Northern Hemisphere Jet Stream Position Indices as Diagnostic Tools for Climate and Ecosystem Dynamics

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ABSTRACT: The latitudinal position of the Northern Hemisphere jet stream (NHJ) modulates the occurrence and frequency of extreme weather events. Precipitation anomalies in particular are associated with NHJ variability; the resulting floods and droughts can have considerable societal and economic impacts. This study develops a new climatology of the 300-hPa NHJ using a bottom-up approach based on seasonally explicit latitudinal NHJ positions. Four seasons with coherent NHJ patterns were identified (January–February, April–May, July–August, and October–November), along with 32 longitudinal sectors where the seasonal NHJ shows strong spatial coherence. These 32 longitudinal sectors were then used as NHJ position indices to examine the influence of seasonal NHJ position on the geographical distribution of NH precipitation and temperature variability and their link to atmospheric circulation pattern. The analyses show that the NHJ indices are related to broad-scale patterns in temperature and precipitation variability, in terrestrial vegetation productivity and spring phenology, and can be used as diagnostic/prognostic tools to link ecosystem and socioeconomic dynamics to upper-level atmospheric patterns.

KEYWORDS: Atmospheric circulation; Planetary waves; Waves, atmospheric; Climate variability; Seasonal cycle; Ecosystem effects

1. Introduction

Midlatitude extreme weather events, especially when they are persistent and broad-scale, have significant socioeconomic and ecosystem impacts that encompass densely populated, intensely managed, and protected natural areas (WMO 2010). In North America alone, the last decade has been marked by several unprecedented and large-scale extreme weather events (WMO 2010; Coumou and Rahmstorf 2012). In 2012, for instance, record high March temperatures and the earliest spring in 112 years devastated fruit crops across the upper Midwest and Great Lakes regions (Ault et al. 2013; Karl et al. 2012). Persistent cold temperatures and heavy snowfall across Canada and the northeastern United States in the winter of 2013–14 resulted in extensive power failures and massive cancellations in airline and rail services. The severe 2012–15 drought in California culminated in the lowest reconstructed snowpack of the past 500 years in the Sierra Nevada (Belmecheri et al. 2016), resulting in the broad-scale die-off of millions of trees and record wildfires (Asner et al. 2016). The drought also threatened California’s economy and human welfare through diminished hydroelectric power generation and water shortages for both urban and agriculture consumers (Bartos and Chester 2015). In each of these cases, the extreme weather was associated with anomalous and persistent ridging and troughing of the Northern Hemisphere jet stream (NHJ) over North America (Jensen 2015; Yang et al. 2002; Wang et al. 2014).

The strength, frequency, and persistence of midlatitude extreme weather events are linked to midlatitude atmospheric circulation patterns and are projected to increase under future climate change (Barriopedro et al. 2011; Reichstein et al. 2013; Zscheischler et al. 2015). There is strong evidence that amplified quasistationary planetary waves favor extreme weather events in the midlatitudes (Coumou et al. 2015; Screen and Simmonds 2014). In particular, a slow and strongly meandering NHJ is associated with anomalous persistence of weather
extremes at the surface (Dole et al. 2011; Galarneau et al. 2012; Tachibana et al. 2010). Such persistent blocking patterns form when planetary Rossby waves—associated with the NHJ—have a larger amplitude than usual. Some recent studies have postulated that a weakening of the temperature gradient between the Arctic and the tropics may favor such increased wave amplitudes (Francis and Vavrus 2012; Petoukhov et al. 2013; Tang et al. 2014). This north–south temperature gradient has been weakening over the past few decades as a result of Arctic amplification (Screen and Simmonds 2010), with the amplified warming of the Arctic compared to the rest of the Northern Hemisphere forced by greenhouse warming (Gillett et al. 2008) and positive feedback mechanisms (Stroeve et al. 2012). The link between Arctic amplification, a meandering NHJ, and persistent blocking patterns has been proposed as a mechanism to explain the increasing frequency of extreme weather events in the midlatitudes over recent decades (Francis and Vavrus 2012; Screen and Simmonds 2014). This proposed mechanism, however, has been questioned (Screen and Simmonds 2013; Barnes 2013) due to the lack of observational evidence and to modeling uncertainties (Barnes 2013; Hopsch et al. 2012).

The increasing number of midlatitude weather extremes in recent decades, the role of the NHJ in modulating these extremes, and potential future changes in NHJ amplitude and persistence have led to a recent surge in research interest in NHJ climatology (Rikus 2015; Woollings et al. 2014). This interest is not limited to the meteorological and climate modeling community but has permeated into research fields that study the impact of climate and future climate change on ecosystem and societal dynamics (e.g., Stark et al. 2016). However, the NHJ is a complex system of thousands of kilometers in length and hundreds of kilometers in width (Berggren et al. 1958). To assess the socioeconomic and ecosystem impacts of future changes in the NHJ features requires a detailed NHJ climatology and NHJ evaluation metrics (or tools) that can be compared readily to societal and ecosystem variables.

Jet stream climatology analyses have been approached using various methods and working definitions (Rikus 2015, and references therein). Most jet stream studies are based on reanalysis datasets from either the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR, 1948–present) and/or 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40; 1958–present; e.g., Archer and Caldeira 2008; Archer and Caldeira 2009; Bals-Elsholz et al. 2001; Ellis and Barton 2012; Gallego et al. 2005; Kuang et al. 2014; Peña-Ortiz et al. 2013; Strong and Davis 2005; Woollings et al. 2010). From this reanalysis dataset, wind speed values at 200, 300, or between 100 and 400 hPa are used to derive daily or monthly mean average or maximum wind speed (e.g., Gallego et al. 2005; Kuang et al. 2014; Manney et al. 2014; Woollings et al. 2014). A minimum wind speed threshold of 30 m s$^{-1}$ is typically applied (e.g., Peña-Ortiz et al. 2013). Most jet stream climatologies also have focused on winter jet stream variability and its relationship to atmospheric circulation patterns (Archer and Caldeira 2008; Athanasiadis et al. 2010; Bals-Elsholz et al. 2001; Barton and Ellis 2009; Riehl 1963; Smith et al. 1998; Strong and Davis 2007; Strong and Davis 2008). Furthermore, jet stream climatology has been studied for the entire Northern and/or Southern Hemispheres (Bals-Elsholz et al. 2001; Gallego et al. 2005;
Peña-Ortiz et al. 2013; Rikus 2015; Strong and Davis 2007) but has been found to have the strongest interannual variability over the North Pacific (Yang et al. 2002; Barton and Ellis 2009) and North Atlantic (Woollings et al. 2014); thus, many studies focused on these specific regions. Few studies have investigated NHJ variability for all seasons and over the entire Northern Hemisphere to characterize interannual variability and historical trends of NHJ features (latitude, altitude, and velocity; Archer and Caldeira 2008; Peña-Ortiz et al. 2013).

Our study presents an NHJ climatology that spans the entire Northern Hemisphere, includes all four seasons, and focuses on the NHJ latitudinal position. The methodology used here is an alternative for the previous depictions and characterization of the NHJ mean latitudinal position and variability and complements the jet stream indices that Woollings et al. (2014) developed for the North Atlantic sector. A bottom-up approach is applied, informed by the seasonal and spatial coherence in NHJ latitudinal position that allows us to define seasonally and longitudinally explicit indices of NHJ latitudinal variability. In pursuing the diagnosis of NHJ climatology, a principal goal was to develop seasonal and spatial NHJ latitudinal position indices that can be used as independent variables (from atmospheric circulation indices) to reduce the vast complexity of NHJ dynamics into variables useful to researchers and managers to relate ecosystem (e.g., forest disturbances, phenology, agricultural and forest productivity) and socioeconomic (e.g., frequency of extreme weather events and related impacts) dynamics to upper-level atmospheric patterns. As an example of an application, we analyze the relationship between NHJ indices and spatial fields of the normalized difference vegetation index (NDVI) and spring phenology index, the extended spring indices (SI-x), to illustrate the relationship between the NHJ latitudinal position, temperature anomalies, photosynthetic activity or “greenness,” and spring leaf onset.

2. Methods

2.1. Diagnosis of the latitudinal position of the NHJ

We focus our NHJ climatology on the entire Northern Hemisphere (0°–90°N) and in doing so do not categorize subtropical (STJ) and polar front jets (PFJ) separately. The NHJ can be distinguished as either a subtropical (thermally driven) or midlatitude polar front (eddy driven) (Hartmann 2007) over some regions, such as northern Africa and Asia, but only one NHJ stream is observed over the western Pacific and Atlantic Ocean. Separating the STJ and PFJ based on latitudinal subdivision is therefore not unambiguously applicable because of the fragmented nature of the jet. Additionally, when averaged over time (monthly seasonal resolution), the jet forms a single-band, spiral-like structure in the Northern Hemisphere (Kuang et al. 2014). Several studies proposed methods to characterize or depict the multiple jet structure (Gallego et al. 2005; Peña-Ortiz et al. 2013) but were only successful for the Southern Hemisphere and often considered—like we did—one single jet for the Northern Hemisphere (Archer and Caldeira 2008).

To identify the latitudinal position of the NHJ, we used the Twentieth Century Reanalysis, version 2, dataset (20CR; Compo et al. 2011), which covers the period
1871–2012 with a 2° spatial resolution and a 1-month temporal resolution. Early meteorological observations are strongly affected by inhomogeneity due to changing station density (Donat et al. 2011). We therefore limited our analysis to the period 1930–2012, which composes a suitable time frame to investigate NHJ variability at interannual to decadal time scales, but we acknowledge that biases toward more station-rich regions might exist in the earlier part of our study period. From this dataset, we extracted the grid of mean monthly 300-hPa scalar wind (m s\(^{-1}\)) for the Northern Hemisphere. For each month, the latitudinal position of the NHJ was defined as the latitude at which the monthly averaged 300-hPa zonal wind speed (m s\(^{-1}\)) was strongest (Barton and Ellis 2009), and this NHJ latitude was extracted for each longitude. This provided 12 monthly matrices (year × longitude) of NHJ latitudinal position at each longitude from 1930 to 2012.

### 2.2. Development of NHJ indices

To develop NHJ latitudinal position indices from the above-described matrices, we proceeded as follows (Figure S1):

1) For each month, the time series (1930–2012) of NHJ latitudinal position were correlated between all longitudes, thus creating 12 monthly correlation matrices (180° × 180° longitudinal grid cells) of NHJ longitudinal coherence. For each monthly correlation matrix, the average interseries correlation coefficients \( r(\bar{r}) \) were computed for each longitude with its neighboring longitudes, using 10 correlation windows ranging from 1 (2°) to 10 (20°) grid cells. This resulted in 10 (longitudinal windows) \( \bar{r} \) values for each longitude and for each month.

2) The series of 180 \( \bar{r} \) values were then correlated between months for each of the 10 \( \bar{r} \) correlation windows (e.g., the 10° \( \bar{r} \) series—consisting of 180 \( \bar{r} \) values—of December was correlated with the 10° \( \bar{r} \) series of January). These correlations resulted in 10 (12 × 12) matrices of between-month correlations and allowed the identification of temporal coherence of NHJ latitudinal position.

3) The series of monthly NHJ position were most coherent (positively and significantly correlated for all \( \bar{r} \) windows) for the months of January–February (JF), April–May (AM), July–August (JA), and October–November (ON). We selected these four combinations of months to determine the seasonal (winter, spring, summer, and fall, respectively) NHJ indices.

4) The monthly NHJ latitudinal positions (cf. section 2.1) were then averaged for the four seasons identified in step 3 and the longitudinal \( \bar{r} \) values were recomputed using 10 correlation windows (cf. step 2). The \( \bar{r} \) values of various \( \bar{r} \) window sizes show similar longitudinal sectors where the NHJ latitudinal position shows the strongest spatial coherence (defined as NHJ cores hereafter) with smoother features for the 20° window compared to the 2° window (Figure S2).

5) A peak detection method (using the “pracma” package in R) were applied to the seasonal series of 180 \( \bar{r} \) values for the 10° longitudinal windows to
determine the spatially coherent NHJ positions for each season (Figure S2). This longitudinal window was chosen because it is a robust representation of the NHJ cores within the longitudinal window range. The peak detection method identifies the eastern and western boundaries of the seasonal NHJ cores.

Based on the longitudinal coherence (spatial correlation between neighboring longitudes) of bimonthly NHJ time series, we detected 32 NHJ cores [8 for winter (JF), 8 for spring (AM), 7 for summer (JA), 9 for fall (ON); Figure 1; Table S2]. The NHJ cores are defined as longitudinal sectors where NHJ latitudinal position shows the strongest spatial correlations between neighboring longitudes (Figure S2).

For each year, the latitudinal NHJ positions over the longitudes in each of these NHJ cores were averaged to create 32 time series (1930–2012) of spatially and seasonally explicit latitudinal NHJ positions (NHJ index hereafter).

The distribution of each NHJ index was tested for normality using the Shapiro–Wilk test. Correlation analyses described below were performed using parametric
and nonparametric methods (Pearson and Spearman, respectively) based on the Shapiro–Wilk test results (Table S1).

Each NHJ index time series was transformed to an array of $z$ scores in order to relate NHJ latitudinal position anomalies (north–south of average) to regional climate using the Climate Research Unit (CRU) gridded ($0.5^\circ \times 0.5^\circ$) monthly time series data (CRU TS3.23; Harris et al. 2014) and to sea level pressure (SLP; HadSLP2; Allan and Ansell 2006) in a correlation map analysis (Table S2). The NHJ indices were further compared to seasonal Pacific–North American (PNA), North Atlantic Oscillation (NAO), Arctic Oscillation (AO), and El Niño–Southern Oscillation (ENSO 3.4) data available from the NOAA climate prediction center (1959–2012). For each atmospheric circulation index, a bimonthly average was calculated corresponding to the seasons identified for the NHJ indices (JF, AM, JA, and ON). Correlation coefficients were computed between the NHJ index and each of the atmospheric circulation indices (Table S3).

The significance level for field and time series correlations was set to $p < 0.05$. Additionally, linear trend analyses were conducted for each NHJ index.

The analysis of seasonal NHJ index correlations with corresponding seasonal temperature, precipitation, SLP, and atmospheric circulation indices over the entire NH is intended to evaluate and validate the NHJ indices scheme developed in the present study.

To demonstrate the application of such NHJ indices, we investigated the relationship between the NHJ indices with NDVI derived from Global Inventory Modeling and Mapping Studies (GIMMS) dataset available from 1980 to 2006 (Tucker et al. 2005) and with a gridded product of modeled first leaf date, one of the SI-x available for 1930–2012, representing greenup for temperature-sensitive species that leaf out in the spring (Ault et al. 2015b).

3. Results

3.1. Seasonal and spatial NHJ index distribution

The longitudinal extents of the identified NHJ cores differ between seasons, with wider longitudinal ranges over the North Pacific sector in winter compared to other seasons (Figure 1). Two cores were identified in the North Pacific and in the North Atlantic sectors in all seasons. A larger number of cores was identified in the fall season (nine compared to seven or eight for the other seasons), particularly over the Eurasian continent (four cores).

For each season, we defined NHJ interannual variability as the standard deviation from the NHJ position averaged across the entire Northern Hemisphere. Interannual NHJ variability is strong—on the order of $6.5^\circ–8^\circ$ in latitude—for all seasons and is weakest in spring ($6.5^\circ$). The range of interannual variability is larger than the mean seasonal cycle, defined as the standard deviation between mean seasonal NHJ positions ($\sim6^\circ$; Figure 1).

The distribution of the NHJ positions—averaged over all longitudes ($180^\circ$)—between seasons mimics the seasonal NH temperature gradient (Kuang et al. 2014; Figure 1), with the NHJ in a more equatorward position during winter ($34^\circ \pm 8^\circ$N) compared to spring ($48^\circ \pm 6^\circ$N), summer ($49^\circ \pm 6.5^\circ$N), and fall ($42^\circ \pm 7.5^\circ$N).
Similar magnitudes of seasonal latitudinal ranges have been reported for the North Atlantic jet (Woollings et al. 2014).

The latitudinal range of NHJ positions is larger in the Western Hemisphere than in the Eastern Hemisphere (Figure 1); in the eastern parts of North Africa, Asia, and the western Pacific, the seasonal NHJ positions show single peak patterns, meaning that the NHJ position often occurs at the same latitude during a particular season and shows limited interannual variability. In these eastern regions, the NHJ is primarily continuous between longitudes—resulting in broad longitudinal NHJ cores—particularly for the winter months (Figure 1). A wider or multimodal latitudinal distribution is observed over the North Atlantic and eastern Pacific sectors, particularly for the winter months. While we did not separate the STJ and PFJ in this study, the large variability observed for the latitudinal range of jet indices over North America and Eurasia during the winter and fall months can be attributed to the large variability of the PFJ reported for all the seasons compared to the STJ, which has variability higher in spring and fall (Molnos et al. 2017).

3.2. Influence of NHJ position on regional climate

3.2.1. Precipitation variability

The season with the most significant correlations between NHJ indices and precipitation is winter. NHJ indices for the winter season on average correlate significantly with winter precipitation in 20.8% of the NH grid cells versus only 12.4% in the fall to 15.4% in the spring and 13.9% in the summer (Table S2). The NHJ cores showing significant correlations with JF precipitation are mainly located over the North Pacific/North America (cores JF-4, JF-5, and JF-6 in Figure 2) and the North Atlantic (cores JF-7 and JF-8). For AM, the cores with strongest precipitation correlations are located mainly over the Eurasian continent (cores AM-3), North Pacific (AM-4), and eastern North Atlantic (AM-8). For JA and ON, the cores with strong correlations are fewer and are mainly significant over the North Atlantic (JA-6).

The NHJ position influences regional precipitation variability through its modulation of storm tracks: when the NHJ is in a northerly position, storm tracks bringing precipitation are deflected to the northern latitudes, resulting in positive correlations between NHJ index and precipitation anomalies in these regions and vice versa. This is demonstrated for core JF-5 in North America during the winter season (Figure 2): a northerly (southerly) NHJ position is related to positive (negative) precipitation anomalies in the Northwest and negative (positive) precipitation anomalies in the Southwest. The NHJ position in the North Pacific/North America region thus creates a dipole precipitation pattern during the winter season. In the North Atlantic region (JF-7; Figure 2), in winter, the dipole is located over the British Isles (positive anomalies) and southwestern Europe and northwestern Africa (negative anomalies).

The NHJ position has a significant influence on spring precipitation variability in both the Eastern and Western Hemispheres. For the summer season the NHJ–precipitation relationship is significant primarily over the North Atlantic region (JA-6 and JA-7), with similar dipole and precipitation anomalies as those of the winter season (Figure 2).
3.2.2. Temperature variability

The relationships between NHJ indices and temperature variability are generally stronger than for precipitation variability and they show broader spatial patterns (Table S1, Figure 2). As for precipitation, correlations with temperature are generally stronger during winter (significant correlations in 38% of the NH grid cells on average) than in other seasons (range of 18%–22% of the NH grid cells on average). In the northwestern hemisphere, and for the winter season, a consistent and significant dipole is observed for the northern and Central American regions (JF-6; Figure 2); northerly NHJ anomalies are associated with warmer temperatures in the southeastern United States and Central America and colder temperatures in the western and northern United States. Similarly, the North Atlantic NHJ indices (cores JF-7 and JF-8) show a strong and opposing dipole with northerly positions associated with warmer temperatures in both the southeastern United States and Eurasia and colder temperatures in the northeastern United States, Greenland, and North Africa (Figure 2).
For the spring season, all the NHJ indices show strong correlations with temperature anomalies. The two NHJ indices located in the Northeastern Hemisphere (AM-1 and AM-2) exhibit similar relationships with temperature anomalies, with a dipole centered over central and southern Asia (cold anomalies associated with northerly position) and northern and eastern Asia (warm anomalies associated with southerly position). The summer NHJ position and temperature relationship also displays a dipole pattern (Figure 2). The dipole corresponds to positive temperature anomalies associated with northerly NHJ position in the northeastern United States and the British Isles and negative anomalies in Greenland (JF-6; Figure 2). For the fall months, the dipole patterns associated with NHJ indices over the northeastern hemisphere correspond to negative anomalies over western Europe, Scandinavia, and northeastern Asia and positive anomalies over East Africa, the Arabian Peninsula, and central Asia.

### 3.3. Atmospheric circulation patterns

Correlation patterns between the winter NHJ index and SLP in the North Atlantic (JF-7) and North Pacific regions (JF-6) reflect the NAO and the PNA pattern, respectively. When the NHJ is in an anomalously northerly position over the North Atlantic, it generates stronger than normal cyclonic conditions to the north and anticyclonic conditions to the south, resulting in a deeper than normal Icelandic low and higher than normal Azores high. The relationship between the JF-7 NHJ index and the NAO is thus positive, with northerly NHJ latitudinal positions associated with positive NAO phases, and we found significant correlations for all seasons but fall and across multiple cores (Figure 2; Table S3). The NHJ index–NAO relationship is thus in line with the temperature and precipitation teleconnections described in sections 3.1 and 3.2. For instance, positive values of the winter NHJ index over the North Atlantic sector are linked to positive temperature anomalies over western Europe and the southeastern United States and negative anomalies in Greenland and northwestern Africa, a pattern also observed during positive NAO phases. Positive winter NAO phases are also associated with above-normal precipitation over northern Europe and Scandinavia and below-normal precipitation over southern and central Europe, a pattern illustrated in the NHJ–precipitation correlation for the North Atlantic sector.

In addition to this, our results support a connection between NHJ variability and ocean–atmosphere interactions over the North Pacific Ocean; we found significant correlations between winter and spring NHJ indices for cores 5 and 6 and PNA and ENSO patterns (Table S2, Figure 2). The relationship is negative, with northerly NHJ positions associated with negative ENSO and PNA indices. NHJ indices in the North Pacific sectors are linked to a precipitation dipole pattern with wet conditions over the southwest coast of North America when the NHJ is displaced southward (and dry conditions when the NHJ position is in the north). This north–south shift of the NHJ reflects a north–south shift of the North Pacific storm tracks and projects strongly upon the PNA pattern (Athanasiadis et al. 2010). The positive precipitation anomalies in the American Southwest associated with positive ENSO phases and southerly NHJ position correspond to an amplified storm track and more persistent NHJ affecting rainfall on the southwestern coast of North America.
3.4. Long-term NHJ variability

Most of NHJ index trends (1930–2012) are not significant or large in magnitude (Figure S3). The strongest trends were found during spring in the northwestern hemisphere (AM-6 in North Pacific/North America and AM-7 in the North Atlantic) and in the northeastern hemisphere (AM-3 and AM-4 over East Asia). All spring trends are negative—for instance, the mean trend for AM-6 is $-0.02^\circ$ in latitude per year with a maximum of $-0.4^\circ$ in latitude per year—except for three sectors in the North Atlantic–western Europe region (AM-1, AM-2, and AM-8) with nonsignificant positive trends. The poleward shift (positive trend) of $3.3^\circ$ in latitude observed for AM-8 over the 1930–2012 period (Figure S3) is not significant but agrees with poleward trends documented for the Atlantic sector using 20CR reanalysis data and for all seasons (Woollings et al. 2014). For the winter season, only the NHJ in the North Pacific sector (JF-5) shows a significantly negative trend of $-0.03^\circ$ in latitude per year, reflecting an equatorward shift of $2.5^\circ$ over 1930–2012. This corresponds to the magnitude found for the entire North Pacific sector from NCEP–NCAR reanalysis data over the second half of the century (Barton and Ellis 2009). The only significant summer trend is found for JA-6 ($58^\circ–16^\circ W$) and is $-0.015^\circ$ in latitude per year. In contrast to the other seasons, fall NHJ indices are all positive, but only one sector (ON-7) has a significant trend of $0.04^\circ$ in latitude per year.

3.5. Applications

The NHJ indices developed here can be applied to study the impact of NHJ variability on various ecosystem functions (e.g., phenology, disturbances, and productivity), extreme weather events (e.g., hurricanes, heat waves, and floods), and societal processes in a spatially explicit way.

As an example, we compared the spring NHJ indices to a satellite-derived NDVI time series (1981–2006), which is a proxy for vegetation greenness and integrates numerous photosynthetic factors related to ecosystem structure and function (Rafique et al. 2016; Zhou et al. 2001). The NHJ index that showed the most significant correlations spatially with NDVI was AM-4 ($152^\circ W–150^\circ E$; Figure 3). The AM-4 NHJ index was negatively correlated with NDVI over northern Eurasia, Scandinavia, northwestern America, and Central America but positively over northeastern America, particularly over the Great Lakes region. Furthermore, the NHJ index–NDVI field correlation mimics the NHJ–spring temperature field correlation (Figure 3), suggesting NHJ-related spring temperature anomalies as the drivers of anomalies in greenness and by extension land surface phenology. Northerly spring NHJ positions in the North Pacific—corresponding to negative PNA phases ($r = -0.45$, $p < 0.05$; Table S3)—result in cooler than average spring temperatures and reduced/delayed greenness in northern Eurasia and in warmer than average spring temperatures and advanced/increased greenness in northeastern America.

We further investigated spatial patterns of spring onset variability associated with NH modes of variability by comparing the spring NHJ indices with the SI-x, a gridded product of modeled spring onset dates. This model uses daily temperature records from Global Historical Climatology Network (GHCN) weather stations.
along with a station’s latitude to predict spring onset across the United States (Schwartz 1996; Ault et al. 2011; Ault et al. 2015b). The spring onset dates have been shown to correlate strongly with changes in temperature (Cayan et al. 2001, Ault et al. 2015a), and therefore we expect SI-x to capture changes in temperature associated with the AM NHJ indices.

The NHJ indices AM-5 (150°–120°W) and AM-6 (120°–94°W) showed the most significant spatial correlations with SI-x indices (Figure 4). The field correlations display a spatial dipole pattern for both indices: AM-5 has negative correlations over southwestern and southeastern United States and positive correlations with SI-x in the northern Great Lakes region; AM-6 has negative correlations over the western United States and positive correlations south of the Great Lakes region.

There are strong negative correlations between the day of the spring onset and the position of the jet stream for AM-6 in the western United States ($r = -0.46$, $p < 0.01$; Figure 4e). As the jet position in AM-6 shifts north (positive NHJ anomalies), the region near to and north of the shift experiences earlier spring onset (negative SI-x anomalies). On the other hand, adjacent regions at similar latitudes, such as the Great Lakes and northeastern Canada regions, experience later spring onset as the NHJ position in AM-6 shifts north ($r = 0.34$, $p < 0.1$; Figure 4f).

We performed principal component analyses on the SI-x dataset to explore large-scale pattern in the leaf onset index and its covariability with NHJ position indices. Previous analyses of leaf index spatial patterns in northwestern America showed the existence of two leading patterns that explained $\sim 50\%$ of the variance. These two patterns of leaf onset are associated with the PNA and the northern annular mode (NAM; Ault et al. 2011). In our analyses, six leading modes were identified across North America (not all shown here). The first six modes were scaled by the square root of the eigenvalues and orthogonally rotated using the varimax criterion (Richman 1986).

Two of these modes (rPC3 and rPC4) combined explain 22% of the common variance and are negatively and significantly correlated with AM-6, the index located over North America (Figure 5). Southerly NHJ AM-6 positions thus result in positive anomalies in rPC3, corresponding to early leaf onset in western North
America and late leaf onset in the northeast (Figure 5). For rPC4, southerly NHJ AM-6 positions and positive anomalies are associated with early spring in the Pacific Northwest and later spring in the southeastern and southwestern United States, consistent with our results shown in Figure 4.

4. Discussion

We propose a bottom-up NHJ definition method purposefully designed to be as widely applicable as possible. Our approach is similar to other NHJ climatologies using a single isobaric surface (Gallego et al. 2005; Ellis and Barton 2012) and

Figure 4. Significant spatial correlations ($P < 0.1$) of April–May NHJ index 5 (AM-5) and April–May NHJ index 6 (AM-6) with a gridded product of modeled leaf onset date, one of the SI-x available from 1930 to 2012 (Ault et al. 2011). AM-5 and AM-6 regions are indicated by bold black vertical lines. For AM5, the western boundary is located at 150°W and therefore does not appear in the map. (a),(d) Annual day of leaf onset dates were averaged over four regions corresponding to high positive and negative spatial correlations ($p < 0.05$) with AM-5 and AM-6 (red and blue boxes). Leaf onset date and AM-5 and AM-6 index anomalies are plotted in the time series figures for regions with (b),(e) negative correlations and with (c),(f) positive correlations.
based on monthly/seasonal time scales (Woollings et al. 2014). However, it differs from other approaches that include information from multiple pressure levels and at daily time resolution (Archer and Caldeira 2008; Peña-Ortiz et al. 2013), which have shown to be important considerations in capturing short-term temporal and spatial variations of the NHJ altitude. NHJ definitions based on a single isobaric surface tend to misrepresent variability due to actual variations in height and can give wrong estimations when computing trends in the position (Strong and Davis 2005). On the other hand, our approach identifies longitudinally explicit indices of NHJ latitudinal variability in contrast to most NHJ climatologies that average over large and chosen longitudinal sectors (e.g., Woollings et al. 2014) and do not take the noncontiguous, fragmented, and meandering structure of the NHJ into account. Our approach has advantages with respect to other approaches discussed because it enables consideration of interannual and decadal variability at the seasonal scale as well as characterization of the NHJ variability associated with interannual precipitation, temperature, and SLP variability over specific geographic areas showing spatial coherence of the NHJ latitudinal position.

If we consider a particular sector like the North Atlantic, the latitudinal displacement of the NHJ during the winter and fall seasons has been shown to modulate precipitation anomalies—explaining up to 50% of their variance—in the Mediterranean Basin (Gaetani et al. 2011), consistent with the correlations we find between NHJ indices over the North Atlantic sector and precipitation anomalies in the Mediterranean Basin (JF-7; Figure 2). A spatial dipole is observed in the North Atlantic sector; when the NHJ is in a northerly (southerly) position, northern Europe receives more (less) than usual precipitation and the Mediterranean...
receives less (more) than usual precipitation. This spatial dipole is strongly linked to the NAO and thus is in sync with the strong positive relationship found between winter NHJ position in the North Atlantic sector and the NAO index (Table S2). Northern and southern NHJ positions correspond to positive and negative NAO phases and are related to the advection (or absence thereof) of relatively warm air from the Atlantic Ocean (Mahlstein et al. 2012). The NHJ–NAO relationship confirms previous findings by Woollings et al. (2014) showing that the winter North Atlantic jet has three preferred latitudinal positions ranging from a southern to a central and to a northern position, which are related to the NAO and east Atlantic (EA) patterns.

In the northeastern Pacific and North American sectors, the wintertime NHJ features (JF-5, JF-6, and JF-7) are strongly and negatively dominated by an ENSO-related pattern (Strong and Davis 2008). During El Niño years, the NHJ in these cores is displaced farther south than average, thus directing storm tracks across the southwestern United States and producing wetter than average conditions there and in Baja California (Minnich et al. 2009; Figure 2). Our results are consistent with previous studies showing an equatorward NHJ shift during winter El Niño events with intensification of storm tracks over the Pacific and North America (Brönnimann 2007; Eicher and Higgins 2006; May and Bengtsson 1998). Similarly, the temperature and precipitation anomaly patterns over the United States during winters when the NHJ (JF-5 and JF-6) is displaced southward (Figure 2) strongly resemble the patterns during positive PNA winters. Southerly NHJ positions in this region result in a deepening of the Aleutian low and the development of an enhanced ridge over the west coast of North America (Figure 2), conditions typical for positive PNA phases (Barstons and Livezey 1987; Trouet and Taylor 2010).

The role of NHJ in modulating storm-track activity and atmospheric blocking patterns also expresses itself in temperature anomalies (Figure 2; Wang et al. 2014). With the NHJ in an anomalously southward position, the low pressure fields to the north of the NHJ extend further south than average and the high pressure blocking fields to the south of the NHJ become more intense (Figure 2). These anomalously low and high pressure fields are associated with anomalously cold and warm conditions, respectively. This is for instance demonstrated by the North Atlantic NHJ-related summer temperature anomalies over Europe (Figure 2), where a southern (northern) NHJ position results in cold (warm) conditions in the British Isles and Scandinavia and warm (cool) temperatures in the Balkans, corresponding to the spatial correlation pattern of the summer NAO (Trouet et al. 2012).

Regional NHJ-related temperature anomalies impact various large-scale ecosystem functions. Spring temperature anomalies (Wolf et al. 2016) in particular are reflected in large-scale patterns of spring phenology such as vegetation greenness (Figure 3) and regional patterns of leaf onset (Figure 4). The NHJ is thus an important driver of continental-scale, ecological teleconnections.

Spatiotemporal variation in spring onset (i.e., leaf out) in North America and Eurasia have been shown to be associated with large-scale modes of atmospheric circulation and sea surface temperature variability modes such as the positive and negative phases of NAM, PNA, NAO, ENSO, and the Pacific decadal oscillation (PDO; Cook et al. 2004, 2005; Li et al. 2008; Cayan et al. 2001, 2001; McCabe et al. 2011, 2013; Ault et al. 2011, 2015a). The ENSO and PDO positive anomalies indicate anomalous high pressure over western Canada and low pressure in the
Southeast, which favors warm air advection in the Northwest and result in earlier leaf onset associated with PDO and ENSO. Negative anomalies on the other hand are associated with a later leaf onset in the Northwest and earlier in the Southeast. The NAO has a similar role to the PDO and ENSO in modulating the spring onset; however, it affects spring onset most notably in the Northeast United States and Eurasia.

Atmospheric modes of variability help the interpretation of the spatial patterns and interannual variability of the leaf onset over the conterminous United States; however, they tend to be complex and their impact differs by regions. Alternatively, the spring NHJ indices provide a straightforward interpretation of spring onset spatial patterns and their link to upper-atmospheric circulation, as illustrated by the results of Figures 4 and 5. The positive link between NHJ AM-6 and NAO further confirms these results (Figure 2; Table S3). During positive phases of the NAO, the NHJ is more poleward in the eastern United States and the North Pacific storm track exhibits more variance resulting in earlier leaf onset. Negative NAO phases favor a more meridional jet stream and consequently a delayed leaf onset in the southeastern United States (Thompson and Wallace 2001). In North America, there is considerable covariation between leaf out and other springtime hydroclimatological and ecological phenomena. For example, SI-x first leaf covaries both broadly with 1 April snow water equivalent (McCabe et al. 2013) and center of mass in streamflow in western North America (Cayan et al. 2001). Both western North American SI-x and snowpack/snowmelt also covary broadly with wildfire occurrence. Winter and spring NHJ anomalies over the North Pacific are an important driver of Sierra Nevada wildfire regimes (E. R. Wahl et al. 2017, unpublished manuscript) through their influence on snowmelt, snow-to-rain ratios, and thus the length of the fire season (Westerling et al. 2006; Westerling 2016).

These application examples demonstrate the potential of NHJ indices as diagnostic tools to study the interactions between upper-troposphere atmospheric circulation anomalies and ecosystem functions, which are particularly relevant in the context of ongoing anthropogenic climate change, its impact on ecosystems, and potential atmosphere–biosphere feedback mechanisms.

NHJ positions and related blocking patterns are most impactful to ecosystems and society when they persist through time and result in prolonged periods of extreme weather. This is exemplified by the Russian heat wave and Pakistan floods in summer 2010 (northern outlier in JA-1 in Figure 2; Galarneau et al. 2012), the extreme winter cold (polar vortex) in the northeastern United States in 2014 (Wang et al. 2014), and the California drought of 2012–15 (Swain 2015). Recently, persistently southward positions of the summer NHJ over the North Atlantic region have resulted in heat waves in the Balkans (Coumou et al. 2015) and floods over the British Isles (Screen et al. 2015). Warm episodes or heat waves observed since the 1970s in the Mediterranean Basin have been associated with the presence of NHJ to the north of the Alps and an anticyclone vorticity over the Mediterranean (Mahlstein et al. 2012; Ogi et al. 2003), a configuration that leads to an adiabatic warming of the troposphere and induces the displacement of the isothermals northward from North Africa (Baldi et al. 2006). A strong link between the North Atlantic NHJ position and temperature extremes also exists in winter, with a higher chance for cold extremes to occur over Europe and North America when the NHJ is in a southward position and over North Africa and
Greenland when the NHJ is in a northward position (Figure 2). The high number of midlatitude extreme events over the last decade has encouraged a suite of observational and modeling studies investigating the relative role of and interaction between anthropogenic climate forcing, natural climate variability, and amplified quasi-stationary planetary waves in favoring such weather extremes (Coumou and Rahmstorf 2012; Otto et al. 2012; Petoukhov et al. 2013; Screen and Simmonds 2014). Variability in the amplitude and speed of the NHJ, in particular, is strongly debated as a potential mechanism linking recent midlatitude weather extremes to anthropogenic warming (Francis and Vavrus 2012; Screen and Simmonds 2013; Wallace et al. 2014).

In addition to increased NHJ amplitude, anthropogenic climate change potentially induces trends in NHJ position. There is a wide agreement that the NHJ has shifted poleward in recent decades (Lorenz and DeWeaver 2007; Yin 2005), but the magnitude of the NHJ latitudinal shift and its significance remains debated (Peña-Ortiz et al. 2013). Coupled global climate model projections show intensification and poleward shifts in twenty-first-century storm tracks, implying poleward shifts in the jet streams of both hemispheres in response to anthropogenic warming (Yin 2005). Our results do not show a clear or a significant poleward shift of the NHJ but rather suggest that the NHJ latitudinal trends differ across the seasons, with both poleward and equatorward shifts occurring for different NHJ indices (Figure S3). Furthermore, recent decades do not specifically exhibit an unusual or remarkably significant trend in the long-term context of the 20CR data (Franzke and Woollings 2011). Inconsistencies in documented NHJ trends (including our study) mainly arise from differing NHJ climatology methods and the considered reanalysis data and time periods (Rikus 2015). Most importantly, discrepancies in the NHJ trends discussed above arise from the categorization of the NHJ into STJ and PFJ based on latitudinal criteria that are often challenging (Kuang et al. 2014). In a global NHJ analysis over the second half of the twentieth century, Peña-Ortiz et al. (2013) showed that the NHJ exhibited a poleward shift in winter over zonally extended regions. However, when considering specific sectors such as the North Atlantic, there was an equatorward shift of the STJ and a poleward shift of the PFJ, which in fact reflects the tendency for a split jet or multimodal jet occurrence-preferred regime flow reported for this sector (Franzke et al. 2011). The equatorward shift of the spring NHJ observed across the majority of the regions of our analysis (except the North Atlantic) is in agreement with previous analyses using both 20CR and NCEP–NCAR reanalysis (Peña-Ortiz et al. 2013).

When considering globally averaged NHJ latitudinal positions in all reanalysis datasets, the observed poleward shift is not statistically significant for all seasons (Archer and Caldeira 2008; Peña-Ortiz et al. 2013; Rikus 2015), which is in line with our results. The difference in sources of reanalysis data used for NHJ climatology makes it challenging to calculate long-term trends of NHJ features (latitude, pressure, and velocity). This has been demonstrated in opposing signs in statistically significant trends in both hemispheres from different reanalysis datasets (Peña-Ortiz et al. 2013; Rikus 2015). Paleoclimate NHJ reconstructions with high temporal resolution might therefore be needed to put recent NHJ trends in a historical context and to study NHJ climatology at decadal to centennial time scales.
5. Conclusions

We applied a novel, bottom-up approach to NHJ climatology based on its explicit seasonal and spatial coherence with the objective to develop NHJ latitudinal position indices that can be used in a wide range of applications. We identified 32 distinct NHJ indices for four seasons (Figure 1).

Our approach complements existing NHJ climatologies and encompasses the entire Northern Hemisphere and all four seasons. It further reinforces the premise of prior NHJ climatology studies that NHJ variability and its influence on regional climate are strongest over the North Pacific and North Atlantic regions and in the winter season.

Our NHJ indices are related to atmospheric circulation indices over the North Pacific and North Atlantic across all seasons and control storm-track locations. The NHJ indices have a significant relationship with temperature patterns over spatially broad geographic areas and thus can be used to assess the relationship between the NHJ position and interannual temperature variability and extremes. Our study confirms the value of NHJ indices as diagnostic/prognostic tools of climate anomalies and their interannual variability and geographic distribution. As such, we envision the scientific value of our NHJ indices primarily as 1) intuitive tools to link ecosystem and socioeconomic dynamics to upper-level atmospheric patterns and 2) decadal-scale time series that can provide additional insight in the ongoing debate about the influence of anthropogenic climate change on NHJ dynamics.

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References


