Quasiresonant amplification of planetary waves and recent Northern Hemisphere weather extremes

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In recent years, the Northern Hemisphere has suffered several devastating regional summer weather extremes, such as the European heat wave in 2003, the Russian heat wave and the Indus river flood in Pakistan in 2010, and the heat wave in the United States in 2011. Here, we propose a common mechanism for the generation of persistent longitudinal planetary-scale high-amplitude patterns of the atmospheric circulation in the Northern Hemisphere midlatitudes. Those patterns—with zonal wave numbers m = 6, 7, or 8—are characteristic of the above extremes. We show that these patterns might result from trapping within midlatitude waveguides of free synoptic waves with zonal wave numbers k ≈ m. Usually, the quasistationary dynamical response with the above wave numbers *m* to climatological mean thermal and orographic forcing is weak. Such midlatitude waveguides, however, may favor a strong magnification of that response through quasiresonance.

atmospheric dynamics | mid-latitude Rossby wave trapping

The summer of 2003 was highly exceptional in the Northern Hemisphere (NH) (1–4). Its remarkable feature was a persistent "blocked" circulation pattern over Europe (1–4). Anomalous heat reigned for much of the summer over a large part of Europe, reaching the highest temperature anomalies in Switzerland, northwestern France, and southern Germany. Schär and colleagues (2004) (3) proposed that the observed climatic warming trend (*i*) shifted the probability distribution of summer temperatures toward warmer values and (*ii*) widened this probability distribution so that extreme values become much more likely, possibly as the result of a positive feedback between temperature and soil dryness. We note that a shift and widening of the probability distribution due to global warming almost certainly will lead to a marked increase in the frequency of extreme warm-season events (5–7). However, even when the warming trend found in the data is fully taken into account, and if an increase in SD of 50% is assumed, the extreme temperatures and duration of the summer 2003 heat wave still would be highly unlikely. For example, a return period of 100 y was estimated by Luterbacher et al. (2) for the European region. In the meantime, several other unusually strong regional summer extremes already have occurred in recent years that make it questionable that only a purely stochastic mechanism of extremes is at work (8). The global observations attest that these extremes, such as the Russian heat wave in 2010 and the record heat wave in the United States in 2011, persisted over nearly the whole summer— which is not inherent in ordinary blockings with a characteristic e-folding time of about 5–7 d—and were in fact of hemispheric scale: a stable anomalous atmospheric circulation pattern enveloped the whole NH (4, 9-14).

Here, based on daily National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) (15) reanalysis data, we highlight that the NH midlatitude quasistationary meridional velocity during the aforementioned regional summer extremes was characterized by unusual high-amplitude wave patterns with zonal wave numbers $m = 6$, 7, or 8. The latter might result from trapping of quasistationary free waves with zonal wave numbers $k \cong m$ within midlatitude waveguides, leading to a quasiresonant amplification of the above wave numbers m as described in sections I and II.

I. Quasiresonance Hypothesis

Generally the large-scale midlatitude atmospheric circulation is characterized by (*i*) traveling free synoptic-scale Rossby waves with zonal wave numbers $k \geq 6$ propagating predominantly in the longitudinal direction with the phase speed $c \approx 6 - 12$m/s, and (*ii*) quasistationary planetary-scale Rossby waves with $c \approx 0$, frequency $\omega \approx 0$, and various zonal wave numbers m as a response of atmospheric circulation to quasistationary (e.g., climatological mean) spatially inhomogeneous diabatic sources/sinks and orography (16–28). The quasistationary component of midlatitude free synoptic-scale waves with $k \approx 6 - 8$ normally is weak, with the magnitude of the meridional velocity less than (1.5–2) m/s (26, 27). Below, k and m will denote the zonal wave numbers, respectively, of free synoptic waves and quasistationary planetary-scale Rossby waves mentioned above. Our hypothesis is that during the extreme summer events considered, certain persistent high-amplitude wave structures evolved in the field of the large-scale midlatitude atmospheric meridional velocity (hereafter, V) to which the quasistationary component of free synoptic waves with $k \approx 6 - 8$ made an exceptionally large contribution. These structures may arise from changes in the midlatitude zonal mean state. Namely, when the indicated changes lead to latitudinal trapping within the midlatitude waveguides of quasistationary free synoptic waves with $k \approx 6 - 8$, the usually weak midlatitude response of wave numbers $m = 6$, 7, and 8 to quasistationary thermal and orographic sources/sinks may be strongly magnified through quasiresonance.

II. Methods: Planetary Wave Quasiresonance Theory

In our study, we use a linearized nonstationary, nondivergent, barotropic vorticity equation on a sphere (23) at the equivalent barotropic level (EBL). Taking into account the assumed height [500–300 hPa, (20, 24)] of the EBL, we write this equation in a quasigeostrophic approximation as follows (see also Eq. S1a):

$$\left(\frac{\partial}{\partial t}+\alpha\frac{\partial}{\partial\lambda}\right)\Delta\Psi' + \left(2\Omega-\frac{\Delta\overline{u}}{a\cos\varphi}\right)\frac{\partial\Psi'}{\partial\lambda} = \frac{2\Omega\alpha a^2}{\tilde{T}}\sin\varphi\frac{\partial T'}{\partial\lambda} - \frac{2\Omega\sin\varphi\alpha_{or}a^2}{H}\frac{\partial h_{or}}{\partial\lambda} - \left(k_h\frac{\Delta\Psi'}{a^2}+k_z\frac{\Delta\Psi'}{H^2}\right). \quad [1]$$

In Eq. **1**, t is time; λ is longitude; φ is latitude; Ω and a are the earth's rotational angular velocity and radius, respectively; $\tilde{T}$ is a constant reference temperature; Δ is the horizontal Laplace operator on a unit sphere; $\alpha = \overline{u}/a\cos\varphi$ is the atmospheric circulation index, where $\overline{u}$ is the zonally averaged zonal wind at the EBL; h_{or} is the large-scale orography height, $\alpha_{or} = \overline{u}_{or}/a\cos\varphi$, where $\overline{u}_{or}$ is the zonal wind at the zonally averaged orography

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height $\bar{h}_{or}$ (17, 24); Ψ' is the stream function at the EBL; and T' is the midtroposphere azonal temperature describing, in the general case, stationary and nonstationary components of thermal forcing and intrinsic natural variability of this atmospheric variable; whereas, k_h and k_z are the horizontal and vertical coefficients of "eddy viscosity," respectively, and H is the atmospheric density scale height. Although the atmosphere generally is a baroclinic environment, in our study we apply the barotropic atmospheric vorticity Eq. **1** at the EBL. The quasibarotropic character of the midlatitude atmospheric circulation in the troposphere during the considered extremes, with weak shift in height of geographic position of respective maxima and minima, is demonstrated clearly by the corresponding distribution of V at different pressure levels (700 hPa, 500 hPa, and 300 hPa) for the European summer 2003 and the Russian 2010 heat waves (Fig. S1), as well as for the heat wave in the US summer of 2011 and the Great European Flood of 1997 (Fig. S2). Notably, for the quasiresonance mechanism to occur, as proposed in our paper, the waves have to be arrested within the troposphere, thus preventing an escape of the wave energy to the stratosphere. This condition is fulfilled for the waves with zonal wave numbers 6–8 (25).

Eq. **1** is a wave equation, and we first calculate the latitudinal distribution of the dimensional meridional wave number l for an arbitrary quasistationary (i.e., with $\omega \approx 0$ and $c \approx 0$) free plane wave with a given k as a Wentzel-Kramers-Brillouin (WKB) solution (19, 20) to a stationary version of Eq. **1** with a zero right-hand side. This yields (see also Eq. **S5**):

$$l^2 = \frac{2\Omega\cos^3\varphi}{a\bar{u}} - \frac{\cos^2\varphi}{a^2\bar{u}}\frac{d^2\bar{u}}{d\varphi^2} + \frac{\sin\varphi\cos\varphi}{a^2\bar{u}}\frac{d\bar{u}}{d\varphi} + \frac{1}{a^2} - \left(\frac{k}{a}\right)^2. \qquad [2]$$

Eq. **2** describes l^2 as a function of $\bar{u}$. l^2 may change sign at some latitudes, the so-called turning points (TPs) (19–22), so that l may be a real or purely imaginary number. If $\bar{u}$ also vanishes at a TP, the latter represents the so-called critical point (CP) (19–22). According to ref. 19, the energy of the considered free wave experiences a strong damping at the CP. At a TP with $\bar{u} \neq 0$, a strong reflection of this wave occurs (21). Eq. **2** is not valid in the immediate vicinity of any TP (20), and the latitudinal dependence of the quasistationary free wave energy is described there by a square of the Airy function (20), which is wavelike for $l^2 > 0$ and evanescent otherwise (20). The above analysis implies that in a particular case in which two midlatitude TPs are present for a quasistationary free synoptic wave with $k \approx 6-8$, the latter wave may become a high-amplitude free wave trapped within the latitudinal range (waveguide), $\Lambda_{W,t}$, confined between the two TPs. This is because only a near-zero leakage and absorption at the lateral boundaries of the waveguide of the wave energy for such a free wave can take place in that case, provided that (*i*) $\bar{u} > 0$, $l^2 > 0$ within the waveguide, and $\bar{u} > 0$, $l^2 < 0$ outside but in the vicinity of the waveguide. As far as Eq. **2** is derived in the WKB approximation (20), two more requirements are imposed (29–31): (*ii*) $|dl^{-1}/ad\varphi| < 1$ within the waveguide's internal part (interior), Λ_W, implying that the change in the meridional wavelength Λ_φ for the trapped free wave over a distance $\Lambda_\varphi/4\pi$ is small there compared with Λ_φ, and (*iii*) the total width $\Lambda_{W,t}$ of the waveguide exceeds the characteristic scale Δ_A of the relevant Airy function (29–31) for the considered trapped free wave (*SI Text*, section A.4).

Usually, the midlatitude solutions with zonal wave numbers $m = 6, 7$, and 8 to the fully fledged stationary Eq. **1** have low amplitudes (see e.g., refs. 20, 26, and 27). However, if conditions *i*–*iii* are satisfied, there may be occasions when those amplitudes become much stronger. This may happen if zonal mean conditions change in such a way as to trap a quasistationary free synoptic wave with $k \approx 6-8$ in the midlatitude waveguide. Then, a solution Ψ'_m to the fully fledged stationary Eq. **1** for $m = 6-8$ results in the following equation for the corresponding amplitude $\tilde{A}_m$ of V, within the interior Λ_W of the waveguide for the trapped free synoptic wave, in the case of $k \cong m$ (see also Eq. **S15**):

$$\tilde{A}_m = \tilde{A}_m^{Ort} \frac{2\Omega\sin\varphi_{m,0}\cos^2\varphi_{m,0}}{\left\{\left[K^2 - M^2\right]^2 + (L/a^2 + Ro^2/L)M^2\right\}^{1/2}}, \qquad [3]$$

provided that (*iv*) the meridional wave number l of this free synoptic wave falls into the range, Δl_m, of the meridional wave numbers l_m which gives a dominant contribution within Λ_W to the combined amplitude $\tilde{A}_m^{Ort}$ of the quasistationary orographic and thermal terms in the right side of Eq. **1** (*SI Text*, section A.3). In Eq. **3**, L and Ro are accordingly the characteristic Rossby radius and Rossby number for the eddies governing the values of k_h and k_z in the friction term in Eq. **1** (*SI Text*, section A.3), $K = k/a$, $M = m/a$ and $\varphi_{m,0}$ is the central latitude in Λ_W. On the strength of Eq. **3**, $\tilde{A}_m$ may reach a high quasiresonant value for wave number m in the case of $k \to m$. We refer below to the wave patterns with an exceptionally large contribution from the quasiresonant wave numbers $m = 6, 7$, and 8 as wave 6, wave 7, and wave 8, respectively, thus extending the concept of planetary Rossby wave resonance (32) to the case of latitudinally dependent $\bar{u}$.

III. Processing of Observational Data

To test the validity of our hypothesis, we start by plotting maps of the NH midlatitude V at 300 hPa for the above-mentioned regional European summer extremes of 2003, 2010, and 1997 (Fig. 1) using daily NCEP–NCAR reanalysis data (15). These patterns appear to be wave 6, wave 7, and wave 8, as demonstrated by Fig. 2, which plots the fields of V for a latitude strip around the globe for the same summer extremes, as well as for the heat wave in the United States in the 2011 summer. Fig. 3 shows the year-to-year time series for the amplitudes of monthly mean (July and August) Fourier components of V for $m = 6$ (Fig. 3*A*), $m = 7$ (Fig.

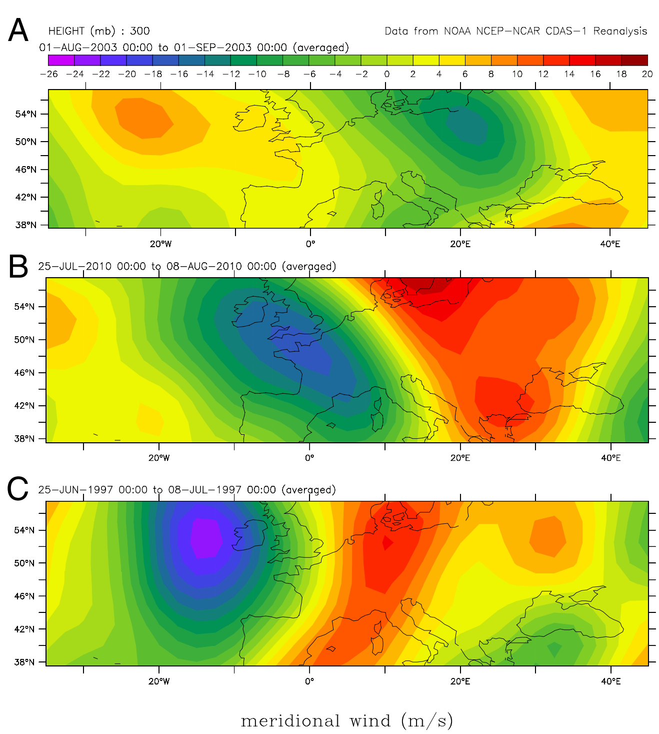

Fig. 1. Maps of the meridional winds (in meters per second) at 300 hPa over the North Atlantic–European sector during the three recent summer extremes in Europe. Shown are maps for (*A*) the record European summer heat wave in August 2003; (*B*) the most devastating phase of the Russian heat wave, July 25 to August 7, 2010; and (*C*) the most destructive episode of the Great European Flood, June 25 to July 7, 1997.

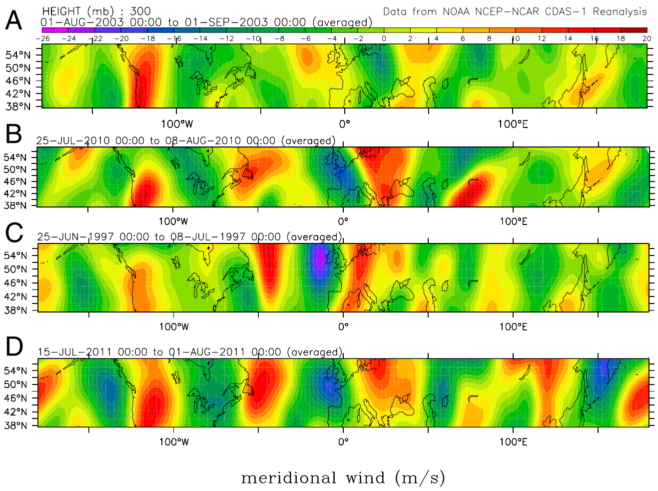

Fig. 2. Maps of the global (in the longitude) midlatitude meridional wind (in meters per second) at 300 hPa for the four recent summer extremes. (*A*–*C*) Maps of the extremes depicted in the analogous panels of Fig. 1. (*D*) The most serious phase (July 15–31) of the summer 2011 heat wave in the United States. The quasiresonant patterns with a strong contribution from zonal wave numbers $m = 6$ (*B* and *D*), $m = 7$ (*A*), and $m = 8$ (*C*) are seen clearly.

3*B*), and $m = 8$ (Fig. 3*C*) at 300 hPa, averaged over the (37.5–57.5)°N latitudinal range (see also movies 1 and 2 in ref. 33). These time series are derived from the same daily reanalysis data (15) for the most reliable interval, 1980–2011, for observational and reanalysis data (34). The $m = 6$ component was very strong (amplitude greater than 4m/s at 300 hPa) during the extreme month with the devastating Russian heat wave and Indus river flood (the month from July 15 to August 15, 2010, hereafter referred to as July 2010, for brevity) and the heat wave in the United States in July 2011, as well as in August 1983, August

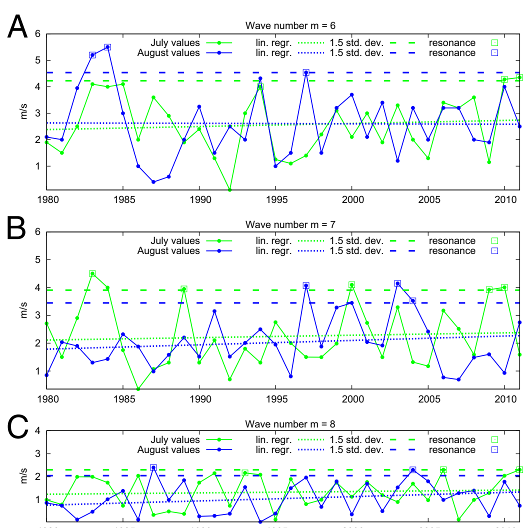

Fig. 3. The 1980–2011 time series for the amplitudes (in meters per second) of monthly Fourier components of meridional wind at 300 hPa averaged over the (37.5–57.5)°N latitudinal belt. The respective amplitudes are shown for the wave components with zonal wave numbers $m = 6$ (*A*), $m = 7$ (*B*), and $m = 8$ (*C*) for July (green) and August (blue). The squares in each plot mark the amplitudes for those months with the quasiresonance conditions for the above wave components. In each plot, the inclined dotted straight lines display the linear regressions for the appropriate monthly time series, whereas the horizontal dashed lines depict 1.5 SD from the respective 1980–2011 monthly climatology.

1984, July 1994, and August 1997 (Fig. 3*A*). In the extreme August 2003 and July 2010, the amplitude of the component with $m = 7$ also was markedly larger than usual (about 4m/s at 300 hPa, Fig. 3*B*). A similar situation with respect to the component with $m = 7$ occurred in July 1983, July 1989, August 1997, July 2000, late July/early August 2004 and July 2009 (Fig. 3*B*). Finally, the $m = 8$ component (Fig. 3*C*) had a high amplitude (about 2.5m/s at 300 hPa) in July 2011, July 2006, August 2004, and August 1987. All the months listed above exhibit amplitudes of monthly Fourier components for $m = 6, 7$, or 8 that are about 1.5 SD from the 1980–2011 monthly climatology of V for the corresponding m(Fig. 3 *A*–*C*). All these months feature record-breaking regional extremes in terms of the near-surface temperature, precipitation, and soil moisture (*SI Text*, section A.6). Hence, they may be referred to as extreme months based on their being in the highest 10th percentile regarding the above regional climate parameters. The inclined dotted straight lines in Fig. 3 *A*–*C* display, respectively, the linear regression for the wave numbers $m = 6, 7$, and 8 over the 1980–2011 time span. As seen in Fig. 3*A*–*C*, the corresponding linear trend in the amplitude of wave number 6 is close to zero for July and August, whereas wave numbers 7 and 8 exhibit moderate positive linear trends for both months.

IV. Midlatitude Waveguides and Quasiresonant Wave 6, Wave 7, and Wave 8 Patterns

As discussed above, the wave 6, wave 7, and wave 8 patterns might be related to trapping of quasistationary free synoptic Rossby waves with $k \approx 6-8$ within the midlatitude waveguides. This is illustrated in Fig. 4, which plots the "stationary wave number" $K_s^2 a^2 = \tilde{\beta} a^2 \cos^2\varphi / \bar{u}$ (left y axis), where $\tilde{\beta}$ is the meridional gradient of the absolute vorticity (19, 20) at 300 hPa, for the most destructive episodes of the European summer 2003 heat wave (highest temperatures in Switzerland and France between July 31 and August 14) and the Elbe and Danube floods of 2002 (torrential rains in the region between August 4 and 13). Also in Fig. 4, the analogous $K_s^2 a^2$ curve is shown for the nonresonant (in terms of the amplitudes of quasistationary zonal wave numbers $m = 6, 7$, and 8) period of August 1–15, 1993. Based on Eq. **2**, the difference between the values of $K_s^2 a^2$and k^2 just gives $l^2 a^2$ for a given k. A nonlinear scale for k in the right-hand y axis in Fig. 4 is such that the abscisses of the points of intersection of the $K_s^2 a^2$ curves with horizontal lines $k = k_0$ give the latitudinal positions of the TPs for the waves with zonal wave numbers k_0. In the case of two points of intersection in Fig. 4 of the $K_s^2 a^2$curve with the $k = k_0$ horizontal line, the abscisses of these points mark the latitudinal boundaries (TPs) of the waveguide within which the free wave $k = k_0$ may be trapped. According to Eq. **3**, a quasiresonant amplification of wave number $m \approx k$ may occur within the waveguide's interior Λ_W if conditions *i*–*iv* are met between the corresponding two TPs for a given k.

The results shown in Fig. 4 suggest that conditions *i*–*iv* were satisfied within the relevant waveguide's interior during the considered extreme episodes of August 2003 and August 2002, respectively, for the free synoptic waves with $6.65 < k < 6.91$ and $6.11 < k < 6.75$. This favored the occurrence of a wave 7 pattern with the amplitude $< \tilde{A}_7 > \approx 8.0$m/s in August 2003, and wave 6 and wave 7 patterns with $< \tilde{A}_6 > \approx 7.7$m/s and $< \tilde{A}_7 > \approx 5.4$m/s in August 2002. $< \tilde{A}_m >$ are the result of the respective averaging, over the (37.5–57.5)°N belt and the above-mentioned extreme episodes, of the amplitudes of the Fourier components of V represented by the solution $\tilde{A}_m$ to Eq. **3** for realistic values of L and Ro (35) within Λ_W, and by the Airy function outside this latitudinal range (*SI Text*, sections A.3 and A.4). The amplitude $\tilde{A}_m^{Ort}$of the combined forcing on the right-hand side of Eq. **3** was computed using the appropriate observational data for surface orography and temperature at 300 hPa (*SI Text*, sections A.3 and A.4). The above amplitudes $< \tilde{A}_6 >$ and $< \tilde{A}_7 >$ are found to be in a good agreement to an accuracy about $(1 - 1.5)$m/s with those calculated directly from daily NCEP–NCAR reanalysis data on Vat 300 hPa (15) averaged

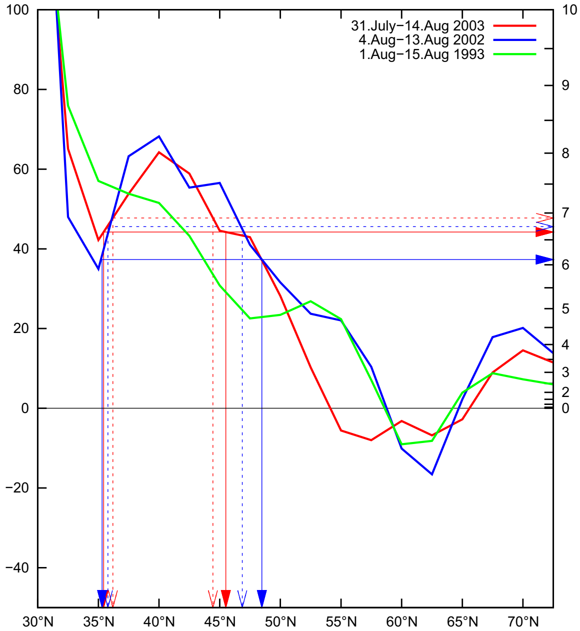

Fig. 4. Latitudinal distribution of the square of the "stationary wave number" (the left *y* axis, dimensionless; see text for more details) at 300 hPa for the most severe episodes of the European summer heat wave (July 31–August 14, 2003) and the Elbe/Danube flood (August 4–13, 2002) compared with that for the period August 1–15, 1993, without weather extremes. Abscisses of points of intersection of any of the above-mentioned curves with any horizontal line k (the right *y* axis) mark the latitudinal positions of the TPs for the wave with zonal wave number k. A pair of solid (dashed) vertical arrows mark the latitudinal boundaries of the widest (narrowest) waveguide during the relevant event, and the solid (dashed) horizontal arrows show in the right *y* axis the lowest (highest) value of k in the respective group of quasiresonant waves.

over the corresponding episodes of the extremes and the (37.5–57.5)°N latitudinal range (*SI Text*, section A.3). According to Eq. **2**, quasiresonance conditions *i–iv* held also for the synoptic wave numbers $k \approx 6-8$ during the most destructive phases of all other regional summer extremes mentioned in section III, within appropriate waveguides (*SI Text*, section A.3). By contrast, based on Eq. **2**, only one TP existed in the midlatitudes of the NH for the free synoptic waves with $k \approx 6-8$ during the period of August 1–15, 1993 (Fig. 4), thus preventing the occurrence of waveguides for these k and, by this means, violating quasiresonance conditions *i–iii*.

Similar calculations using Eq. **2** suggest that all extreme months discussed in section III (as well as June and July 2012, Fig. S3) with the amplitude of monthly component $m = 6, 7$, or 8 about 1.5 SD (Fig. 3 *A–C*) meet the quasiresonance conditions *i–iv* within the relevant midlatitude waveguides. The respective monthly quasiresonant Fourier amplitudes $< \tilde{A}_m^{mon} >$, computed using the same procedure described for calculation of $< \tilde{A}_m >$, are in agreement to within $(0.5-1)$m/s with the monthly amplitudes marked by squares in Fig. 3 *A–C* (*SI Text*, section A.3). [We recall that the latter were calculated directly from monthly NCEP–NCAR reanalysis data (15) on V at 300 hPa, averaged over the (37.5–57.5)° N latitudinal range.]

Requirements *i–iii* correspond to a condition of negligibly small dispersion and absorption of the wave energy at the waveguide's lateral boundaries. This implies that Eq. **3** and its solutions $< \tilde{A}_m >$ and $< \tilde{A}_m^{mon} >$ for the considered free waves are valid only within rather narrow waveguides (channels) and in their close vicinity mentioned above. Hence, these solutions do not hold for the quasistationary free synoptic components $k \approx 6-8$ with only one midlatitude TP, because of a pronounced meridional dispersion of the wave energy and absorption/reflection at a CP (19–23). Observational data and numerical solutions to Eq. **1** (see, e.g., refs. 18, 20, 26, and 27) suggest that, in this case, the midlatitude amplitudes of quasistationary wave number 6 do not exceed $(2-3)$m/s, whereas wave numbers 7 and 8 possess even lower amplitudes there. On the other hand, our calculations of l^2 using Eq. **2** testify that most (about 70% of) Julys and Augusts with low to intermediate amplitudes for all three wave numbers $m = 6, 7$, and 8 (44 mo altogether) exhibit only one midlatitude TP for $k \approx 6-8$, thus violating quasiresonance conditions *i–iii*. In this regard, the above-mentioned August 1993 depicted in Fig. 4 is a representative example for 31 of 44 mo. For the remainder of the above-specified set of months (13 members), conditions *i–iii* are satisfied and, hence, two midlatitude TPs exist. Requirement *iv* fails, however, rendering the quasiresonance Eq. **3** and its solutions $< \tilde{A}_m >$ and $< \tilde{A}_m^{mon} >$ not applicable to those months.

V. Comparative Assessment of Contribution from Intrinsic Natural Variability and Quasiresonance to the Amplitudes of Wave 6, Wave 7, and Wave 8 Patterns

An important question is what role the change of $\tilde{A}_m^{Ort}$ on the right-hand side of Eq. **3**, due to intrinsic natural year-to-year variability, plays in comparison with the role of quasiresonant amplification. Might this variability be a reason for the large amplitude of the studied wave numbers during the extreme months? Our calculations attest that the magnitude, $\tilde{A}_{m,v}^{Ort}$, of the year-to-year variability of $\tilde{A}_m^{Ort}$ normalized by its 1980–2011 climatology, $\tilde{A}_{m,cl}^{Ort}$, was for all $m = 6, 7$, and 8 in the $(37.5-47.5)$°N belt less than 20% and 17% in most Julys and Augusts, respectively (*SI Text*, section A.5 and Fig. S4). All the quasiresonant Julys listed in sections III and IV (Fig. 3 *A–C*) are within this majority of months, and only one quasiresonant August, 1984, does not enter the above majority of Augusts, for $m = 6$. This means that the main contribution to the strong amplification (by a factor of 3–4) of the amplitudes of the above wave numbers during the months with regional extremes, except perhaps August 1984, does not result from intrinsic natural variability, but rather from the considered quasiresonance mechanism. This implies, in particular, that we can estimate the values of $\tilde{A}_m$ for extreme months in Eq. **3**, with the aforementioned accuracy using the climatological value of $\tilde{A}_{m,cl}^{Ort}$ on the right-hand side.

VI. Quasiresonance and Deceleration of Synoptic-Scale Free Waves

As mentioned above, Eqs. **2** and **3** and their solutions are valid only in the case of quasistationary free synoptic waves with low values of the frequency ω and longitudinal phase speed $c = \omega/(M/\cos\varphi_c)$, where φ_c is the central latitude of the considered midlatitude belt. To check the applicability of this quasistationary approximation to the observed slow components of wave numbers 6, 7, and 8 (monthly mean and 15-d running means), we created movie 4 shown in ref. 33. This movie demonstrates the 15-d running means, ω_{15}, of ω (in radian per day) for the longitudinal phase of the Fourier components of the meridional average over (37.5–57.5)°N of the meridional velocity at 300 hPa with zonal wave numbers $5-8$ for June to August of each year within the 1980–2011 interval, based on daily NCEP–NCAR reanalysis data (15). Movie 4 reveals that the above 15-d running means for Julys and Augusts are rather small (less than 0.4 rad/d in magnitude) and vacillate in close vicinity to zero for all years. The corresponding magnitudes of the phase speed, c_{15}, are less than 3 m/s, which is inherent in quasistationary planetary waves (27). Hence, the above-mentioned assumption of quasistationarity of the 15-d running means of free waves with $k \approx 6-8$ is valid for all Julys and Augusts in the 1980–2011 period. However, the quasiresonance months with extreme character might show lower values of the c_{15} magnitude compared with nonresonance months. This would attest that additional deceleration of the studied waves in the extreme months had to occur to put the quasiresonance mechanism into operation. To check whether this is the case, we performed a t test of the null hypothesis regarding the difference between time averages over 1980–2011 of the above time series of 15-d running means for quasiresonance and nonresonance months, respectively. The test showed that at the 90% confidence level, the null hypothesis cannot be rejected (i.e., these time series are indistinguishable in the sense of their averages) for $m = 7$ and $m = 8$, whereas it fails for $m = 6$. We note in this connection that the above difference between averages did not exceed 0.025 rad/d (0.2 m/s in terms of c_{15}) for all three m. We additionally created a movie for nonsmoothed daily values, ω_d, of ω for waves 5, 6, 7, and 8 (movie 5 in ref. 33), using the same data source (15), with contributions from all fast and slow components of the studied waves accounted for. The analogous t test shows that the corresponding resonant and nonresonant time series are indistinguishable at the 90% confidence level for all $m = 6 - 8$.

VII. Branstator's Mechanism of Circumglobal Teleconnection and the Quasiresonance Mechanism

The observational evidence for the important role of a strong subtropical jet in winter as a source of circumglobal longitudinal teleconnections, due to large-scale quasistationary Rossby waves with $m \leq 5$, was first described by Branstator (2002) (16). Branstator's mechanism (16) subsequently was applied to the explanation of recent summer extremes in several papers (e.g., refs. 10 and 14). The important element that our paper contributes is to recognize that because the zonally averaged state varies from month to month and year to year, the properties of midlatitude quasistationary free synoptic waves with $k \approx 6 - 8$ also vary so that whether they will be trapped varies with time. Therefore, whether these waves will contribute to quasiresonant amplification of quasistationary wave numbers $m = 6, 7$, or 8 is time dependent. Also, as distinct from Branstator's mechanism, the action of the quasiresonance mechanism essentially depends on the shape rather than the magnitude of the circumglobal jets.

VIII. Discussion

Our calculations of l^2 using Eq. **2** reveal that the occurrence of a steep and narrow subtropical jet, as well as a deep midlatitude minimum and a subpolar maximum in the latitudinal distribution of $\overline{u}$, is the primary precursor of the occurrence of two midlatitude TPs for quasistationary free synoptic waves with $k \approx 6 - 8$. This peculiarity of $\overline{u}$ results in a change of sign of the right-hand side of Eq. **2** from negative to positive and then back to negative in the extratropical latitudes for these wave numbers. This brings about the occurrence of a pair of midlatitude TPs as the necessary precondition for trapping the above waves in midlatitude waveguides. Based on the NCEP–NCAR reanalysis data (15), the discussed specific feature of the $\overline{u}$ distribution is inherent in all the extreme months considered. This is illustrated by Fig. 5*A* for extreme August 2003, July 2010, July 2000, and July 1993. On the other hand, 31 mo with low to intermediate amplitudes for all three wave numbers $m = 6, 7$, and 8 possess only one midlatitude TP. Accordingly, such months do not exhibit the indicated peculiarity of $\overline{u}$ as exemplified by July 1981, August 1993, and August 2001, as well as the 1980–2011 climatology, shown in Fig. 5*A*. We note that the latitudinal distribution of $\overline{u}$ at 300 hPa depicted in Fig. 5*A* is highly consistent with that for the corresponding lower-troposphere temperature, on the strength of the thermal wind relation (TWR) (Fig. 5*B*).

The 32-y period analyzed in our paper is too short to draw firm conclusions as to the frequency of the studied quasiresonant extreme events in the future. However, there exist some indications for more favorable conditions for the occurrence of the above peculiarity in the shape of $\overline{u}$ in recent decades. The ongoing inhomogeneous process of global warming, mostly the result of anthropogenic forcing, causes the so-called Arctic amplification induced by the reduction of snow and polar sea ice cover (36). By virtue of the TWR, the corresponding decrease in the temperature gradients within the (45–65)°N latitudinal range results in reduced-strength midlatitude westerlies (37). This, in

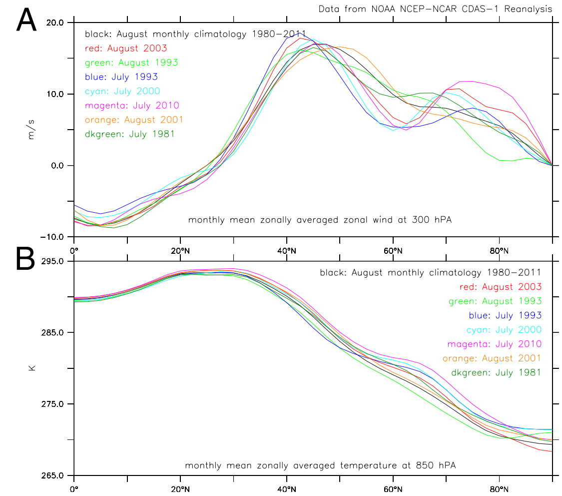

Fig. 5. Latitudinal distributions for zonally averaged monthly zonal wind (in meters per second) and temperature (in kelvins) for extreme August 2003, July 2010, July 2000, and July 1993 in comparison with nonresonance July 1981, August 1993, August 2001, and the 1980–2011 climatology. (*A*) Zonally averaged zonal wind at 300 hPa for August 2003 (red), July 2010 (magenta), July 2000 (cyan), July 1993 (blue), July 1981 (dark green), August 1993 (green), August 2001 (orange), and the 1980–2011 climatology (black). (*B*) Same as *A* but for zonally averaged temperature at 850 hPa.

turn, favors a steeper and narrower distribution of $\overline{u}$ in the northern flank of the subtropical jet. According to Eq. **2**, the combined effect of reduction of midlatitude westerlies and steepening of the northern flank of the subtropical jet may lead to a more frequent appearance of the northern TP for the free waves with $k \approx 6 - 8$. The shape of $\overline{u}$ also is steeper and more narrow in recent years in the southern flank of the subtropical jet in the (30–45)°N range, which may be attributed to an ongoing trend in the lower-troposphere temperature in these latitudes (38). In accordance with Eq. **2**, this may bring about a more frequent occurrence of the second, southern, TP for the free waves with $k \approx 6 - 8$. As mentioned above in this section, the described peculiarity in the shape of $\overline{u}$ is observed in all the extreme months studied. Their number experiences a noticeable increase over the last 11-y period, i.e., 2002–2012 (eight extreme months of the considered type, including July and August 2012) compared with the previous two periods, i.e., 1991–2001 and 1980–1990, with four extreme months in each of them (Fig. 3 *A*–*C* and *SI Text*, section A.6). On the other hand, according to Eq. **2**, the number of months with weak to intermediate wave numbers $m = 6, 7$, and 8 and one midlatitude TP for all $k \approx 6 - 8$ decreased from 14 in 1980–1990 to 10 in 1991–2001, and further to 7 in 2002–2011. An overall positive linear trend in the wave 8 amplitude for August during the 32-y period studied also is found (Fig. 3*C*). Using the Student t test, we show that this trend is statistically significant at the 90% confidence level (33). At the same time, we cannot exclude the possibility that a substantial component of recently observed trends, e.g., of the surface air temperature on spatial scales smaller than continental, may result from intrinsic natural variability (39) and not just from the process of global warming mostly due to anthropogenic forcing that we discussed above. Moreover, the considered quasiresonance is not the only possible mechanism for amplification of zonal wave numbers $m = 6 - 8$. In the nonresonant July 1991, for instance, the component $m = 8$ reveals a noticeable monthly amplitude (Fig. 3*C*), and conditions *i*–*iii* are satisfied (so two TPs exist) for $k \approx 8$. However, according to Eq. **2**, the values of l for all $k \approx 6 - 8$ are outside (although very close to) the range of the meridional wave numbers l_m with dominant contribution to $\tilde{A}_m^{Ort}$, thus invoking failure of condition *iv*. The same observation applies to the nonresonant July 1983, July 1985, and August 1994 with relatively high amplitudes for $m=6$ (Fig. 3*A*). Also, in July 1984 with high amplitudes for $m=6$ (Fig. 3*A*) and $m=7$ (Fig. 3*B*), as well as in August 2000 with a pronounced amplitude for $m=7$ (Fig. 3*B*), conditions *i–iii* fail for all $k \approx 6-8$, so only one midlatitude TP occurs for these waves. Note that July 1985 (together with August 2000) and July 1991 (along with August 1994) were the months with a very strong summer La Niña and El Niño, respectively. As for July 1984, the occurrence of high-magnitude waves 6 and 7 in that nonresonance month with a weak summer La Niña and low positive summer North Atlantic Oscillation needs further investigation.

IX. Conclusions

We find a strong contribution from persistent high-amplitude zonal wave numbers $m=6$, 7, and 8 to several recent severe regional summer extremes. These wave structures may result from trapping of quasistationary free synoptic waves with zonal wave numbers $k \cong m$ within relevant midlatitude waveguides. The waveguides favor a subsequent strong quasiresonant amplification of the usually weak quasistationary response of wave numbers $m=6$, 7, and 8 to climatological mean thermal and orographic forcing. An important point is that these wave structures may arise from changes in the wave propagation properties of midlatitudes, caused by changes in the zonal mean climate state, in terms of the lower-troposphere temperature and zonal wind at the EBL. If the observed increasing number of summer months with high-amplitude wave numbers $m=6$, 7, and 8 indeed is the result of ongoing global warming, then we have described a possible dynamical mechanism for how global warming might contribute to future extreme summer events. This complements earlier results by Stott et al. (2004) (40) and Rahmstorf and Coumou (2011) (7). However, there are important differences. Stott et al. (40) compare the magnitudes of natural and anthropogenic forcing, but do not provide a physical mechanism for the occurrence of extreme summers. Rahmstorf and Coumou (7) analyze whether events break a record, but not by what margin. In contrast, the atmospheric wave quasiresonance described here as a mechanism for weather extremes can explain the exceptional magnitude of several recent extremes: a particular quasistationary free synoptic wave with $k \approx 6-8$ becomes trapped as soon as the two midlatitude TPs for this wave appear, favoring the possibility of a strong dynamical response to climatological mean diabatic and orographic forcing with zonal wave numbers $m=6-8$. The data and results we present suggest that atmospheric conditions already might have changed to the extent that the considered quasiresonant wave amplification may occur rather frequently. The most recent example might be the destructive heat waves in the United States and southern Europe accompanied by catastrophic floods in China and Japan in June–July 2012. Wave numbers 6 and 7 were observed for much of that time over the NH midlatitudes (Fig. S3).

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