North Atlantic Multidecadal Variability Enhancing Decadal Extratropical Extremes in Boreal Late Summer in the Early Twenty-First Century

JIE ZHANG, ZHIHENG CHEN, HAISHAN CHEN, QIANRONG MA, AND ASAMINEW TESHOME

Key Laboratory of Meteorological Disaster, Ministry of Education/Joint International Research Laboratory of Climate and Environment Change/Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing, China

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ABSTRACT

In the beginning of the twenty-first century, weather and climate extremes occurred more and more in extratropical summer, linked to the magnified amplitudes of quasi-stationary waves and external forcing. The study analyzes the relations between multidecadal extratropical extremes in boreal late summer and the North Atlantic (NA; 35°–65°N, 40°W–0°) multidecadal variability (NAMV) in the mid- to high latitudes. The results show that multidecadal extratropical extremes link with the intensified NAMV and the related positive–negative–positive (+ – +) zonal mode of sea surface temperature (SST). 1) The SST mode favors the eastward shift of the negative-phase NA oscillation (NNAO), with a latitudinal pattern of cyclone anomalies over the western European coast and anticyclones over Greenland; NNAO is helpful to baroclinic energy transfer and a longitudinal wavelike pattern. 2) The SST mode and the eddy-driven jet of NNAO are conducive to a southeast extension of the NA jet in close conjunction with the Afro-Asian jet, thereby enhancing the jet waveguide and barotropic energy transfer for the maintenance of a low-frequency wave. 3) The effect of the intensified NAMV on warming Europe contributes to the longitudinal temperature gradient-like “cooling ocean and warming land” pattern, which enhances the meridional wind and wave amplitude of the low-frequency wave. Based on these causes, the intensified NAMV and the + – + SST mode favor the enhancement of the low-frequency wave and quasi-resonant probability, which magnifies the amplitude of the quasi-stationary wave and enhances extratropical extremes on the decadal time scale.

1. Introduction

Since the beginning of the twenty-first century, there have been significant increases in extratropical summertime extremes in the Northern Hemisphere (Coumou and Rahmstorf 2012; Huang et al. 2016a; 2017). The extratropical heatwave extremes with serious impacts include summer heatwaves in North America (2011, 2014, and 2016) and European continents (2003, 2019), as well as in Russia and Japan in 2010 (Stott et al. 2004; Hong et al. 2011; Johnson et al. 2018). The extratropical drought/flood extremes with serious impacts occurred in Europe in 2016/2017 (García-Herrera 2019) and in China in 2009/2010, 2012, and 2016 (J. Zhang et al. 2019). Are these extremes impacted by global warming or internal variability of the Earth–atmosphere interaction

system? The causes should be discussed separately; because of the increasing risks of economic loss and the damage of ecological environment (Palmer and Räisänen 2002; Zhang et al. 2015; Huang et al. 2016b, 2019), it is critical to explore the mechanism of extremes for prediction, evaluation, and disaster prevention.

From the perspective of circulation anomalies, the magnified quasi-stationary waves frequently occur (Petoukhov et al. 2013; Coumou et al. 2014; Petoukhov et al. 2016), along with weakening and northward shifts of the jets and double-jet formation for the waveguides (Francis and Vavrus 2012; Coumou et al. 2014, 2015). Furthermore, the jet anomalies of the Northern Hemisphere, characterized by large variability in jet position, strength, amplitude, and width, modulate the extratropical weather extremes (Screen and Simmonds 2014), and act as one of the potential mechanisms of recent extratropical weather extremes. Jet anomalies link to anthropogenic warming, aerosols, and natural variability (Baines and Folland 2007; Francis and Vavrus 2012; Zhang et al. 2015). The westerly jets

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Corresponding author: Jie Zhang, gs-zhangjie@163.com

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include the polar jet and subtropical jet, and the subtropical jets include the midlatitude North Atlantic (NA) jet (Trouet et al. 2018), the North Pacific jet (Strong and Davis 2008; Belmecheri et al. 2017), and the Afro-Asian jet (Branstator 2002); however, all of them show inconsistent variability at interannual to decadal time scales. Therefore, considering their different impacts, the jet effects on summer extremes should be discussed separately.

The NA jet has been identified to result in extratropical extremes such as heatwaves and droughts in Europe (Trouet et al. 2018), and NA jet variability is often characterized by using circulation indices such as the North Atlantic Oscillation (NAO) and the east Atlantic pattern (Woollings and Blackburn 2012). Moreover, extratropical extremes also link to NAO, consisting of a north–south dipole between Greenland and the midlatitude NA (Sillmann and Croci-Maspoli 2009). In addition, the Atlantic–Eurasian pattern manifests decadal variability and is termed the Eurasian multidecadal teleconnection (Li and Ruan 2018), which is a key component of NAO effect on Asian climate anomalies (Li et al. 2019).

Given that the variability of extratropical extreme exhibits a wide range of time scales, it is an essential step in weather and climate predictions and risk estimation to understand the characteristics and drivers of extreme and related circulation variability. Previous studies show that NAO is closely related to the mid- to high-latitude NA sea surface temperature (SST; Shaman et al. 2009; Trouet et al. 2018); the Atlantic–Eurasian pattern is a pivotal atmospheric bridge between the NA SST and Eurasian precipitation (Sun et al. 2015). In addition, the NA SST pattern is closely associated with recent rapid increase of warm extremes in summertime (Johnson et al. 2018). Therefore, the NA SST pattern is a considerable forcing in modulating extreme variations.

NA SST shows remarkable multidecadal variability (NAMV; Delworth and Mann 2000), manifested by the SST oscillation of uniform warm and cold patterns, and the dominant mode of NA SST in the NA (0° – 80° N) is multidecadal oscillation (Schlesinger and Ramankutty 1994; Kerr 2000). There is a consensus that the NAMV is primarily driven by fluctuations in the strength of the Atlantic meridional overturning circulation (AMOC; Black et al. 2014), anthropogenic forcing, internal dynamics, and air–sea interaction (Otterå et al. 2010; Chang et al. 2011), although no consensus exists as to the mechanism of the AMOC's effect on NAMV (Booth et al. 2012; Clement et al. 2015; Drews and Greatbatch 2016; O'Reilly et al. 2016; Zhang et al. 2016; Zhang 2017). However, research has suggested that AMOC variations can induce the multidecadal NA SST because

of associated heat transport fluctuations (Goldenberg et al. 2001; O'Reilly et al. 2016). In turn, the multidecadal NA SST also influences the AMOC, due to meridional advection by northward currents (Delworth et al. 2016; Li et al. 2017). Through dynamic processes, the NAO leads the NA SST variability by 15–20 years. Besides, atmospheric circulation affects the thermodynamic forcing, heat advection, and surface turbulent heat flux anomalies of the NA (Eden and Jung 2001), thereby modulating the AMOC and the multidecadal NA SST (Li et al. 2017).

For the perspective of NA SST effects on the decadal Eurasian climate, NAMV drives the variability in European climate at decadal time scale (Kushnir 1994; Schlesinger and Ramankutty 1994; Delworth and Mann 2000; Knight et al. 2006; Guan et al. 2019), and the warm-phase NAMV (referred to as NAMV+) is responsible for north-wet and south-dry anomalies in Europe during the 1990s and 1950s (Robson et al. 2012; Sutton and Hodson 2005; Sutton and Dong 2012). The NA acts as a significant source of natural climate variability over the NA basin and adjacent continents (Ruprich-Robert et al. 2017), and the increasing AMOC modulates the long-term loss of Arctic sea ice and Northern Hemisphere warming, especially in the late 1990s and early 2000s (Delworth et al. 2016). In addition, the Atlantic multidecadal oscillation influences extratropical summertime rainfall in northwest Europe (Knight et al. 2006) via the negative-phase NAO (NNAO) (Sutton and Hodson 2005). Homoplastically, the multidecadal NA SST also leads the NAO by approximately 15 years (Li et al. 2017), indicating the interaction and coupling effects of both NA SST and NAO (Steinman et al. 2015; Madrigal-González et al. 2017). NA SST effects have been investigated by a coupled mode of NA tripole–NAO–AMOC (Li et al. 2017), identifying the multi-scale effect of NAMV on Eurasian climate (Li et al. 2019).

From the perspective of NA SST effect on extratropical extremes on the decadal time scale, NAMV+ closely corresponds to the continued rise of extreme occurrences over Europe in the past 15–20 years (Seneviratne et al. 2014). Furthermore, the wave-energy anomaly related to extratropical extremes has been identified as occurring over the NA (Screen and Simmonds 2013; J. Zhang et al. 2019). However, the NAMV effect on the summer extratropical extremes in other Eurasian regions is inconclusive.

To further reveal frequent extremes over the Eurasian continent on the decadal time scale, this study explores the effect of NA SST on the extratropical circulation and quasi-stationary waves at the decadal time scale in order to facilitate extremes prediction.

2. Data and methods

a. Data sources

Long-term monthly surface temperature and pressure-level atmospheric parameters are obtained from ERA-Interim for the period from 1979 to 2018 with a resolution of $1.5^\circ \times 1.5^\circ$ and accessed from <http://apps.ecmwf.int/datasets/>. Pressure-level atmospheric data are used for calculating wave activity flux; 200-hPa zonal wind U is used for reflecting jet distribution; and 500- and 300-hPa meridional wind V is used for determining the frequency and amplitude of waves. To exhibit anomalies of extratropical circulation on longer time scales (beyond the synoptic scale), the quasi-stationary-wave anomaly and low-frequency waves are analyzed. The low-frequency wave index is defined as the average of the first two principal components of 500-hPa V wind in July and August (JA; 20° – 60° N, 60° W– 150° E; J. Zhang et al. 2019), which explains 38.2% of the variance and reflects the variation of the midlatitude Silk Road pattern (SRP).

Long-term monthly sea temperatures (with a resolution of $1.0^\circ \times 1.0^\circ$) are obtained from the Met Office Hadley Centre website (HadISST data; <https://www.metoffice.gov.uk/hadobs/>), and the SST data from 1950 to 2018 are used as climatological data for simulation, because the period is close to one period (65–80 yr) of NAMV. The NAMV index is defined as the low-pass-filtered (trend begins in 1900) annual mean of area-averaged SST in the mid- to high-latitude NA (50° – 65° N, 60° W– 0°), which is a key region for the NAMV, and the observed SST signal associated with the NAMV is strongest there (Sutton and Hodson 2005; Zhang et al. 2016). The time series of the “AMOC fingerprint” is defined as the first leading principal component (PC1) of detrended subsurface ocean temperature anomalies at 400 m in the extratropical NA (20° – 65° N, 80° W– 0° ; Yan et al. 2017). The smoothed Atlantic multidecadal oscillation (AMO) index is retrieved from <https://www.esrl.noaa.gov/psd/data/correlation/amon.sm.long.data> based on the area-weighted average SST from Kaplan SST V2 over the NA from 0° to 70° N. Moreover, the NAO index is retrieved from <https://crudata.uea.ac.uk/cru/data/nao/nao.dat> and is defined as the difference of pressure between Iceland and Gibraltar. The time period of both indices from 1979 to 2018 is selected.

A self-calibrating Palmer drought severity index (sc-PDSI; Dai 2011) is a meteorological drought index with a $2.5^\circ \times 2.5^\circ$ resolution; it provides a good reflection of soil moisture deficit or surplus and therefore is widely used for drought/flood evaluation throughout the world. The PDSI is obtained from the Climate Data Guide website (<https://climatedataguide.ucar.edu/climate-data/>

[palmer-drought-severity-index-pdsi](#)). Severe drought is $\text{PDSI} \leq -3$, severe flood is $\text{PDSI} \geq 3$, extreme drought is $\text{PDSI} \leq -4$, and extreme flood is $\text{PDSI} \geq 4$. Extreme droughts and floods are defined in the study as having absolute PDSI larger than 3.

b. Statistical analyses

Given that there are zonal wavenumbers 6–8 in the midlatitudes and zonal wavenumbers 4–6 in the high latitudes, the JA wave amplitude is calculated using harmonic analysis and V wind (Screen and Simmonds 2013). The JA wave amplitude is the summed amplitude for wavenumber $m = 6, 7$, and 8 at 300 hPa, as averaged over the 37.5° – 57.5° N latitudinal range; it reflects the amplitude variation of the low-frequency waves. Land–sea temperature contrast (LSTC) is defined as the surface temperature difference between European land (35° – 65° N, 10° – 60° E) and the midlatitude NA (35° – 65° N, 40° W– 0°). We used empirical orthogonal function (EOF) analysis to display the spatial and temporal patterns of 200-hPa U wind, SST, and 500-hPa V wind. The running means of the data are applied to obtain low-pass filtering of the variables. The statistical significance of the linear regression coefficient, the anomaly field, and the correlation between two series are assessed via a two-tailed Student's t test and Monte Carlo test; the Mann–Kendall mutation test is used. The correlations are from original series, with effective freedom of 40 (1979–2018).

The wave activity flux defined by Takaya and Nakamura (2001; this flux is referred to herein as TNF) is applied to examine the energy propagation of low-frequency waves and to reveal where anomalous wave energy is emitted, absorbed, and transferred.

c. Models

The linear baroclinic model (LBM) is employed to simulate atmospheric responses to an idealized forcing of diabatic heating and vorticity forcing over Europe. The LBM has a triangular truncation of 21 waves and a vertical resolution of 20 levels (Watanabe and Kimoto 2000). The background state in the experiment is the JA climatology of 1979–2018 from the ECMWF interim reanalysis. The forcing center of diabatic heating is over central Europe (50° N, 20° E), and vorticity forcing is over western Europe (50° N, 10° E), with a horizontal scale of $12^\circ \times 6^\circ$. The vertical forcing is located at 700 hPa with 6 K day^{-1} and $10 \times 10^{-8} \text{ s}^{-2}$, the integration time of the model is set to 30 days, and the data during the 15th–30th days with steady state could be used for analyzing circulation characters.

The Community Earth System Model (CESM1.0, Hurrell et al. 2013) developed by the National Center for Atmospheric Research (NCAR) consists of interactively coupled models for the atmosphere (CAM), ocean (POP), land (CLM), and sea ice (CICE). The model components are available at <http://www.cesm.ucar.edu/models/cesm1.0/>. The model is used to investigate the role of observed basin-scale SST patterns on amplitudes, summertime circulation, and extremes. This analysis focuses on the influences of the NA SST pattern. The SST boundaries are set to a 10° buffer of the southern boundaries over which the SST restoration, described below, ramps up from zero. The atmospheric component is the Community Atmospheric Model version 5.1 (CAM5.1) with the finite-volume dynamic framework with a horizontal resolution of $1.9^\circ \times 2.5^\circ$ and 30 vertical layers of the σ - p vertical coordinates. In this study, several physical processes, including radiation processes, cloud effects, convection, boundary layer effects, and so on, are represented in the model. Given that the PC1 exhibits a multi-decadal variation of SST, which shows significant correlation with NAMV index; in addition, as one sea surface pattern, EOF1 is influenced by sea-air interaction and vertical heat exchange between the sea surface and deep sea, which will change the SST pattern and heat distribution. Therefore, as for the sensitivity experiment of the SST forcing, twice the SST/EOF1 is taken as a hypothetical SSTA and is superposed with the original climatological SST as the initial SST. Moreover, given that sea surface wind could modulate the SST/EOF1 mode, the hypothetical SSTA is added to the SST for all months in summer since the second simulation year, so as to keep the SST/EOF1 mode on the decadal time scale. The annual SST from the sensitivity experiment is contrasted with real SST field in the most recent two decades. It is within 0.4°C SST deviation on average between warm and cold phases; therefore, the forcing SST in the sensitivity experiment represents the warm anomaly after 2000 and the NAMV mode. A control simulation uses climatological SST from 1950 to 2018, which is close to the SST during one period (65–80 yr) of NAMV, and its initial circulation fields use 40-yr climatological data (1979–2018). Both the sensitivity and control simulations are run for 20 years, with a time increment of 1 day and monthly output data. The control SRP is the first leading EOF mode of 20-yr V wind under the climatological SST. The sensibility SRP is the first leading EOF mode of 20-yr V wind from the sensibility experiment. However, for the difference between the sensitivity and control experiments, the last 10 years of data are used.

3. Results

a. Increasing low-frequency wave contributions to the midlatitude stationary wave amplitudes and extratropical extremes

To elaborate extratropical extremes, the study selects six regions over the Eurasian continent, namely western Europe (40° – 55°N , 0° – 20°E), eastern Europe (45° – 60°N , 35° – 55°E), central Asia (40° – 55°N , 70° – 90°E), East Asia (35° – 55°N , 110° – 125°E), central Russia (60° – 70°N , 70° – 100°E), and eastern Russia (60° – 70°N , 120° – 150°E). Figure 1 shows time series of extreme flood and drought frequency within 300 grids in JA: extreme droughts increase in western Europe, eastern Europe, East Asia, and central Russia and have high frequency between 1970 and 2000 in eastern Russia; extreme floods increase in central Russia, eastern Russia, and central Asia. Moreover, the total flood/drought trends indicate an increase in western Europe, East Asia, central Russia, and eastern Russia. Additionally, the trend and extreme frequency after the 1990s show increasing extremes. The period analysis shows that these series of extremes have a 14–21-yr period on the decadal time scale (figure omitted), and the significant correlations of 21-yr smoothed data indicate decadal variation of extremes, with an enhancing stage after the 1990s.

As for central Asia, although there is no significant increasing trend of the total droughts and floods, nonetheless there is a significant increasing trend of floods, which is related to a deepening wave trough around Lake Balkhash, linked with enhancement of the quasi-stationary wave, which is favorable for precipitation and flooding (Bothe et al. 2012). In addition, a branch of water vapor transport in central Asia is from the Indian Ocean and Arabian Sea; therefore, the related subtropical circulations are also important for extremes (Huang et al. 2015), which results in complex variation of extremes in central Asia. As for eastern Europe, high-frequency extremes mainly appear in 1972–84 and 1996–2015, exhibiting a decadal variation. After 2000, there is an increasing trend of droughts, similar to the suggestion of Hanel et al. (2018).

Figure 1 also marks selected extremes in six regions, with higher than mean frequency after 2000. Significant extremes occurred in 2004, 2005, 2007, 2010, 2011, and 2012 in western Europe; in 2002, 2004, 2005, 2009, 2010, and 2014 in eastern Europe; in 2002, 2008, 2010, 2012, and 2013 in central Asia; in 2001, 2002, 2004, 2005, 2006, 2007, 2009, 2010, 2011, 2012, 2013, and 2014 in East Asia; in 2001, 2002, 2006, 2012, and 2013 in western Russia; and in 2001, 2003, 2004, 2006, 2007, 2008, 2010, 2013, and 2014 in eastern Russia. Such large variabilities

FIG. 1. The frequency (%) of extreme floods (blue bars; PDSI ≥ 3) and extreme droughts (yellow bars; PDSI ≤ -3) in JA, the trend (red line), and the 21-yr moving-average filter (21-yr moving average; blue line) of total flood and drought frequency in 300 grids in (a) western Europe, (b) eastern Europe, (c) central Asia, (d) East Asia, (e) central Russia, and (f) eastern Russia. Blue dots mark the extremes with frequency after 2000 higher than the mean value (dotted line). Also, r is tendency correlation, r_d is correlation of 21-yr moving-average filter; one and two asterisks (* and **) mark statistical significance at the 90% and 95% confidence levels, respectively, using a Monte Carlo test.

remind us that extremes-related circulation is worthy of exploration.

Given that there are zonal wavenumbers 6–8 in the midlatitudes (Screen and Simmonds 2013), and the quasi-resonant stationary wave links with extratropical extremes, Fig. 2 shows the time series of wavenumber-5–8 amplitudes in JA. The wave amplitude exhibits a low-frequency wave variation. The wavenumber-6–8 component is very strong, with amplitudes at 300 hPa greater than averaged value after 2000, the amplitude is greater than 4 m s^{-1} during the extreme years, and marked extremes occur in 2001, 2002, 2003, 2007, 2009, 2010, 2011, 2012, 2015, and 2017 with high frequency over the study area, which include widely ranging extremes in 2015 and 2017 in Eurasia (Garcia-Herrera et al. 2019; J. Zhang et al. 2019), a heat wave in 2010 in Russia, and droughts in 2010 and 2012 in China, which are consistent with high wave amplitudes, indicating a possible link with high amplitude. High amplitude reflects the contribution of transient waves (including free synoptic waves and low-frequency waves) and transient vorticity to

quasi-stationary waves (e.g., climatology), due to spatially inhomogeneous diabatic sources/sinks and orography (Screen and Simmonds 2014). Increasing amplitudes favor increasing probability of high-frequency extremes, especially in the recent two decades. It is reasonable that quasi-resonance between free synoptic waves and quasi-stationary waves may lead to weather extremes, such as heat waves and floods, because many quasi-resonances occurs on the synoptic time scale, such as blocking highs and cutoff lows (Häkkinen et al. 2011). However, how does quasi-resonance influence extremes on longer time scale such as extreme droughts? Extreme droughts are affected by persistent anomalies of atmospheric circulation; they are a kind of climate extreme related to low-frequency variety of quasi-stationary waves. Thus, it is significant to explore climate extremes through quasi-stationary waves.

Such high frequency in amplified wave amplitude after 2001 reveals the decadal enhancement of quasi-stationary waves, which is possibly related to decadal forcing. The wave amplitude shows significant correlations

FIG. 2. Yearly time series of the 5-yr moving average of (a) wavenumber-5–8 amplitudes A in JA over the 37.5° – 57.5° N latitudinal belt and (b) low-frequency wave index reflecting the Silk Road pattern (SRP), and 5-yr moving averages of AMO, NAMV, and AMOC. The correlation coefficients r of amplitude and the SRP index with AMO, NAMV, and AMOC are from the original series. Blue dots indicate the selected extratropical extremes over the Eurasian continent in JA; asterisks (*) and (**) are as in Fig. 1.

with NAMV and AMOC at a 90% confidence level (Fig. 2a), which reflects the possible linkage with multidecadal NA SST. Previous studies have suggested that low-frequency waves arise and magnify the amplitudes of the quasi-stationary waves (Coumou and Rahmstorf 2012; Coumou et al. 2014; Petoukhov et al. 2013, 2016), the related potential sources of which are the NA and Europe (J. Zhang et al. 2019). The low-frequency wave index is defined as the first two PCs of JA meridional wind in the midlatitudes, which is used to reflect the intensity of SRP (Fig. 2b); the SRP intensity shows an enhancement after 2001 and increasing intensity of the low-frequency waves. There are significant correlations of the low-frequency wave index with AMO and AMOC, indicating a possible linkage with the multidecadal NA SST anomaly, and the significant correlation with wave amplitude shows the quasi-resonance effect of the low-frequency waves, thereby magnifying wave amplitude.

Figure 3 shows the mutation test of NA SST-related parameters, SRP, and wave amplitude A . The weak abrupt points of decadal changes of AMO/NAMV and AMOC begin in 1997, but the significant abrupt points are in 2000, 2003, and 2004. The abrupt points of SRP and wave amplitude occur in 2001–04, after the abrupt points of NAMV/AMO and AMOC, indicating that

FIG. 3. Mutation test of (top to bottom) AMO, NAMV, AMOC, SRP, and A . UF and UB (red and blue thick lines) are variation series of positive and inverse sequence calculations; thin dotted lines are the 95% confidence level, black dashed lines are abrupt points, and red dashed lines are the 95% significance level of abrupt points.

decadal changes of SRP and wave amplitude correspond to the NA SST pattern, with an adjusting stage of 2001–04. How do the low-frequency waves change with multidecadal NA SST? Understanding this is vital for evaluation and prediction of extratropical extremes.

b. Circulation anomalies and their relations with low-frequency waves and wave amplitude

To further identify the circulation anomalies after mutation stage and the enhanced quasi-stationary waves, Fig. 4a shows the difference of circulation-related factors in JA between 2001–18 and 1979–2018. The 200-hPa U deviations exhibit two positive anomaly centers (Fig. 4a); one is over the eastern midlatitude NA, which usually occurs on the east and south flank of the NA jet exit and indicates southeast extension of the NA jet after 2001. The wave activity flux (defined as TNF) after 2001 also indicates a major divergent energy over

FIG. 4. Difference of (a) 200-hPa zonal wind (dU ; shaded, unit: m s^{-1}) and wave activity flux (TNF; unit: $\text{m}^2 \text{s}^{-2}$) and (b) 500-hPa geopotential height ($\pm dZ$; contours, unit: gpm; interval: 5 gpm) and surface temperature in JA (dT_s ; shaded, unit: $^{\circ}\text{C}$) between 2001–18 and climatology (1979–2018). Also shown in (b) is the climatological geopotential height, contoured from 5560 to 5680 gpm with an interval of 60 gpm in (b) (Z5560–5680, green lines). Additional information in (a) includes climatological jets with $U = 15, 20, 25$, and 30 m s^{-1} (U15–30, black lines) and the jet with $U = 20 \text{ m s}^{-1}$ after 2001 (U20–2000s, red line). Climatological jet lines are used in subsequent figures. Dots indicate statistical significance at the 90% confidence level using a t test.

the midlatitude NA, and the wave activity flux is trapped into the Afro-Asian jet (Fig. 4a). A north–south shift in the NA jet in summer is identified to link with floods in western Europe (Dong et al. 2013), record-breaking high temperatures in northeastern Europe (Mahlstein et al. 2012; Stadtherr et al. 2016), and heatwaves (Founda and Giannakopoulos 2009; Koutsias et al. 2012). On the other hand, a southeast shift in the NA jet favors barotropic energy transfer to kinetic energy; in other words, a southeast shift in the NA jet is helpful to wave activity flux and energy dispersal toward the Afro-Asian jet, which acts as a waveguide for the formation and enhancement of the low-frequency waves. Then the sinking energy could lead to circulation anomalies and extremes (J. Zhang et al. 2019). It also identifies the potential relationship between the NA jet anomaly and European extremes. Trouet et al. (2018) suggested an unprecedented increase in NA jet variance since the 1960s, and therefore its effect on extreme variation on multiple time scales should be explored.

Figure 4b shows deviations of surface temperature and 500-hPa geopotential height. Two temperature centers with significantly positive deviation are over the European continent and Greenland to the west of the NA; one center with negative deviation is in the midlatitude NA. Surface temperature is influenced by atmospheric

FIG. 5. (a) The first leading EOF mode of 200-hPa U wind in JA (shaded) and climatological jets (black lines). (b) The 5-yr moving average of $U/\text{PC1}$, NAO, amplitude A , and SRP and the correlation coefficients between them. Climatological jets are as in Fig. 4. Asterisks and blue dots are as in Fig. 2.

circulations; conversely, longitudinal temperature deviation forms a contrast of the “cooling ocean and warming land” pattern, influencing atmospheric circulations (Hoskins and Karoly 1981; He et al. 2018). Because the negative deviation of surface temperature is a section of the NA SST pattern on the multidecadal time scale, the longitudinal temperature gradient relates to multidecadal NA SST. In addition, positive (negative) temperature centers correspond to anticyclonic (cyclonic) anomalies described by geopotential height deviation, which in turn correspond to wave ridges (troughs) by comparing with wave position, revealing strengthening of the climatological wave ridges and wave troughs after 2001, as well as enhancement of quasi-stationary waves (J. Zhang et al. 2019). The latitudinal pattern of the geopotential height anomaly indicates an eastward shift of the NNAO pattern due to a low pressure anomaly over the west coast of northern Europe.

We perform an EOF analysis for 200-hPa U wind to highlight the zonal wind and the NA jet anomaly. The first leading mode explains 33.3% of the total variance, and the mode exhibits a negative–positive–negative ($- + -$) latitudinal pattern (Fig. 5a), with positive values at the southeast of the NA jet exit and northern Europe. From the previous point of view, we can conclude that the jetstream shows both a southeast extension of the NA jet and a northwest shift of the entrance of the Afro-Asian jet in the most recent decade, which favors the conjunction of two jets and strengthening of the Afro-Asian jet waveguide. Moreover, the NA jet anomaly possibly increases barotropic energy transfer to

kinetic energy, thereby enhancing the low-frequency waves (J. Zhang et al. 2019). The PC1 of U shows a multidecadal variation (Fig. 5b), which is closely related to wave amplitude (Fig. 5b), with a correlation coefficient of 0.28 at the 90% confidence level, and has a significant correlation of 0.35 with the SRP at the 95% confidence level. The results reveal that the southeast extension of the NA jet in the twenty-first century corresponds well to magnified wave amplitude and intensity. Figure 5b also exhibits an NNAO in the twenty-first century, with an abrupt point of decadal change in 2004, having a significant correlation coefficient of -0.54 with PC1 of U at the 95% confidence level, and having a significant correlation of -0.29 with wave amplitude at the 90% confidence level. The relation between the NA jet and NNAO emphasizes that NA jet position and speed variability are associated with the NNAO eddy-driven jet and the east Atlantic pattern (Woollings and Blackburn 2012; Hall et al. 2015). The abrupt point of PC1 of U is 2009, which is different from circulation and NA SST mutation, which means that there are other effect factors that should be discussed.

c. LSTC and the relation with low-frequency wave and wave amplitude

To feature the cooling ocean and warming land pattern and its effect on the extratropical extremes, the study defines an LSTC index (see section 2). Figure 6a shows a standardized LSTC index in July and August (JA); both indices show significant increase trends, indicating increases in LSTC and longitudinal temperature contrast between the European continent and the NA, which may strengthen meridional wind and wave amplitudes according to the thermal wind principle and a linearized nonstationary, nondivergent, barotropic vorticity equation (Hoskins and Karoly 1981). Figure 6b displays the time series of JA LSTC, which indicates a multidecadal variation with an abrupt point in 2004, and it has a correlation coefficient of 0.29 with the wave amplitude at the 90% confidence level, and a significant correlation coefficient of 0.58 with the low-frequency wave index at the 95% confidence level. A significant increase in LSTC in the twenty-first century is helpful to the enhancement of meridional circulation, reflecting the enhancement in the low-frequency wave imposed on the quasi-stationary wave, and further is conducive to magnified amplitude of the quasi-stationary wave.

To exhibit the effect of LSTC on atmosphere circulations, Fig. 6c shows the regression of the 500-hPa temperature (dT ; shaded) and the geopotential height (contours) to the JA LSTC index. The significant anomaly centers of temperature exhibit wave patterns in the midlatitudes

FIG. 6. (a) LSTC index and the trend in July and August, (b) the 5-yr moving average of JA LSTC, amplitude A , and SRP and the correlation between them, and (c) the regression of the 500-hPa temperature anomaly (dT ; shaded) and geopotential height anomaly (dZ ; black and gray contours representing positive and negative anomalies, respectively, with an interval of 5 gpm) to the JA LSTC index. The averaged geopotential height contours before and after 2001 are as in Fig. 4. Asterisks are as in Fig. 2. Dots indicate statistical significance at the 95% confidence level using the Monte Carlo test.

and high latitudes, with the negative centers over the North Atlantic and the positive centers over European continent, which correspond to the negative (positive) centers of the geopotential height anomaly and the wave trough (ridge) of the quasi-stationary wave, and the anomalous wave pattern due to LSTC possibly magnifies the amplitude of the quasi-stationary wave.

We also perform a correlation of the LSTC index with the wave amplitude of the wavenumbers 5–8 (figure omitted) and find a significant correlations coefficient of 0.44 with wavenumber 7 in August, and a correlation coefficient of 0.32 with wavenumber 8 in July at the 90% confidence level. These results further identify an increase in the LSTC contributing to the magnified amplitude of the quasi-stationary wave.

d. Circulation anomalies and LSTC effects on the wave energy

To further identify the impact of the aforementioned three factors (southeast shift in the NA jet, NNAO, and increasing LSTC) on the wave amplitude and intensity, the wave activity fluxes (TNFs) are regressed. The divergence wave activity flux is clear between the NA jet exit and the entrance of the Afro-Asian jet, but the effect

varies for each region due to different factors (Fig. 7). The regression of TNFs to PC1 of U (or $U/PC1$) that is statistically significant are mainly located between 20°W and 20°E along the NA jet, reflecting high divergence energy from the NA jet exit and enhancement of wave dispersion between two jets, which is helpful for reinforcing the low-frequency wave. The regression of TNFs to $-NAO$ that is statistically significant covers a large range of the jet belt between 60°W and 30°E along the NA jet and the Afro-Asian jet. NNAO-related vorticity favors baroclinic energy transfer (J. Zhang et al. 2019) because a cyclone anomaly related to NNAO just occurs over northwestern Europe, ahead of the trough of the quasi-stationary wave, which leads to enhancement of convergence and ascending motion in the lower to middle troposphere, and thereby contributes to zonal configuration of warm ascending air and cool descending air that is helpful to baroclinic energy transfer. The regression of TNF to LSTC that is statistically significant is mainly located between 40°W and 10°E along the NA jet, with a convergence TNF appearing over 10°W and the wave trough, which favors deepening of the wave trough and meridional wind. Increasing LSTC exhibited by the nonuniform longitudinal temperature gradient leads to meridional wind and wave enhancement according to the linearized nonstationary, nondivergent, barotropic vorticity equation (Hoskins and Karoly 1981) and thermal wind principle. All these TNF distributions reveal different contributions of the three factors to wave energy and the low-frequency wave, and their effect mechanisms are worthy of further discussion.

To explore the jet and the NNAO anomaly effect on energy conversion, we estimate energy conversion including the local barotropic energy conversion (CK) (Hoskins et al. 1983; Simmons et al. 1983) and local baroclinic energy conversion (CP) (Kosaka and Nakamura 2006):

$$CK = \frac{v'^2 - u'^2}{2} \left(\frac{\partial \bar{u}}{\partial x} - \frac{\partial \bar{v}}{\partial y} \right) - v'u' \left(\frac{\partial \bar{u}}{\partial y} - \frac{\partial \bar{v}}{\partial x} \right), \quad (1)$$

$$CP = \frac{f}{\sigma} v'T' \frac{\partial \bar{u}}{\partial p} - \frac{f}{\sigma} u'T' \frac{\partial \bar{v}}{\partial p}, \quad (2)$$

where u' and v' are anomaly zonal and meridional wind velocity; $\bar{u}$ and $\bar{v}$ are the mean zonal and meridional wind velocity, respectively; T' is the anomaly temperature; f is the Coriolis parameter; and $\sigma = (R\bar{T}/C_p p) - (d\bar{T}/dp)$, with temperature T , specific heat at a constant pressure C_p , and pressure p .

Figure 8 shows the 300-hPa barotropic energy (Fig. 8a; CK) and 700-hPa baroclinic energy (Fig. 8b; CP) after 2001, as well as the correlation between CK and jet

FIG. 7. Regression maps of the 200-hPa wave activity flux (TNF; arrows, unit: $m^2 s^{-2}$) to (a) $U/PC1$, (b) $-NAO$, and (c) LSTC showing statistical significance at the 90% confidence level. Climatological jets (black lines) and the climatological geopotential height contours of 5560–5680 gpm (green lines) are as in Fig. 4. The TNF that is not statistically significant at the 90% confidence level is masked.

anomaly ($U/PC1$, Fig. 8c), and between CP and the $-NAO$ index from 1979 to 2018 (Fig. 8d). The reason to analyze 300-hPa CK is that it is closely related to the NA jet anomaly, which is clear over the upper troposphere; the reason to analyze 700-hPa CP is that lower-level baroclinicity is helpful to atmospheric stability and ascending motion, and it also corresponds to the effect of eastern extension of the NNAO.

The positive CK at the NA jet exit to the entrance of the Afro-Asian jet indicates the barotropic energy conversion. The positive correlation between CK and $U/PC1$ at the NA jet exit shows that increasing U wind and southeast extension of NA jet favor barotropic energy conversion from the background state to seasonal kinetic energy.

Along the west coast of northwest Europe, positive baroclinic energy observed after 2001, which reflects increasing baroclinic condition, corresponds to cyclone anomalies and an eastward shift in the NNAO. The correlation between CP and $-NAO$ shows positive correlation over Europe, indicating an increase of baroclinic energy conversion to seasonal kinetic energy, corresponding to the NNAO. The reason is that eastern extension of the NNAO appears over the west coast of northwest Europe, ahead of the stationary wave trough

FIG. 8. (a) Barotropic energy (CK) at 300 hPa after 2001 (shaded, unit: $\text{m}^2 \text{s}^{-2}$) and (b) baroclinic energy (CP) at 700 hPa after 2001 (shaded, unit: $\text{m}^2 \text{s}^{-2}$), (c) correlations between CK and U/PC1 (shaded), and (d) correlations between CP and -NAO (shaded). Black dots in (c) and (d) indicate statistical significance at the 95% confidence level using the Monte Carlo test.

with baroclinicity, which is favorable for ascending motion; such a baroclinic configuration with zonal warm-ascending air and cold-descending air favors baroclinic energy conversion to kinetic energy. The kinetic energy enhances wave activity motion and wave energy dispersing along the jet waveguide; it is the same as the regression of wave activity motion to -NAO in Fig. 7b.

The results reveal that southeast extension of NA jet and NNAO favor increasing barotropic and baroclinic energy conversion to kinetic energy, which is helpful to enhancement of wave activity motion and low-frequency waves.

e. Effects of SST pattern on the circulation and LSTC anomaly

A strengthened NA jet has been suggested to link with SST variances in the central NA and NA basin (Black et al. 2014; Liu et al. 2017; Trouet et al. 2018), as well as with warming in Europe (Sun 2014), because of zonal nonuniform heating and the thermal wind principle, except for dynamic processes of the eddy vorticity flux. We investigate the linkages of the NA SST with the NA jet, NAO, and LSTC. The first SST leading mode explains 40.2% of the total variance (Fig. 9a); the mode exhibits a positive-negative-positive (+ - +) latitudinal pattern, with a weakly negative anomaly in the midlatitude NA (40° – 60° N) at the southeast end of the NA jet exit and with a positive anomaly across other regions of the NA (20° – 80° N). Figure 9b indicates that the NA SST/PC1 correlates with the U/PC1, NAO, and LSTC, with significant correlation coefficients of 0.32, -0.57, and 0.33 at the 95% confidence level, respectively; this indicates that the NAMV pattern with a + - + zonal pattern is possibly related to the eastward shift in the NNAO, due to a low pressure

anomaly over south of Iceland. Also, there is a zonal SST mode of central cooling and south warming on the south flank of NA jet exit, which is helpful for a southward shift of the NA jet, based on the thermal wind principle. According to Figs. 7 and 8, anomalies of NNAO and a southward shift in the NA jet closely relate to barotropic/baroclinic energy transfer to kinetic energy, which thereby excites and enhances the low-frequency waves. The NAMV SST pattern with a + - + zonal pattern possibly contributes to an increase in LSTC in the 2000s, because of a cooling midlatitude NA and the NAMV effect on warming central Europe (Sutton et al. 2005, 2012).

Figure 9b shows the low-pass-filtered AMO, AMOC, and NAMV index during the entire period of 1979–2018. The SST/PC1 pattern is well correlated with the original NAMV index (Sutton and Hodson 2005), AMO, and AMOC, with correlation coefficients of 0.8, 0.82, and 0.66, respectively. The AMO could explain some interdecadal components of summer hot days and heatwaves in subtropical regions for 1979–2016 (Kushnir 1994; Zhang et al. 2018). However, explanations for AMO and extratropical extremes are lacking. The statistically significant correlation of NAMV with the SST/PC1 pattern reveals that the SST/EOF1 pattern could reflect multidecadal variation of the mid- to high-latitude NA SST through circulation anomalies such as eastward extension of the NNAO, a southeast shift in the NA jet, and increasing LSTC. The SST/EOF1 pattern is linked to the extremes-related amplitude of waves (Fig. 2).

AMOC anomalies at the mid- to high latitudes have been observed to lead the fingerprint by ~ 4 years with respect to the mid- to lower-latitude fingerprint as a proxy for AMOC variations (Smeed et al. 2014) due to

FIG. 9. (a) The first EOF mode of NA SST in JA, (b), the PC1 of SST time series of NAMV, AMO, and AMOC, and the regression maps of the (c) 200-hPa U wind (unit: m s^{-1}) and (d) geopotential height (lines, unit: gpm) and surface temperature (shaded, unit: $^{\circ}\text{C}$) to the SST/PC1. Red lines in (d) are positive, and blue lines are negative. Climatological jets (black lines) in (a) and (c) are as in Fig. 4a; black dots in (c) and (d) are as in Fig. 6.

the slow propagation of heat transport (Zhang and Zhang 2015). The correlation of leading AMOC index with the SST/PC1 pattern shows a statistically significant correlation. Previous study has shown that the AMOC stores approximately one-half of global excess heat during an accelerating phase from the mid-1990s to the early 2000s, which contributes to the global warming slowdown in the beginning of the twenty-first century (Chen and Tung 2018). It is expected that an intensified AMOC will last at least approximately two decades, which will further result in low-level oceanic heat uptake manifesting as a period of rapid global surface warming, as well as favoring persistence of the NAMV SST pattern.

Figures 9c and 9d show regressions of 200-hPa U , 500-hPa geopotential height, and surface temperature to the NA SST/PC1. The U anomaly related to the SST pattern exhibits a $- + -$ zonal pattern over the NA and Europe with a positive anomaly at the exit of the NA jet to northern Europe and a negative anomaly over southern Europe and the northern NA jet, which exhibits a southeast extension of the NA jet exit and northward extension of the entrance of the Afro-Asian jet. The regression result of the geopotential height is like the eastward shift in the NNAO pattern (Fig. 9d), which is consistent with recent decadal anomalies of NAO (Ulbrich and Christoph 1999). On the one hand, such a pattern identifies a cyclone anomaly over western Europe; on the other hand, the cyclone leads to the eddy-driven jet effect on the southeast extension of the

NA jet exit. The regression of surface temperature (Fig. 9d) exhibits a negative anomaly in the midlatitude NA and a positive anomaly in eastern Europe, which is manifested as a cooling ocean and warming land pattern in the midlatitudes, showing a positive anomaly of LSTC during the early twenty-first century. The regression maps also reveal a low-frequency wave pattern (figure omitted), which is close to the quasi-stationary wave with a similar wavenumber.

Figure 9 indicates that the NAMV SST pattern could represent multidecadal change of NA SST, and it is possibly favorable for multidecadal variability of the southeast extension of the NA jet, the eastward shift in the NNAO, and the increase in LSTC. Conversely, previous research has shown that multidecadal variations of the NAO can induce multidecadal variations in the AMOC and poleward ocean heat transport in the Atlantic (Smeed et al. 2014), which dominates long-term high-latitude SST, and the Arctic, superimposed on long-term anthropogenic forcing. In addition, poleward shifts in the NA jet in the future correspond to increased anthropogenic forcing (Iqbal et al. 2018). Those reveal that multidecadal variability of the mid- to high-latitude circulations are the result of air-sea interaction and ocean dynamics and thermodynamics, superimposed on long-term anthropogenic forcing, except for the remote forcing of the tropical SST pattern (Okumura et al. 2001; W. Zhang et al. 2019). These multidecadal circulation anomalies in the mid- to high latitudes act as the background of

FIG. 10. Simulation (left) geopotential height (shaded, unit: gpm) and wind velocity (UV ; arrows) at (a) 500 and (b) 200 hPa with diabatic heating forcing over Europe (center: 50°N , 20°E) at 700 hPa, and (right) geopotential height (shaded, unit: gpm) and wind velocity (UV ; arrows) at (c) 500 and (d) 200 hPa with vorticity forcing. Climatological ($U\text{-clim} = 20$; green lines) and simulated ($U\text{-sens} = 20$; pink lines) 20 m s^{-1} U winds at 200 hPa are shown in (b) and (d). Climatological (green lines) and simulated geopotential height (5560, 5620, and 5680 gpm; pink lines) at 500 hPa are shown in (a) and (c).

frequent extratropical extremes on the multidecadal time scale.

f. Simulation of increase in the LSTC and NNAO-related vorticity anomaly

To identify the magnifying wave amplitude due to a nonuniform temperature distribution and the increasing LSTC, this study conducts one experiment related to the longitudinal nonuniform temperature. A forcing of diabatic heating is performed over Europe (centered at 50°N , 20°E) at 700 hPa. In addition, to identify the contribution of the eastward shift in the NNAO, corresponding to the cyclone anomaly over western Europe, another experiment with positive vorticity forcing (centered at 50°N , 10°E) is conducted at 700 hPa (schemes are shown in the model section).

The simulation results show that diabatic heating and positive vorticity forcing are similar in the midlatitudes. Both of them are favorable for two significant wave patterns exhibited by geopotential height over the midlatitudes and high latitudes (Figs. 10a,b). The anticyclonic and cyclonic anomalies correspond to the wave ridge and trough of the quasi-stationary wave, which indicates that the LSTC-related diabatic heating and the NNAO-related vorticity forcing could excite the low-frequency waves, with the same phase and wavenumbers as the quasi-stationary wave, which favors resonant probability.

From the jet perspective, the Afro-Asian jet exhibits shrinking and a decrease of 20 m s^{-1} zonal winds from

central Asia to the southern Mediterranean Sea and northern Africa under the vorticity forcing. But an increase of 20 m s^{-1} zonal winds occurs over Europe and the east coast of the North Atlantic under the LSTC-related diabatic forcing. These findings indicate a northward shifting in the entrance of the Afro-Asian jet. Besides, there is significant eastward extension of the 20 m s^{-1} U wind, which indicates an eastward extension of the NA jet exit due to the NNAO eddy-driven jet. Moreover, the jet anomaly is conducive to an increase in energy transfer from the background to kinetic energy and energy dispersion trapped in the Afro-Asian jet, and the jet waveguide favors warming over Europe (Branstator 2002; Wang et al. 2014). On the other hand, NNAO is favorable for a low-frequency wave exhibited by a geopotential height anomaly, such as blockings (He et al. 2018). The simulation results agree with above diagnostic analysis, which further identify that the LSTC-related diabatic heating and NNAO-related vorticity anomalies may excite the low-frequency wave along two jets and magnify the amplitude of the quasi-stationary wave.

g. Simulation of the NA SST pattern effect on extremes

To further quantify the magnification of wave magnitude, intensity, and relations with the intensified NAMV-related SST mode, SST forcing in the sensitivity experiment has been conducted by combining twice the first leading SST mode with climatological SST and annual simulated SST in summer (the description is in the

FIG. 11. Simulated anomalies of positive SST mode (Sens-Ctrl; sensitivity minus control) of (a) 200-hPa U (shaded, unit: m s^{-1}) and TNF (vectors, unit: $\text{m}^2 \text{s}^{-2}$), (b) 500-hPa geopotential height (shaded, unit: gpm) and UV wind velocity (unit: m s^{-1}), and (c) 700-hPa air temperature (unit: $^{\circ}\text{C}$) from CESM. Climatological geopotential height [blue lines in (b) and (c)] and jet [thin black lines in (a)] are as in Fig. 4, but for the control simulation. Dots are as in Fig. 4.

model section). The key circulation anomalies such as jet anomaly, NAO pattern, and LSTC are analyzed. The 200-hPa U wind from the sensitivity experiment shows a positive anomaly at the NA jet exit and north of the entrance of the Afro-Asian jet (Fig. 11a), which indicates a southeast extension of the NA jet. Such anomalies could well connect the NA jet with the Afro-Asian jet, thereby enhancing the jet waveguide between two jets. From the energy perspective, the U -wind deviation could change the interaction between background and seasonal energy transfer (Hoskins and Karoly 1981), further resulting in increased seasonal kinetic energy. The wave activity flux at the 200-hPa level (Fig. 11a) further certifies the divergence energy in the positive- U region and the NA jet exit. Moreover, wave energy disperses along the Afro-Asian jet and the subpolar jet, which favors enhancement of the low-frequency waves.

The anticyclone and cyclone anomalies that correspond to the SST/PC1 pattern are exhibited by the geopotential height anomalies (Fig. 11b), which exhibit an eastward shift of the NNAO-like pattern described by the latitudinal pattern of cyclone anomalies over northwestern Europe and anticyclones over Greenland.

NAO-like eddies also contribute to an extension of high-frequency eddies that drive the jet (de Vries et al. 2013). The meridional pattern of cyclone anomalies over northwestern Europe and western Siberia and anticyclones over eastern Europe and eastern Siberia indicate a wave train; the cyclonic (anticyclonic) anomalies correspond to wave troughs (ridges) of the quasi-stationary waves, and favor increasing amplitudes of the quasi-stationary waves. The surface temperature anomalies corresponding to the SST/PC1 pattern show a meridional wavelike pattern (Fig. 11c) with a negative anomaly over the midlatitude NA to western Europe and East Asia and positive anomalies over central Europe to central Asia. The pattern reveals that NAMV could contribute to the cooling ocean and warming land pattern, in addition to the European warming under global warming (Dong et al. 2013). The pattern favors enhancement of meridional circulation and increasing amplitude of the quasi-stationary wave. Besides, the anticyclone anomaly around the Ural Mountains favors the enhancement and eastward of the Ural blocking high (Matsueda and Endo 2017), which explains some extremes over Eurasia (García-Herrera et al. 2019).

To emphasize the difference between the control SRP and the sensitivity SRP, the first V -wind leading modes (20° – 60° N, 30° W– 150° E) in JA from the control and sensitivity simulation are performed. The centers of the V -wind mode are connected (Fig. 12a), which represents the climatological SRP, NAMV-related SRP pattern, and SRP pathways. From the perspective of SRP pathways, there is a northward shift of the sensitivity SRP wave over the Eurasian continent, by comparing with control SRP, which reveals the magnified wave amplitude that enhances the north wind and the anticyclone anomaly over North China that enhances extreme droughts (J. Zhang et al. 2019). The positive and negative centers of the V -wind mode reflect the SRP phase. By comparing the SRP phases, it is found that there is an east shift in SRP centers between 40° – 50° N and the high latitudes (50° – 70° N) to the east of 60° E, with less than a quarter period, which reveals an eastward shift of climate anomalies corresponding to the eastward NNAO and the southeast extension of the NA jet. Moreover, an eastward shift in the wave pattern could explain the eastward Ural blocking high (Matsueda and Endo 2017; García-Herrera et al. 2019). However, west shifts of SRP centers occur over the NA and northern Europe between 50° and 70° N. Therefore, the phenomenon shows a complex relation between the physical process of SRP shift and NNAO and eastward extension of the NA jet, which needs further discussion.

To further identify the contributions of the intensified NAMV-related SST mode to the wave amplitude and extratropical extremes, the time series of wave amplitude from the 20-yr control simulation and sensitivity simulation are calculated. The circulation parameters in the first year are replaced with the mean value of 20-yr control simulations before calculating the wave amplitude, acting as a reference. Considering the close phase (less than a quarter period) of wavelike circulation between the control and sensitivity results, the standardized difference between sensitivity and control is shown (Fig. 12b). To feature SRP intensity, the standardized $V/PC1$ series from sensitivity and control, which represent wave intensity, are shown in Fig. 12b. The results show that the wave intensity under the control simulation is close to the mean value of control simulation; however, most of them are higher in the sensitivity experiment than the control, and the wave amplitude from sensitivity experiment is also higher than control experiment, especially after the ninth year, revealing increases in wave intensity and wave amplitude due to an increase in intensified NAMV. The simulated result is in accordance with the above diagnostic analysis.

FIG. 12. (a) Contrast of V -wind EOF mode representing sensitivity SRP (Sen., shaded) and climatological SRP (lines) and the central pathway (red is Sen. and blue is Ctrl SRP). (b) Simulated amplitude difference (A Diff.; green line, standardized) between 20-yr sensitivity and control simulation and SRP low-frequency wave intensities ($V/PC1$) from the 20-yr control simulation (Ctrl Diff.; blue bars) and sensitivity simulation (Sen. Diff.; yellow bars). P-Clim and N-Clim in (a) are the positive and negative V -wind distributions, respectively.

4. Summary and discussion

The magnification of wave magnitude is shown to closely relate to extratropical extremes. The causes of decadal-scale increase in extremes in the twenty-first century are still uncertain, although many materials have discussed the extremes under global warming (e.g., Palmer and Räisänen 2002; Francis and Vavrus 2012; Huang et al. 2017; Johnson et al. 2018). From the perspective of internal variability of the Earth–atmosphere interaction system, the NAMV is an important forcing due to its impact on the widespread atmospheric quasi-stationary wave at the multidecadal time scale. This study reveals the linkage of NAMV and the anomalies of quasi-stationary wave with respect to the following three aspects: 1) Intensified NAMV with a zonal + – + SST mode favors southeast extension of the NA jet, according to thermal wind principle. 2) Intensified NAMV with a zonal + – + pattern and positive anomaly temperature over the mid- to high latitudes is helpful to zonal pressure anomaly, which possibly favors the eastward shift in the NNAO pattern, and thereby strengthens eddy disturbance over western Europe and enhances the eddy driven jet, contributing to southeast extension of the NA jet. 3) Intensified NAMV with cool midlatitude SST and NAMV effect on warming Europe contributes to the midlatitude cooling ocean and warming land pattern, which increases meridional circulation and meridional wind, according

FIG. 13. Schematic diagram summarizing three physical processes of the intensified NAMV effect on low-frequency waves (LFW) and magnification of the amplitude of quasi-stationary waves (QSW). Other abbreviations are as follows: JS is the NA jet; KE is the seasonal kinetic energy, energy conversion from jet to KE reflects barotropic energy; B is the baroclinic energy conversion to seasonal KE; LSTC is the temperature contrast between the land and sea described by the longitudinal temperature gradient $\partial T'/\partial \lambda$; and V' is the meridional wind anomaly.

to the V -wind thermal wind principle and barotropic vorticity equation (Hoskins and Karoly 1981).

The magnification of wave magnitude is shown to be linked to the decadal anomaly of the southeast extension of the NA jet, increasing LSTC, the eastward shift in NNAO, and so on. The schematic diagram (Fig. 13) shows the mechanism of the NA SST pattern effect on the low-frequency waves and the magnification amplitude of the quasi-stationary wave. Three physical processes are marked. In process (a) the southeast extension of the NA jet anomaly favors barotropic energy transfer to seasonal kinetic energy and the waveguide between the NA jet and Afro-Asian jet, which enhances jet stream waviness (Francis and Vavrus 2012) by altering in jet width, position, and intensity. In process (b) an eastward shift in NNAO is conducive to baroclinic energy conversion to seasonal kinetic energy, as is an eddy-driven jet; both processes lead to an increase in energy transfer and

dispersion, which excites or enhances the low-frequency wave. In process (c) an increase in LSTC leads to enhancement of the meridional wind, which enhances the amplitude of the low-frequency wave. The reinforcing low-frequency waves increase the quasi-resonance probability and amplify the amplitude of the quasi-stationary wave (Dong et al. 2013), thereby favoring extratropical extremes with high frequency in summer.

Similar to the NA jet anomaly, the latitudinal position anomaly of the North Pacific jet (Shaman et al. 2009; Belmecheri et al. 2017) is also changed. However, the linkage of the North Pacific jet anomaly with extratropical extremes and the relationships between the NA jet and the North Pacific jet receive less attention. Except for the NAMV pattern, the NNAO can also lead to cooling of the midlatitude NA SST (Delworth et al. 2016), which also favors an increase in LSTC, and further explains the low-frequency wave anomalies. The study just discusses the

NA SST effect on the extremes on the multidecadal scale; however, it is significant to further discuss other internal variabilities of the Earth–atmosphere system and anthropogenic warming. Because of lagging behind the NAMV mutation of the decadal change of the above three factors and wave parameters (amplitude and intensity), it is inferred that a coupling effect of NAMV and other forcings should be further explored.

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