Large-Scale Flow and the Long-Lasting Blocking High over Russia: Summer 2010

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ABSTRACT

Several studies show that the anomalous long-lasting Russian heat wave during the summer of 2010, linked to a long-persistent blocking high, appears mainly as a result of natural atmospheric variability. This study analyzes the large-scale flow structure based on the ECMWF Re-Analysis Interim (ERA-Interim) data (1989–2010). The anomalous long-lasting blocking high over western Russia including the heat wave occurs as an overlay of a set of anticyclonic contributions on different time scales. (i) A regime change in ENSO toward La Niña modulates the quasi-stationary wave structure in the boreal summer hemisphere supporting the eastern European blocking. The polar Arctic dipole mode is enhanced and shows a projection on the mean blocking high. (ii) Together with the quasi-stationary wave anomaly, the transient eddies maintain the long-lasting blocking. (iii) Three different pathways of wave action are identified on the intermediate time scale (~10–60 days). One pathway commences over the eastern North Pacific and includes the polar Arctic region; another one runs more southward and crossing the North Atlantic, continues to eastern Europe; a third pathway southeast of the blocking high describes the downstream development over South Asia.

1. Introduction

The summer of 2010 in Eurasia was characterized by anomalously high temperatures due to a blocking high centered over western Russia and, simultaneously, a large-scale shift of the Asian summer monsoon region associated with high precipitation and floods in Pakistan (Blunden et al. 2011). The structure of the precipitation and the anomalously flow pattern of the Pakistan flood of 2010 is analyzed in more detail in Houze et al. (2011). Both extreme phenomena, the heat wave and the flood events, seem to be connected (Lau and Kim 2012; Galarneau et al. 2012; Martius et al. 2012, manuscript submitted to Quart. J. Roy. Meteor. Soc.). Downstream of the blocking high Rossby wave breaking appeared, ensuring reinforcement of the precipitation events over Pakistan (Martius et al. 2012, manuscript submitted to Quart. J. Roy. Meteor. Soc.), and led to trough deepening over northwest Pakistan (Galarneau et al. 2012). At the same time, monsoonal depressions were displaced and ensured moisture transport toward Pakistan (Martius et al. 2012, manuscript submitted to Quart. J. Roy. Meteor. Soc.; Lau and Kim 2012). Hong et al. (2011) found that La Niña–induced low-level easterly anomalies over South and Southeast Asia led to an enhancement of the moisture transport to the northern Arabian Sea and Pakistan. The predictability of the Pakistan flood is analyzed by Webster et al. (2011).

Large parts of Russia, Belarus, Ukraine, and the Baltic were affected by the long-persisting blocking situation causing severe droughts, crop loss, and numerous forest and peat fires. Anomalous high temperatures have been observed not only over western Russia but also over other regions of the world (e.g., in the north-eastern part of North America; Blunden et al. 2011). The summer temperatures for western Russia reached a record maximum [since at least 1880; (National Oceanic and Atmospheric Administration) NOAA/National Climatic Data Center (2010); Grumm (2011)], which even exceeded the extreme 2003 heat wave both in amplitude and spatial extent (Barriopedro et al. 2011).

The temperature time series at 1000 hPa (Fig. 1a) near Moscow, Russia (54°N, 40°E; adapted from reanalysis
data), exceeds the average of the recent 22 summers from mid-June onward. This warm signal associated with the blocking high extends over the whole troposphere (Fig. 1b). It should be noted that the temperatures at 100 hPa (Fig. 1c) are significantly lower than average, indicating a cooling in the lower stratosphere due to adiabatic ascent. This anticorrelation is more pronounced between mid-July and mid-August.

Using medium-range forecasts with different lead times, the occurrence of the blocking feature in 2010 appears to be linked with a high predictability, whereas its long persistence extending to mid-August is not (Matsueda 2011). Thus, the question arises: what are the causes of this long-lasting heat wave or rather the blocking high?

Blocking, in general, denotes the effect of a synoptic system acting as a barrier to the westerly flow splitting the jet stream (Elliott and Smith 1949). The formation of a block over Europe can be ascribed to the convergence (or absorption) of wave activity density flux associated with an incoming anomalous quasi-stationary Rossby wave train (Nakamura et al. 1997), which occurred over Europe in summer 2003 (Orsolini and Nikulin 2006). Although Nakamura et al. (1997) state that, dependent on the position of the blocking over Eurasia, the transients appear to play a secondary role in the formation and amplification process, Shutts (1983) attributes their crucial role in maintaining the blocking due to transfer of eddy energy to the large-scale split of the flow.

In the case of the 2003 heat wave, Chase et al. (2006) identify natural modes like El Niño–Southern Oscillation (ENSO) or volcanism to have a much greater contribution to the heat wave than the linear trend of global warming. However, the 2003 heat wave in Europe has been attributed as an extreme event, possibly due in part to the global warming–induced variability increase (Schär et al. 2004; Stott et al. 2004). Furthermore, the heat wave in 2003 is characterized by an anticyclonic anomaly over western Europe, which is part of a Rossby wave train. As this wave train is apparent throughout the troposphere (Orsolini and Nikulin 2006), the large-scale flow seems to play an important role in European heat waves.

Model simulations indicate that the anomalous circulation during the summer of 2010 over eastern Europe can be ascribed primarily to natural internal atmospheric variability rather than to climate change or ocean boundary conditions like sea surface temperature or sea ice extent (Dole et al. 2011), reflecting changes in the large-scale flow and in transients (Blackburn et al. 2011).

Two large-scale modes of variability characterize the summer 2010 affecting the circulation of the whole year: ENSO and the Arctic Oscillation (AO; Blunden et al. 2011) or North Atlantic Oscillation (NAO). While ENSO shows a transition from El Niño to La Niña conditions, the AO is in a strong negative phase. European weather and ENSO are connected due to teleconnections that, starting from the eastern North Pacific storm track,
continue via the cyclogenesis region over the western North Atlantic and affect downstream the North Atlantic storm track and the North Atlantic/European Großwetter (‘‘Fraedrich mechanism’’ see Cassou and Terray 2001; Drévilleon et al. 2001). Cold (warm) ENSO episodes show more anticyclonic (cyclonic) days over Europe (Fraedrich 1990, 1994).

Over the North Pacific two factors favor more blocking days during La Niña. First, the low-frequency variability (∼7–60 days) extract energy from the time mean flow during La Niña through barotropic instability (Simmons et al. 1983). Second, the more diffusive flow during La Niña results in more blocking, which is maintained by high-frequency eddies (Shutts 1983). Both contribute to the increase in blocking days during La Niña winters (Chen and van den Dool 1997).

Besides the atmospheric dynamics, the land surface–atmosphere feedback is an additional factor that could amplify the blocking highs and the associated heat waves. During the summer of 2003, the reduction of precipitation and the resulting reduced soil water lead to an amplification of the heat wave (Ferranti and Viterbo 2006; Fischer et al. 2007). During the summer of 2010, the influence of land surface–atmosphere coupling on the heat wave was investigated by Volodin (2011). Two ensemble model runs were performed with the coupled atmosphere–ocean model Institute of Numerical Methods of the Russian Academy of Sciences, Climate Model version 4 (INMCM4; Volodin et al. 2010) for June and July 2010: one control simulation with prescribed climatological soil water and one perturbed simulation with monthly averaged soil water of 2010 in the region 45°–58°N, 33°–68°E. The simulations indicate that soil drought in the upstream region is responsible for an additional temperature increase of about 3° in the Moscow region in July 2010.

The article is structured as follows: after a description of the data and methods, the interannual variability is analyzed. This is followed by an investigation of the influence of the stationary waves and the transients on the blocking high during the summer of 2010. The consideration of different time scales will be completed by analyzing the evolution of the intermediate time scale processes. The summary and conclusions are given in the last section.

2. Data and methods

The long-persisting blocking high is analyzed by using the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis Interim (ERA-Interim). This section introduces the data and the applied methods.

a. Data

The interim reanalysis data of the ECMWF (ERA-Interim) span the time period from 1 January 1989 to the present day and represent the state-of-the-art reanalysis dataset. The atmospheric model has a spectral horizontal resolution of T255 (approximately 79-km grid spacing on a Gaussian grid), with 60 vertical levels (Dee et al. 2011) every 6 h. The reanalysis data are improved with regard to the hydrological cycle and a more realistic stratospheric circulation (Dee et al. 2011) compared to the 40-yr ECMWF Re-Analysis (ERA-40). This analysis is based on the daily data of a coarse resolution on an equidistant grid of 2.5° grid spacing or a Gaussian grid, which corresponds to T42 spectral truncation. The chosen resolution is considered to be sufficient because the analysis concentrates on the large-scale flow regimes. The potential resolution dependency of the following results is not tested, because the large scale is considered to be unaffected by the resolution.

To capture the change in ENSO, the dataset is extended by the Niño-3.4 index taken from the NOAA/Climate Prediction Center. This index is calculated for the Niño-3.4 region, defined as 5°S–5°N, 170°–120°W. Because of a westward shift of the key region in the observed atmosphere–ocean coupling, the Niño-3.4 index is chosen (Trenberth 1997). The analysis distinguishes between La Niña and El Niño summers. If the Niño-3.4 index is less than the half negative standard deviation of the whole time series, this summer is defined as a La Niña summer. The same holds, but with opposite sign, for El Niño summers. Therefore six cold and six warm summer events can be identified. The La Niña summers are 1989, 1998, 1999, 2000, 2007, and 2010; whereas the El Niño summers are 1991, 1994, 1997, 2002, 2004, and 2009.

b. Methods: Blocking index, stationary and transient eddy wave fluxes, and teleconnection indices

The methods used to analyze contributions of the large scale flow on the blocking anticyclone over eastern Europe in summer 2010 are described in this section.
1) BLOCKING

The location and time of the blocking is determined following Tibaldi and Molteni (1990, see also Schalge et al. 2011) using three zonal bands: 78.75°, 60°, and 41.25°N, with a range of ±3.75°. During blocking situations the 500-hPa geopotential height of the midlatitudinal band (60°N) should be higher than equatorward (41.25°N) and poleward (78.75°N) in terms of the geopotential height gradient to the south (GHGS) and to the north (GHGN). A longitude is defined as blocked if both GHGS > 0 and GHGN < −10 gpm (“latitude”)−1 are met, with the blocking index given by the magnitude of the GHGS in the considered regions. The percentage of blocking describes the percentage of days of a specific longitude to be blocked; 100% means that this longitude is blocked for all 92 days in summer.

2) TELECONNECTIONS

The summer 2010 is characterized by a change from El Niño to La Niña conditions and by a strong dipole anomaly mode in the Arctic (Wu et al. 2006; Wang et al. 2009). This dipole anomaly mode (DA) is determined by the empirical orthogonal function (EOF) analysis (Wang et al. 2009) applied to pressure or geopotential north of 70°N, with the DA mode represented by the second EOF. The regression maps of the first two EOFs correspond to the AO mode (first EOF, not shown) and the DA mode (second EOF, Fig. 5 for different vertical levels). This dipole pattern shows the positive anomaly over the Beaufort gyre, whose extensions reach Iceland, and the negative anomaly over the Kara Sea.

3) WAVE FLUXES

Evaluating the role of quasi-stationary waves and transient eddies, the wave activity flux (WAF) based on the formula of Plumb (1985) and accordingly Takaya and Nakamura (1997), and the E vector (Hoskins et al. 1983) are deduced. Calculating the climatological summer WAF according to Plumb (1985) for stationary waves, the deviation of the climatological mean (average over JJA for the 22-yr period 1989–2010) from its zonal average is used. The quasi-stationary WAF according to Takaya and Nakamura (1997) is computed using the yearly summer deviations [here: June–August (JJA) 2010] from the climatological mean. The WAF for quasi-stationary waves during the summer of 2010 after Takaya and Nakamura (1997) can be interpreted as temporal wave activity flux anomaly from the climatological zonally asymmetric basic flow.

Further, the influence of synoptic eddies (transients) is determined by the E vector (Hoskins et al. 1983), which can be interpreted as an effective eddy momentum flux vector. The data are filtered using a Blackmon filter (Blackmon 1976) for the bandpass frequency range of 2.2–6 days. Regions of divergence (convergence) characterize areas where eddies accelerate (decelerate) the mean westerly flow (Hoskins et al. 1983).

4) LAG CORRELATION

A lag correlation is applied to filtered and unfiltered data in order to close the consideration of the influence of different time scales on the blocking high anomaly. The data are filtered by using a Lanczos filter (Lanczos 1956). The unfiltered and low-pass-filtered (~10–60 days) data of the 500-hPa geopotential at 54°N, 39°E (near Moscow) are correlated with the entire geopotential field (unfiltered and low pass filtered) at 500 hPa. Beside the zero lag, different lag calculations are examined from −8 to 8 days. To determine significant correlations, a decorrelation time of 4.1 days is assumed after Fraedrich and Lutz (1987). Hence, the degrees of freedom for the independent data arise to 30 when the time range from May to August is considered. Note that nonlinearities or processes like NAO, which is one of the leading modes of variability in the North Atlantic–Europe region, cannot sufficiently be extracted from the data via lag correlation and, therefore, the interpretation is limited.

3. Results

Blocking analysis commences with a study of the interannual variability before the influence of the different time scales is examined.

The 2010 heat wave is induced by a long-lasting blocking anomaly, which starts roughly in mid-June and persists for more than 6 weeks centered around 40°E (Fig. 2). In the climate mean summer season the longitude of maximum blocked frequency is around 25°E lasting about 13 days (or ~14%; Fig. 3). During the summer of 2010 this maximum is shifted eastward and lasts more than twice as long as the mean blocking duration. Three pronounced maxima from mid-June to mid-August are noted reflecting the variability of the intensity of the blocking anomaly (Fig. 2).

The influence of ENSO warm and cold events on European blocking is illustrated by a mean of the percentage of blocking for La Niña and El Niño summers, respectively (Fig. 3). If the mean percentage of blocking for La Niña is above the 95% confidence interval of the mean distribution for the whole ERA-Interim summer period, the signal is assumed to be significant. During the ERA-Interim time period El Niño warm events do not have significant impact on summer European blocking.
but during La Niña summers the mean frequency of blocking in the 30°–60°E area significantly exceeds the climatological mean, indicating an influence of La Niña on the European blocking high. Although of lower significance this result remains if the La Niña during the summer of 2010 is excluded (not shown).

A comparison between the blocked longitudinal distribution and the geopotential anomaly (defined as deviation from the 22 JJA ERA-Interim mean) at 300 hPa for JJA 2010 reveals that the maxima of the mean blocked longitudes coincide with the positive anomalies near 40°E (Figs. 3 and 4b, respectively).

a. Interannual variability of the mean large-scale summer flow

The geopotential anomalies for JJA 2010 at 1000 and 300 hPa reveal pronounced patterns (Figs. 4a,b, respectively). The anomalies are tested against the long-term summer mean by a Student’s $t$ test, assuming a Gaussian distribution (Taubenheim 1969) with a confidence level of 2.576 times the mean error. Note that shaded regions in Fig. 4 are statistically significant (>95% level). Over western Russia, a positive anomaly extends over the whole troposphere up to lower-stratospheric levels associated with higher-tropospheric temperatures (Fig. 4). In the upper troposphere a negative Pacific–North American (PNA) pattern appears with a negative anomaly over the Rocky Mountains and positive anomalies south of the Aleutians representing a weaker North American high/Aleutian low, related with a positive temperature anomaly across the eastern United States. Although the PNA is a mode of natural variability, its phase is argued to be influenced by ENSO forcing a quasi-stationary Rossby wave train emanating from the sub-tropics (near the Niño-3.4 region), which forms one part of the PNA dipole (Horel and Wallace 1981; Hoskins and Karoly 1981).

Spring 2010 is characterized by a weakening and dissipating El Niño warm event signal, which changes in July toward a strengthening of the La Niña cold phase (NOAA/National Climatic Data Center 2010). This negative ENSO signal supports the negative phase of the PNA defined as a positive anomaly near the Gulf of Alaska, a negative anomaly over the Rocky Mountains, and a positive anomaly over the eastern United States. Therefore, this part of the anomaly structure in the upper troposphere (300 hPa) is assumed to be related to
La Niña (Fig. 4b). The negative PNA is also visible in the 300-hPa temperature anomaly with higher temperatures over the Gulf of Mexico and the adjacent North American region and lower temperatures over the Rocky Mountains, although the signal over the Rocky Mountains is less significant (Fig. 4d).

The PNA-related wave train (indicated by a black arrow over North America in Fig. 4b), provides the initial point for two wave trains emerging over the North Atlantic Ocean: a northern one heading northward via Greenland to eastern Europe where it is associated with the blocking high; the other, southward, across the North Atlantic heading toward southern Europe.

In addition to the PNA pattern, a second teleconnection mode can be identified in the upper-tropospheric geopotential anomaly over the Arctic: the dipole anomaly mode (Wu et al. 2006; Wang et al. 2009) is defined by a negative geopotential anomaly over the Kara Sea and a positive one extending from the Beaufort Sea to Greenland, which shows a basically barotropic structure (Fig. 4b, black arrow). The highest values of the index time series of the DA mode occur during the summer of 2010 (since summer 2007; J. Wang 2011, personal communication). Because of a high pressure system over Greenland this anomaly weakens the NAO leading to a shift of the traveling transients (Löptien and Ruprecht 2005). During the summer of 2010 the NAO index is negative showing some intraseasonal variability. From June to August the monthly NAO index fluctuates (NOAA/National Weather Service/Climate Prediction Center): $-0.82$, $-0.42$, and $-1.22$. This NAO phase affects the atmospheric circulation over the North Atlantic and, due to the influence on synoptic-scale eddies, also affects, farther downstream, the blocking high. Hence,
the DA mode needs to be included to the analysis. These modes also occur in lower-stratospheric levels with mostly positive anomaly values (100 hPa not shown), due to lifting of the lower stratosphere.

To determine the fraction of the geopotential anomaly which can be attributed to the DA mode, the respective EOF and corresponding regressed map of the geopotential are determined. The regressed map of the

![Fig. 5. Regressed map of the second EOF of the geopotential height (gpm) at (a) 1000, (b) 500, (c) 300, and (d) 100 hPa derived from corresponding principle components and the JJA means for the ERA-Interim period and the principle component of the second EOF for (e) 300 hPa. Stereographic projection begins at 20°N.]
DA mode at four levels displays the barotropic structure (Wu et al. 2006) of the DA pattern in the Arctic region and also a high pressure system over eastern Europe (Fig. 5). The principle component of the DA mode over the whole ERA-Interim time period exhibits three relative maxima of the positive phase in 1999, 2007, and 2010. Roughly 30% of the geopotential anomaly at 300 hPa can be explained by the DA mode, indicating the strong influence of this mode on the long-lasting blocking high, although it is unclear if the DA mode appears as a consequence of the blocking high or rather forcing the anticyclonic anomaly.

The wave trains are identified in the geopotential anomaly and analyzed in section 3b.

b. WAF induced by stationary waves and transients

As shown by Dole et al. (2011), the long-lasting heat wave can be mainly ascribed to natural (internal) atmospheric variability. After analyzing the role of the stationary waves, the transient wave analysis is applied to determine their influence on inducing and maintaining the long-lasting blocking high.

1) STATIONARY WAVE FLUX

The WAF according to Plumb (1985) and Takaya and Nakamura (1997) provides some insight into the quasi-stationary wave pattern for the climatological time period and summer 2010. The WAF based on Plumb (1985) illustrates the stationary wave structure for the climate mean summer season on a zonally symmetric basic flow (Fig. 6). Note that the deviations from the zonal mean are defined here on the basis of the whole summer ERA-Interim period. In contrast, WAF according to Takaya and Nakamura (1997) can be applied to quasigeostrophic disturbances (stationary and migratory) that are embedded in a zonally varying background flow (Takaya and Nakamura 1997). On a climatological basis several wave trains appear at 300 hPa (Fig. 6), propagating into the subtropical jet.

Over the eastern North Pacific one wave train starts and extends over the Rocky Mountains. Farther downstream, the waves propagate more northward reaching Greenland, where another wave train develops, extending more southward from the Labrador Sea to the mid–North Atlantic. Over the Azores a third wave train is evident, showing a more zonal component (Fig. 6). This indicates that the waves cross the subtropical jet stream, which acts as a waveguide. Especially over the east of the North Atlantic and North Pacific, the jet stream at 300 hPa reveals a region of weakening jets.

Analyzing the quasi-stationary wave structure during the summer of 2010, the wave activity flux is determined according to Takaya and Nakamura (1997) (Fig. 7). Based on the stationary wave assumption, the convergence of the wave activity flux in regions of weak westerlies can be associated with an incoming wave train. This accumulation of wave activity yields an amplification of the blocking high (Nakamura et al. 1997). Note that the basic flow is zonally asymmetric and the flux is considered to be the three-dimensional deviation from the climatological structure (Fig. 6). Besides the climatological mean wave pattern, additional wave structures appear. Near the Aleutians north of the jet stream a...
secondary wave train forms, which is directed to the west coast of North America into the jet. The negative PNA mode is identifiable in both the geopotential anomaly and the stationary wave structure, appearing as a wave train that follows the geopotential anomaly. West of Greenland the Rossby wave train splits into two branches tending northward and southward, respectively. Most interestingly, two Rossby wave branches contribute to the blocking high pattern over eastern Europe: one, originating over the Mediterranean, forces the blocking high from south; the other over Greenland, forces the blocking high from its north. The Mediterranean wave branch converges north of Greece toward the blocking high. Compared with the climatological WAF, this convergent flux can be assumed as an extension of the Mediterranean wave train. East of the blocking high an additional wave train appears over the north of western Siberia which, directed to the low geopotential anomaly, belongs to the DA mode. The comparison between the climatological jet structure and the jet in summer 2010 shows a double-jet structure between roughly 30°–60°E (Figs. 6b and 7b, respectively). The double jet will be discussed later in conjunction with the possible transient forcing.

To analyze the influence of the phase shift in ENSO, from El Niño to La Niña, on the quasi-stationary wave structure, composites of the concerning ENSO phase reveal some insight into the boreal hemisphere response. The composite of WAF according to Plumb (1985) under La Niña summer conditions includes only those summer seasons with the Niño-3.4 index (not shown) lower than half the mean of its negative standard deviation which amounts to six (Fig. 8a).

Compared to El Niño summers, the climatological quasi-stationary wave structure under La Niña conditions exhibits a strengthening of the blocking high over eastern Europe due to an additional wave train originating northwest of the high and propagating over northwest Russia. The changing Mediterranean wave train is in close relation to the amplification of the blocking high, because it shows an additional branch out of the jet toward the blocking high. Farther upstream, the North Pacific wave train changes under La Niña conditions, so that over North America the Rossby waves are oriented in a more northeastward direction. The wave trains in Fig. 8a are also apparent if the summer of 2010 is excluded, indicating the relevance of La Niña conditions on the blocking high. Of special interest is the double-jet structure over Europe under La Niña summer conditions (Fig. 9a), which also appears in the summer of 2010 (Fig. 7b). Additionally, the influence of ENSO on Europe is also evident in a composite of the temperature anomaly at 1000 hPa. The composite indicates significant high temperatures over eastern Europe (not shown).

2) TRANSIENT WAVE FLUX

The impact of the transient eddies on the blocking anomaly is investigated by means of the $\mathbf{E}$ vector (Hoskins et al. 1983). The vertically averaged (150–1000 hPa) $\mathbf{E}$ vector for bandpass-filtered eddies (2.2–6 days; Blackmon 1976) during the summer of 2010 and the divergence/convergence of the $\mathbf{E}$ vector is shown in Figs. 10 and 11, respectively. To consider the mean force of the eddies on the mean flow, the divergence of the $\mathbf{E}$

![Fig. 7. (a) Wave activity flux (m$^2$ s$^{-2}$) according to Takaya and Nakamura (1997) and (b) the jet stream (m s$^{-1}$) at 300 hPa for JJA 2010. Arrows in (a) indicate the horizontal components of the vector at 300 hPa in (m$^2$ s$^{-2}$), while contour lines show the deviation from the summer mean geopotential every ±200 m$^2$ s$^{-2}$.](image-url)
vector is filtered by removing wavenumbers larger than 11. Because of the relation between the total change of the barotropic zonal wind and the divergence of the \( \mathbf{E} \) vector, the divergence suggests a positive eddy feedback on the anomalous wind north of the block by accelerating the barotropic zonal wind (Fig. 11). In addition, the vectors pointing toward the region of negative wind anomalies at about 20°E may indicate an easterly acceleration of the mean flow at this location (Fig. 11). Hovmöller diagrams of the meridional wind component at 250 hPa (not shown) suggest that these transient eddies arise over the North Pacific–North America region and reach the blocking high. The difference between the climatological \( \mathbf{E} \) vector (average of the summer season for the whole ERA-Interim period) and the \( \mathbf{E} \) vector for the summer of 2010 indicates an acceleration of the wind over the Great Lakes, upstream of the blocking high (Figs. 10a,b, respectively). At the end of the North Atlantic storm track the eddies exhibit a more northeastward orientation during the summer of 2010, directed to the blocking high. Summarizing, both quasi-stationary and transient eddies contribute to the maintenance of the long-lasting blocking high.

![Wave activity flux](image1)

**Fig. 8.** Wave activity flux (m² s⁻²) according to Plumb (1985) for (a) La Niña and (b) El Niño JJA seasons in the ERA-Interim period. Arrows indicate the horizontal component of the flux vector at 300 hPa, while contour lines in (a) show the deviation of the zonal mean geopotential every ±200 m² s⁻².

![300-hPa jet stream](image2)

**Fig. 9.** 300-hPa jet stream (m s⁻¹) for JJA season during (a) La Niña conditions and (b) El Niño conditions.
c. Variability at the intermediate time scale

This part focuses on the intermediate time scale (~10–60 days), which is analyzed by a lag correlation analysis of unfiltered and low-pass-filtered data (Figs. 12a,b, respectively). The 500-hPa geopotential near Moscow (54°N, 39°E) is correlated with the geopotential field at 500 hPa using different time lags (Fig. 12). Significant correlations are determined as described in the second section. Two wave trains are directed to the blocking high (indicated by black lines in Fig. 12). One originates over the Gulf of Mexico 6 days before and points to the blocking high at lag 0 (Fig. 12b). In particular, the filtered data show this wave train in more detail, whereas this signal in the unfiltered data is superimposed by other signals. Because of the teleconnections that emerge from the eastern North Pacific storm track and continue via the western North Atlantic over the North Atlantic (Fraedrich 1990, 1994), the genesis of this wave train is assumed to be related to the change in ENSO. The second wave train, more northward, originates over the Gulf of Alaska and extends over Greenland toward the blocking high (Fig. 12b). It starts 6 days before lag 0. Similar to the first wave train, the northward wave train is most pronounced in the filtered data. Both wave trains contribute to the long-lasting blocking high through barotropic energy conversion (Chen and van den Dool 1997) and the release of wave activity. On the eastern edge of the blocking high after lag 0, downstream development starts with one pronounced wave train over Russia toward the western North Pacific indicating the influence on precipitation in Pakistan (Hong et al. 2011; Lau and Kim 2012; Galarneau et al. 2012; Martius et al. 2012). This wave train is clearly seen in the unfiltered data. The above-mentioned wave trains indicate the contribution of the intermediate time scale to the variability of the blocking high.

![FIG. 10. The E vector (Hoskins et al. 1983) vertically averaged from 1000 to 150 hPa (m^2 s^-2) for (a) JJA 2010 and (b) for the whole ERA-Interim summer period. Contour lines show the divergence of the E vector (red: divergence; blue: convergence) every ±2 × 10^-6 m^2 s^-2 (yellow corresponds to the zero contour).](image)

![FIG. 11. Barotropic zonal wind component in m s^-1 (vertical average from 1000 to 150 hPa) for JJA 2010 (contour) and the divergence/convergence (positive values are gray shaded) of the horizontal components of the E vector (m s^-2) after spectral filtering in T11 (same vertical average).](image)
4. Discussion and conclusions

To analyze the long-lasting blocking high in 2010, ERA-Interim data are used, spanning the time period from 1989 to 2010. The main focus of this analysis is to investigate to what extent different time scales contribute to the long-persisting blocking high over eastern Europe. Therefore the quasi-stationary wave structure,

![Graph showing lag correlation of geopotential fields](image_url)

**FIG. 12.** Lag correlation of the 500-hPa geopotential at 54°N, 39°E with the geopotential field at 500 hPa for (a) unfiltered data and (b) filtered data. The time lags from (top) – 8 days to (bottom) 8 days are shown with the time interval of 2 days. Thick black lines indicate the wave trains.
the synoptic-scale transient eddies, and an intermediate time scale (~10–60 days) are analyzed.

The blocking high over western Russia lasted more than twice as long as the mean blocking duration for summer. Because of a change in ENSO toward La Niña, the mean summer blocking frequency is analyzed with regard to La Niña conditions. During the ENSO cold phases the blocking frequency over western Russia was significantly increased, indicating an influence on the blocking high.

The geopotential anomaly pattern in summer 2010 revealed two atmospheric modes: the negative phase of the PNA and the DA mode. The anomaly pattern of the negative PNA gave the initial point for two wave trains over the North Atlantic. These wave trains were evident in the quasi-stationary wave structure that is analyzed by means of the wave activity flux vector according to Plumb (1985) and Takaya and Nakamura (1997). A comparison between the quasi-stationary waves at the usual mean summer conditions and during the summer of 2010 shows an additional wave train toward the blocking high during the summer of 2010. Based on composite analysis alone, the change in ENSO was responsible for modifying the stationary waves.

In addition, the analysis of the DA mode reveals also a relation between this mode of seasonal variability and the blocking high over eastern Europe. Although it is not clear to what extent the DA mode influenced the blocking high or vice versa, a strong relation between both existed.

Furthermore, the transient eddies are investigated by means of the divergence/convergence of the \( E \) vector. The analysis shows that the eddies accelerated the barotropic westerly flow north of the blocking high and contributed in that way to its maintenance. Hence, both transient eddies and the stationary waves contributed through maintaining the blocking high by reinforcing the split of the jet.

On the intermediate time scale two pronounced wave trains occurred over the North Atlantic and were directed toward the blocking high. Through barotropic energy conversion this time scale also contributed to the maintenance of the block. The evident wave trains are associated with the variability of the intensity of the blocking anomaly (Fig. 2). It is suggested that both wave trains can be related to La Niña.

In summary, the long-lasting blocking high period ensues as a consequence of a change in ENSO and the resulting modification of the quasi-stationary wave anomaly and transients. Hence, all time scales contributed to the long-persisting blocking over eastern Europe. The dynamic mechanisms described by Shutts (1983) and Nakamura et al. (1997) works on the blocking high, although Schubert et al. (2011) show that waves at sub-seasonal, or in combination with a seasonal component, were the major contributors to the blocking high in 2010.

Dole et al. (2011) demonstrate that the natural variability is the main cause of the long-lasting blocking high. It has hypothesized that such an event could occur more often due to climate change and the expected change in the year-to-year variability (Schär et al. 2004). Global and regional model simulations indicate its improbability that such an event may occur over eastern Europe until the second half of the twenty-first century (Dole et al. 2011; Barriopedro et al. 2011).

This analysis supports the understanding of long-distance teleconnections between the Pacific Ocean and Europe (Fraedrich 1994; Fraedrich et al. 1993). There is a significant increase in the number of blocking days over eastern Europe, similar to the winter findings by Chen and van den Dool (1997) for the North Pacific. The two identified wave trains over the North Atlantic seem to be forced by the La Niña signal. Therefore, two connections between North Atlantic and North Pacific are shown: one over the western North Atlantic, the favorite cyclogenesis region of extratropical cyclones over the North Atlantic; the other one more northward over the Gulf of Alaska and North America. These wave trains may be the reason for the high weather predictability of the blocking in 2010 (Matsueda 2011).

The above analysis accounts only for the ERA-Interim summer period, which shortens the data time series. An extended dataset could yield more insight into the coupling between both ocean basins and provide more robustness of the results. A further analysis of the role of the intermediate time scale similar to Chen and van den Dool (1997) should answer the remaining question how barotropic energy conversion works in general under La Niña summer conditions. In addition, idealized model experiments and a detailed Rossby wave–breaking analysis (Gabriel and Peters 2008) may contribute to a further understanding of the dynamics and the underlying processes. The influence of ENSO on European climate is not yet well understood, therefore idealized model experiments would help to understand the dynamics of the long-distance coupling between the Pacific and Europe. Furthermore, the influence of Rossby waves on extreme events occurring downstream on the Eurasian continent remains the subject of future research (e.g., Zhu et al. 2011).

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