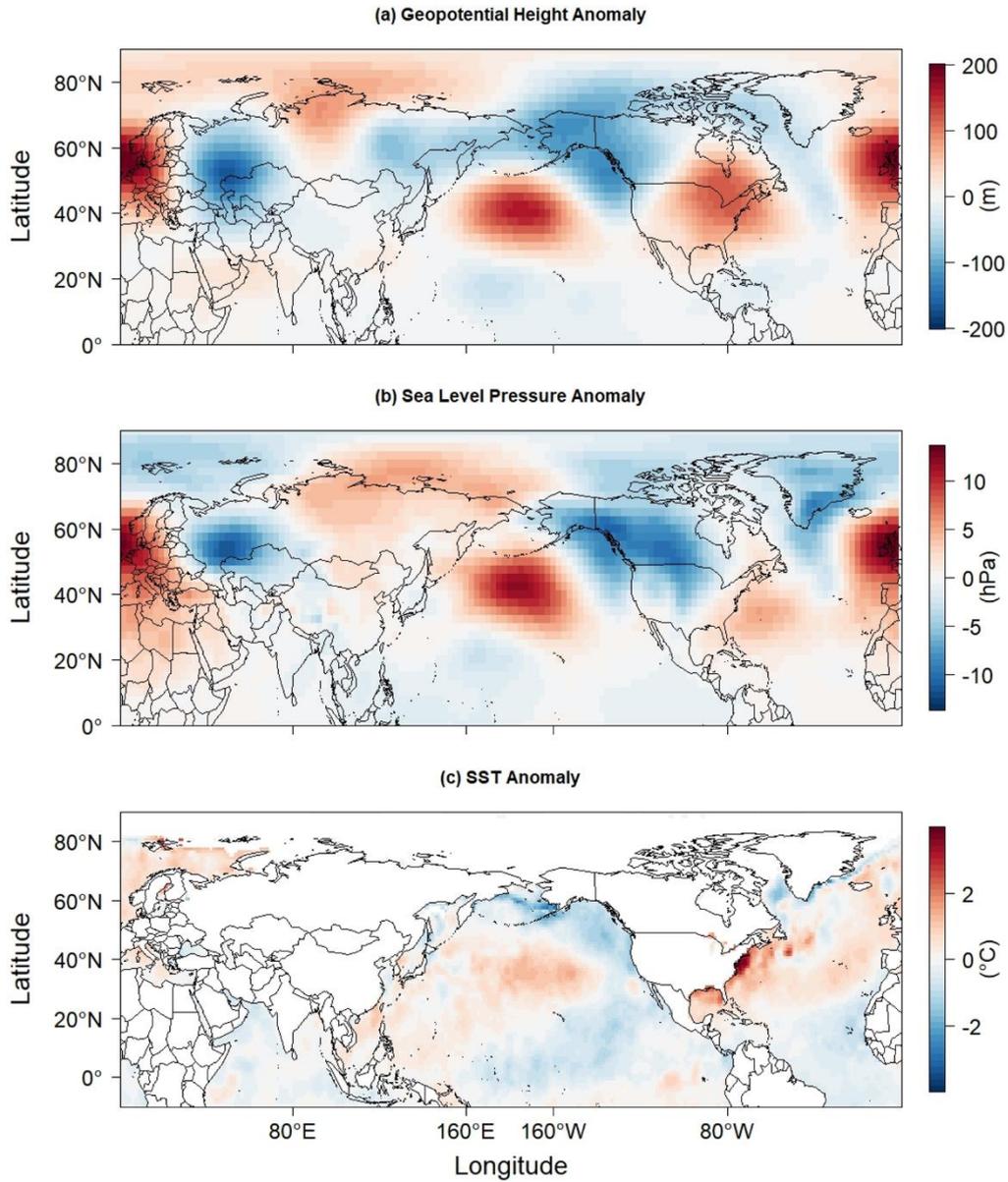
10 **Figure 1:** (a) 344 U.S climate divisions and (b) the LIS study region. Gray shading delineates the region used to calculate the LIS surface water temperature time series.



5 **Figure 2:** (a) The LIS surface temperature anomaly time series and (b) the corresponding event spectrum. Central Pacific El Niño events are indicated by CP and eastern Pacific El Niño Events are indicated by EP. Blue curves represent the 5 most intense negative LIS temperature events, while red curves represent the 5 most intense positive LIS temperature events. The length of the line segments in (b) represents the persistence of the LIS temperature events. The vertical axis corresponds to the intensity of the event.

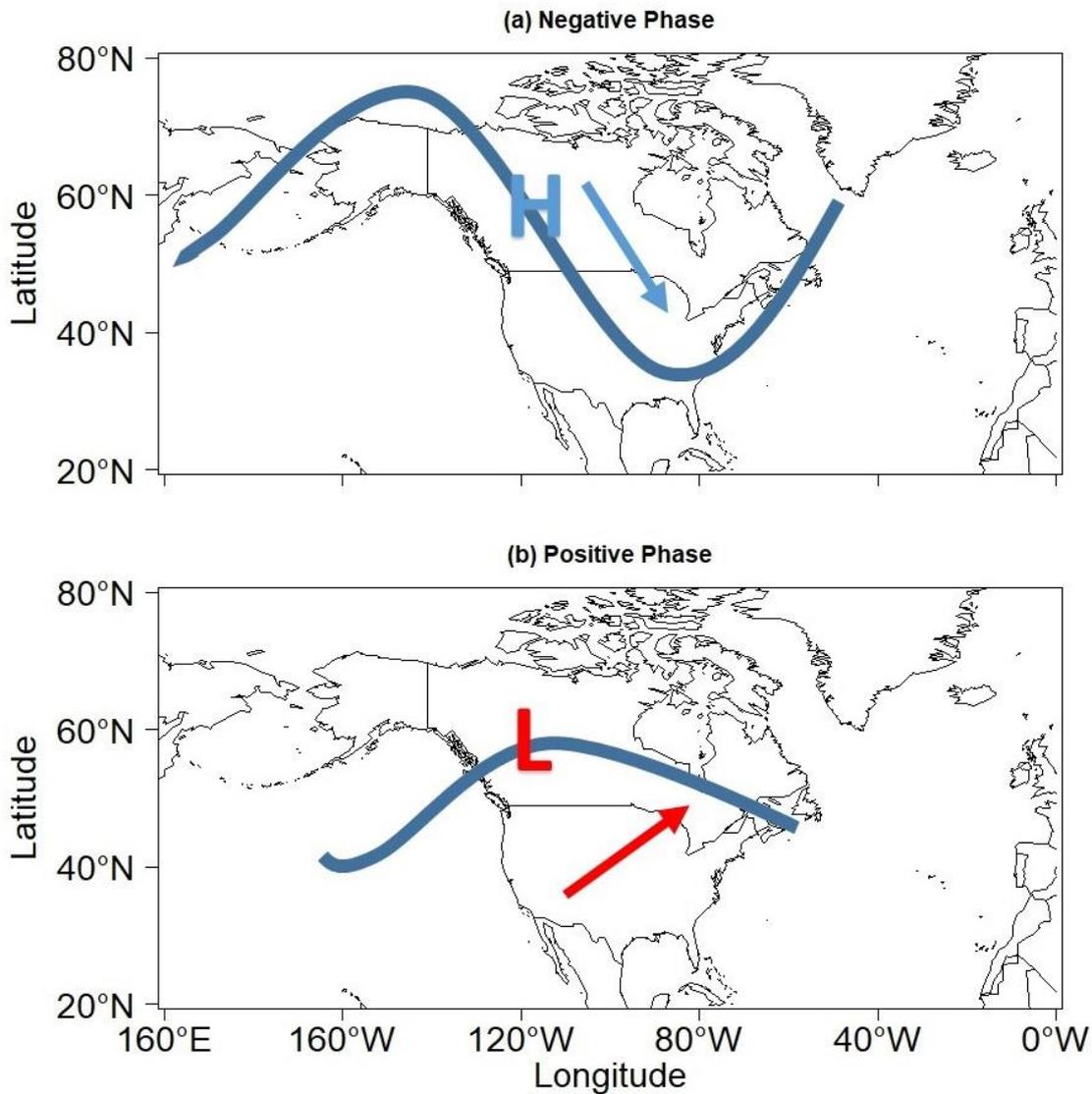


**Figure 3:** Correlation between LIS temperature anomalies and anomalies for (a) DJF 500-hPa geopotential height, (b) SLP, and (c) SST. Contours enclose regions of 5% statistical significance. Crosses in (a) mark the grid point locations used to construct the dipole index.

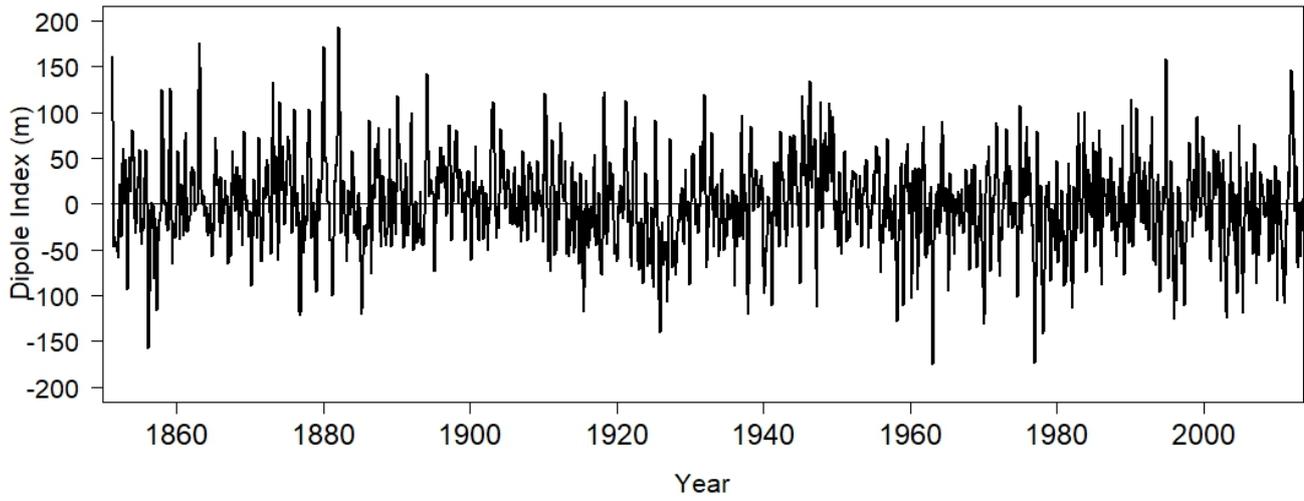


**Figure 4:** Anomalies for (a) 500-hPa geopotential height, (b) SLP, and (c) SST corresponding to the March 2012 LIS temperature event.

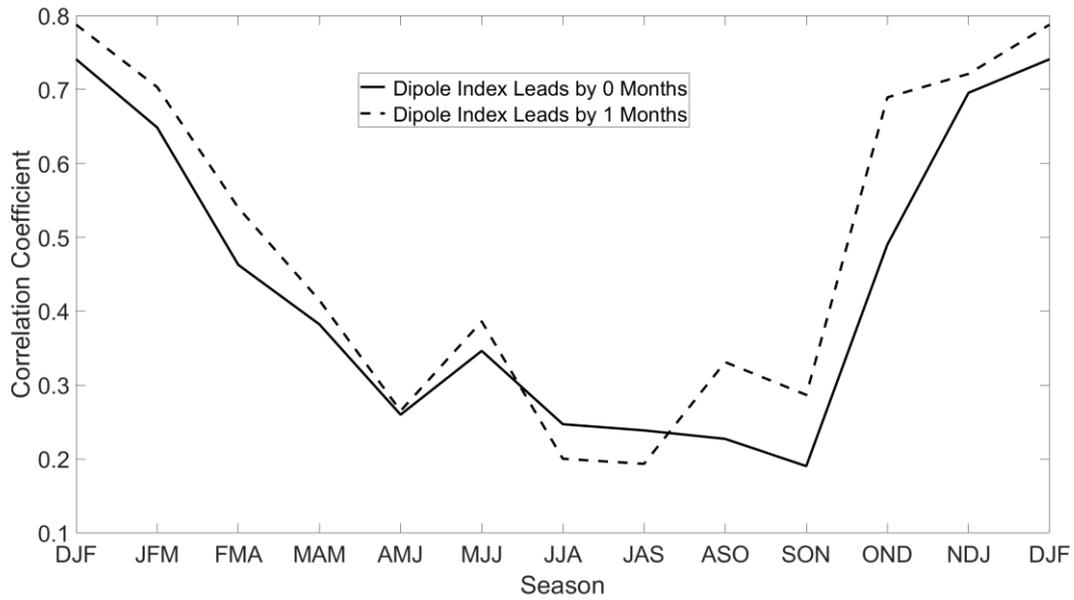
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5 **Figure 5:** (a) Idealized schematic of atmospheric features occurring during negative LIS temperature events and negative phases of the dipole pattern. (b) Same as (a) but for positive LIS temperature events and positive phases of the dipole pattern. Thick blue curves represent the idealized Jetstream configuration, while the blue (red) arrow indicates the general movement of cold (warm) air masses. High pressure is indicated with an H and low pressure is indicated with an L.

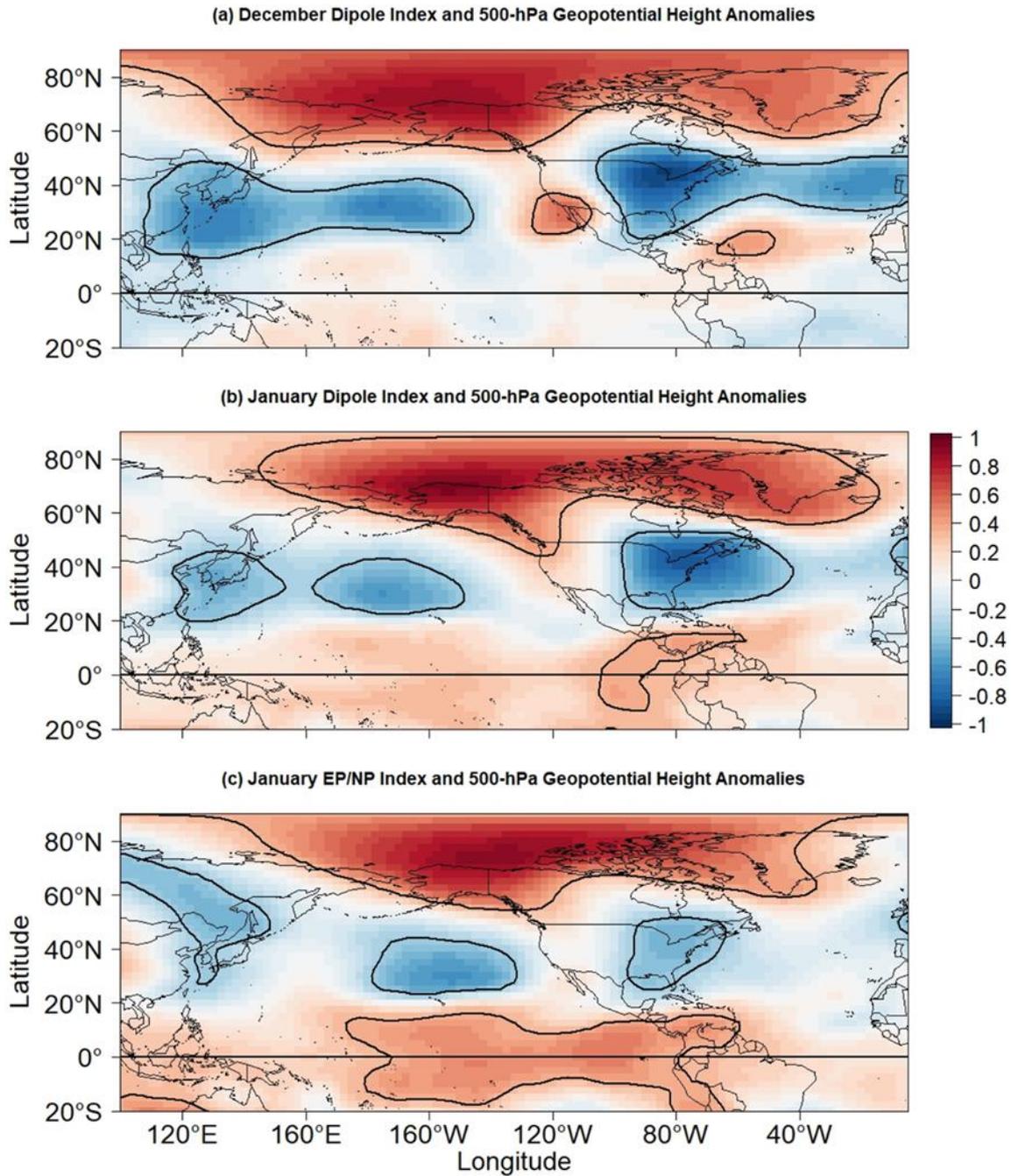


**Figure 6:** 3-month running mean of the dipole index.

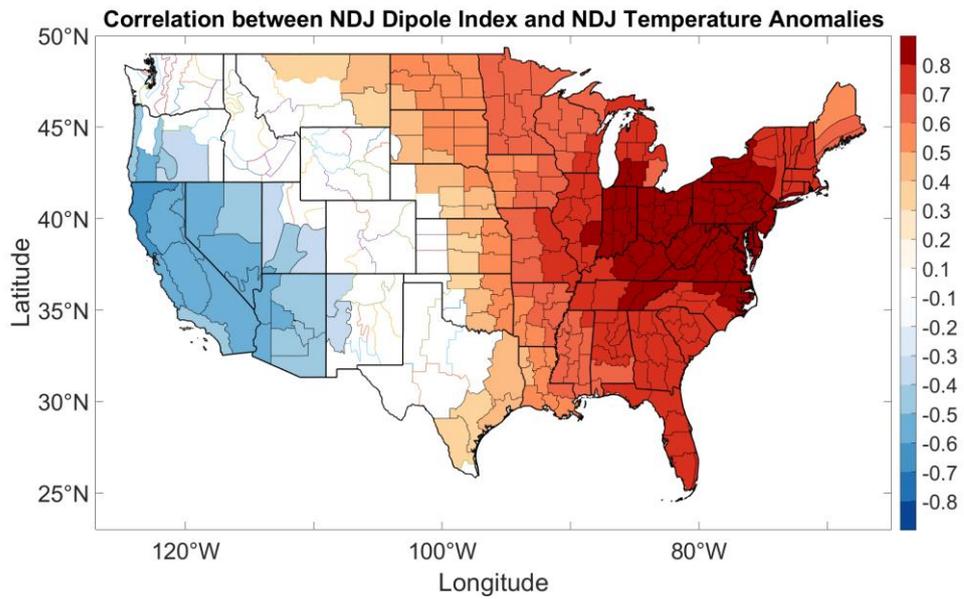


**Figure 7:** Lagged and simultaneous correlations between seasonally averaged LIS water temperature anomalies and the seasonally averaged dipole index. The dotted line represents the correlation between the dipole index of the prior season (dipole leads by 1 month) and water temperature anomalies for the season specified on the horizontal axis.

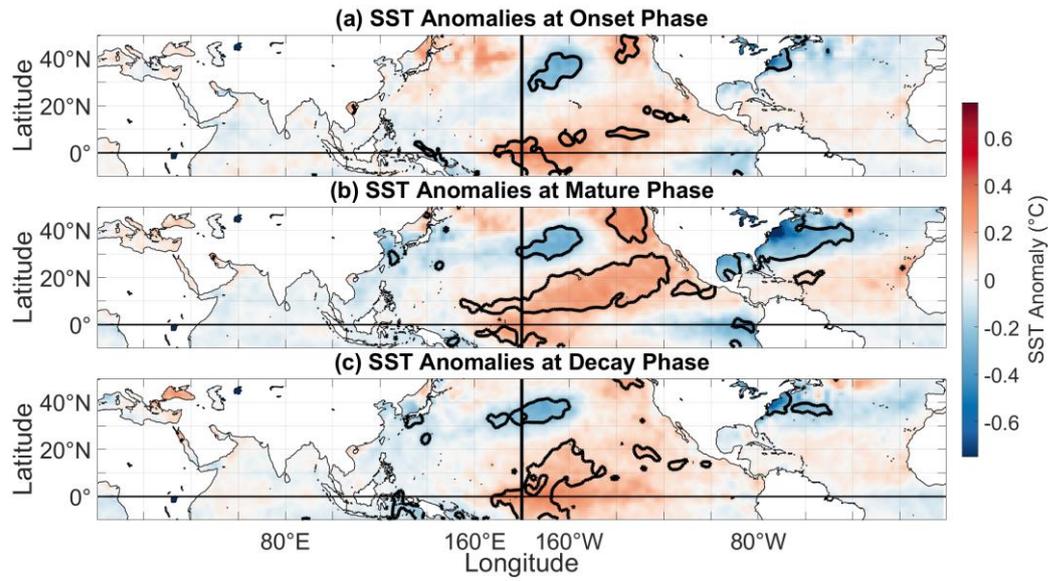
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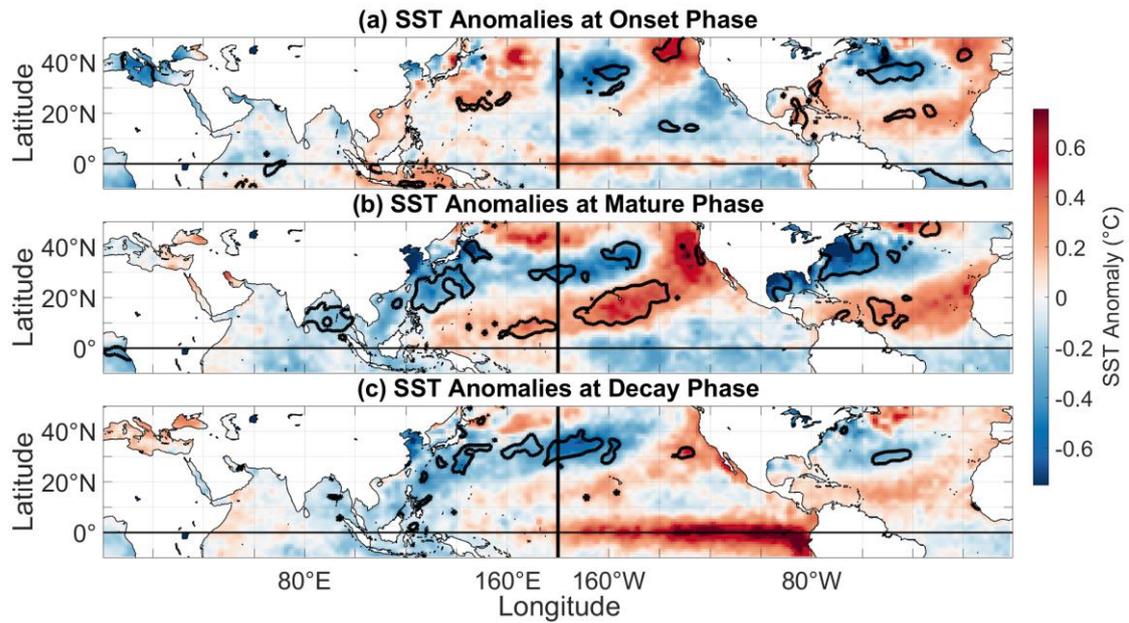
**Figure 8:** Correlation between 500-hPa geopotential height anomalies and indices for the (a) December dipole, (b) January dipole, and (c) January EP/NP patterns. Contours enclose regions of 5% statistical significance.



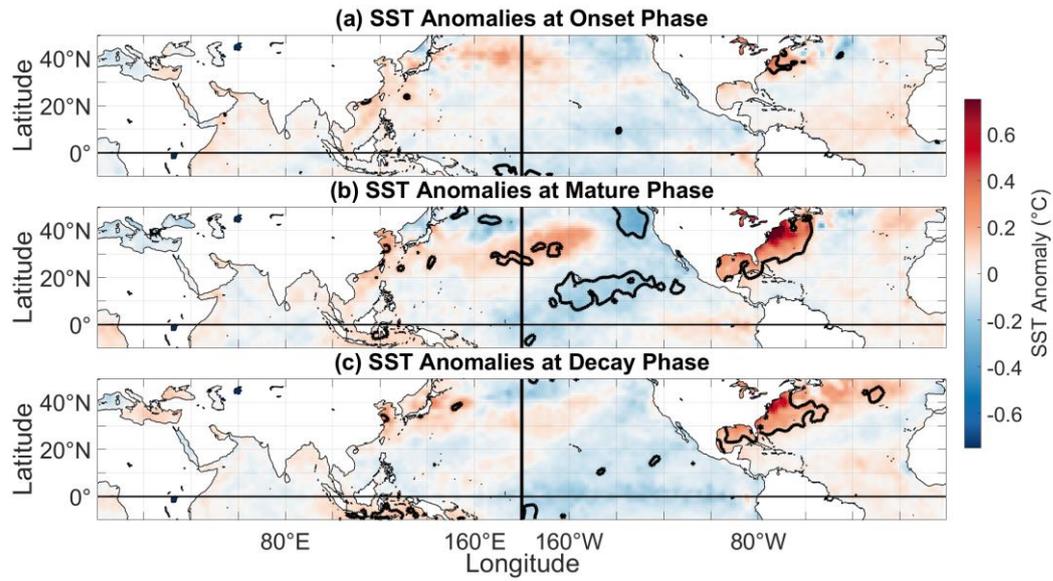
**Figure 9:** Correlation between the NDJ dipole index and NDJ temperature anomalies. Shaded climate divisions are those for which the corresponding correlation coefficients are statistically significant at the 5% significance level.



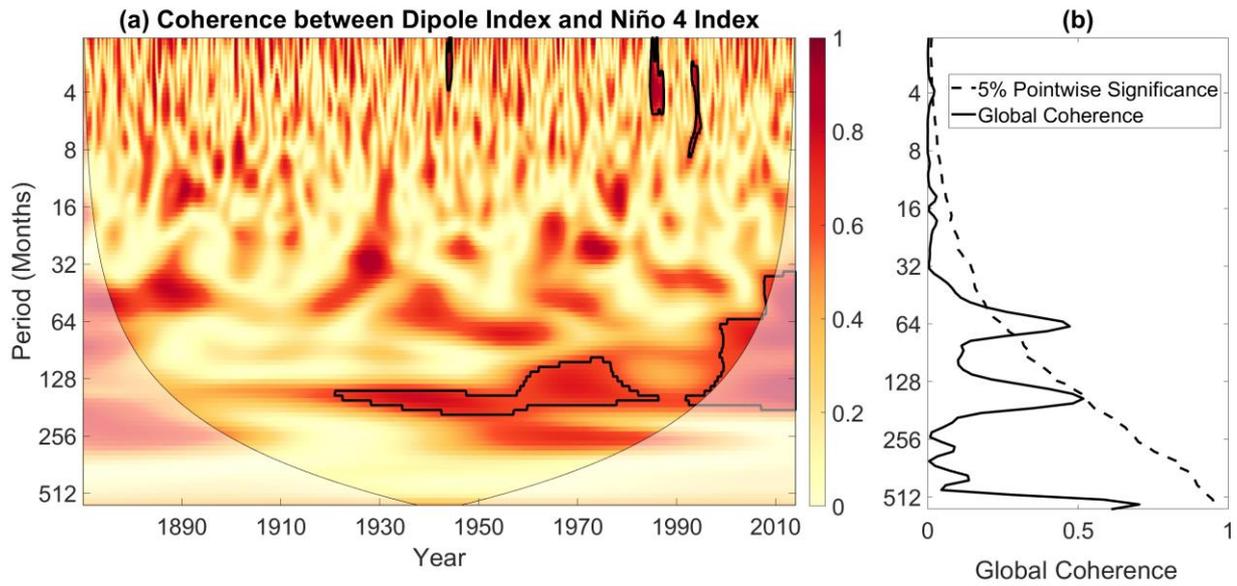
**Figure 10:** Composite mean SST anomalies corresponding to (a) onset, (b) mature, and (c) decay phases of negative LIS temperature events. Contours enclose regions of 5% statistical significance, as determined by a one sample  $t$ -test.



**Figure 11:** Same as Figure 10 but using the criterion that the LIS events fall below 1 one standard deviation from the mean intensity of all LIS cold events.

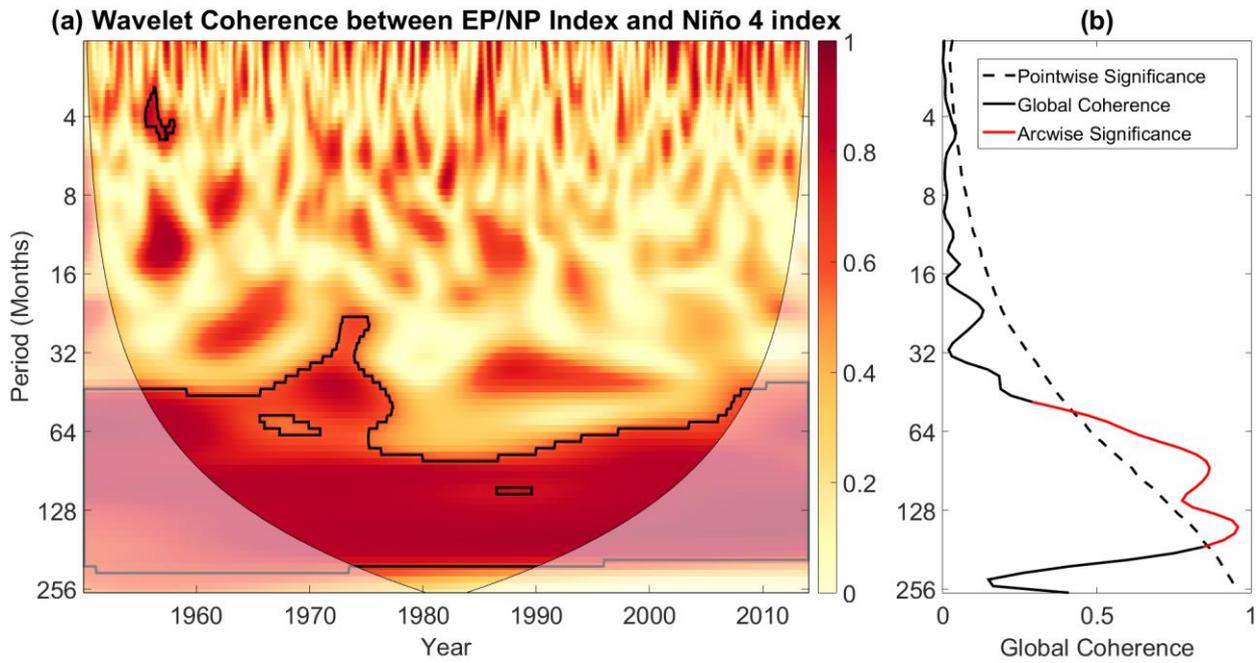


**Figure 12:** Same as Figure 10 except for positive LIS temperature events.



**Figure 13:** (a) Wavelet coherence between the dipole and Niño 4 indices. Contours enclose regions of 5% cumulative areawise significance. (b) The global coherence spectrum corresponding to (a). Dotted line is the 5% pointwise significance bound and the red curves indicate 5% arcwise significant coherence values.

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**Figure 14:** Same as Figure 13 but for the wavelet coherence between the EP/NP and Niño 4 indices.

Table 1. 10 LIS detrended temperature events ranked by the magnitude of their intensities.

Intensity (°C)	Persistence (Months)	Peak	Onset	Decay
20	13	March 2012	October 2011	October 2012
-13	14	January 1982	August 1981	September 1982
13	15	May 1991	December 1990	February 1992
-13	12	February 2003	November 2002	October 2003
-12	14	January 1996	November 1995	December 1996
11	6	December 2001	November 2001	April 2002
10	7	January 1983	October 1982	April 1983
9	14	February 1998	December 1998	January 2000
-8	8	January 2011	September 2010	April 2011
-8	5	January 1981	November 1980	March 1981

Table 2. 10 dipole events in the 1851-2013 period ranked by the magnitude of their intensities. Results are based on the raw monthly dipole index time series.

Intensity (m)	Persistence (Months)	Peak	Onset	Decay
847	11	February 1882	May 1881	March 1882
844	9	January 1880	October 1879	June 1880
805	9	March 2012	July 2011	March 2012
-687	8	January 1977	July 1976	February 1977
-666	9	January 2003	October 2002	June 2003
-638	6	January 1978	December 1977	May 1978
-616	7	September 1876	July 1876	January 1877
-604	12	August 1927	May 1927	April 1928
580	6	January 1863	December 1862	May 1863
572	9	December 1889	November 1889	July 1890

Table 3 Correlation between the dipole index and indices for 5 major climate modes of variability for the 1979-2013 period. Bold entries indicate 5% statistically significant correlation coefficients.

	<b>J</b>	<b>F</b>	<b>M</b>	<b>A</b>	<b>M</b>	<b>J</b>	<b>J</b>	<b>A</b>	<b>S</b>	<b>O</b>	<b>N</b>	<b>D</b>
EPNP	<b>0.74</b>	<b>0.67</b>	<b>0.67</b>	<b>0.66</b>	<b>0.56</b>	<b>0.52</b>	<b>0.47</b>	<b>0.26</b>	<b>0.43</b>	<b>0.66</b>	<b>0.66</b>	-----
WP	-0.28	<b>-0.34</b>	-0.19	<b>-0.37</b>	0.21	<b>0.34</b>	<b>0.42</b>	<b>0.33</b>	0.00	-0.31	<b>-0.6</b>	<b>-0.56</b>
PNA	0.29	0.0	0.0	0.0	<b>0.35</b>	0.12	0.12	<b>0.46</b>	<b>0.43</b>	0.30	0.15	0.0
AO	<b>-0.6</b>	-0.18	<b>-0.49</b>	-0.21	<b>-0.52</b>	<b>-0.40</b>	<b>-0.45</b>	<b>-0.40</b>	<b>-0.37</b>	<b>-0.65</b>	<b>-0.58</b>	<b>-0.62</b>
NAO	<b>-0.59</b>	-0.15	<b>-0.53</b>	-0.13	<b>-0.50</b>	<b>-0.40</b>	-0.18	-0.13	-0.1	<b>-0.55</b>	<b>-0.46</b>	<b>-0.59</b>

Table 4. The mode number of the EOF pattern that most closely resembles the EP/NP pattern, the explained variance associated with the EOF pattern, and the correlation coefficient,  $r$ , computed between the corresponding principal component time series and the EP/NP index. The EOF pattern that most closely resembles the EP/NP pattern was determined by finding the EOF pattern whose principal component time series is most strongly correlated with the EP/NP index. The results are based on NCEP reanalysis for the 1979-2013 period.

Quantity	<b>J</b>	<b>F</b>	<b>M</b>	<b>A</b>	<b>M</b>	<b>J</b>	<b>J</b>	<b>A</b>	<b>S</b>	<b>O</b>	<b>N</b>	<b>D</b>
r	0.66	0.66	0.61	0.62	0.67	0.44	0.51	0.60	0.63	0.69	0.61	-----
Variance (%)	14.4	5.5	3.2	5.0	7.0	1.9	4.3	5.2	4.7	6.0	4.4	-----
EOF Number	2.0	6.0	7.0	6.0	4.0	11.0	5.0	5.0	6.0	5.0	7.0	-----

**Table 5** El Nino events partitioned into Central (CP) and Eastern (EP) pacific types based on the categorization method of Yu et al. (2012). El Nino Events are defined based on the DJFM season. Third column provides the corresponding DJFM LIS temperature anomaly. A more complete table of El Nino events can be found in Johnson and Kosoka (2016).

<b>El Niño years</b>	<b>Event Type</b>	<b>LIS Temperature Anomaly (°C)</b>
1982-1983	EP	1.9
1986-1987	EP	0.2
1987-1988	CP	-0.2
1991-1992	CP	0.3
1994-1995	CP	0.7
1997-1998	EP	0.9
2002-2003	CP	-1.5
2004-2005	CP	-0.4
2006-2007	EP	0.7
2009-2010	CP	-0.6