Forecast Variability of the Blocking System over Russia in Summer 2010 and Its Impact on Surface Conditions

LISA-ANN QUANDT
Karlsruhe Institute of Technology, Karlsruhe, Germany

JULIA H. KELLER
Deutscher Wetterdienst, Offenbach, Germany

OLIVIA MARTIUS
University of Bern, Bern, Switzerland

SARAH C. JONES
Deutscher Wetterdienst, Offenbach, Germany

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ABSTRACT

The Euro–Russian atmospheric blocking pattern in the summer of 2010 was related to high-impact weather, including a mega–heat wave in Russia. A set of scenarios for the synoptic evolution during the onset, mature stage, and decay of the block are extracted from the THORPEX Interactive Grand Global Ensemble multimodel ensemble forecast. These scenarios represent the key features of the forecast variability of the block and of the resulting surface impacts. Two heat indices and a fire index are computed to highlight the forecast variability in societal impacts. The study is a proof of concept, showing how information about surface impacts can be derived from available operational ensemble forecasts in an effective manner, and pointing to possible difficulties in this approach. Comparing the forecast for the heat wave’s impact on large spatial domains, and on a near-gridpoint scale, identifies challenges forecasters may face when predicting the development of a heat wave.

Although the block’s onset was highly predictable, the increase in temperature and the extension of the heat-affected area differed between the scenarios. During the mature stage of the block, the variability of its western flank had a considerable influence on the precipitation and heat distribution. Since the blocking was maintained after the analyzed decay in two of three scenarios, the predictability of the decay was low in this forecast. The heat wave ended independently from the block’s decay, as the surface temperature and the impact indices decreased in all scenarios.

1. Introduction

As atmospheric blocking may cause high-impact weather like heat waves and flooding (e.g., Matsueda 2009), there is a special interest in its predictability and the physical processes that limit forecast quality. Blocking is a large-scale flow pattern that decelerates arriving eddies, as well as the background flow, and forces them to follow a more meridional direction (e.g., Rex 1950; Arakawa 1952; Sumner 1954). Atmospheric blocking is persistent and self-sustaining (e.g., Egger 1978; Liu 1994). Moreover, blocking is associated with low predictability during its onset and decay. That is because the onset of a blocking anticyclone is associated with a transition from a zonal to a meridional flow pattern (and vice versa for the decay), which is challenging for weather prediction (Tibaldi and Molteni 1990; Frederiksen et al. 2004). Predictability is also low along the upstream and downstream troughs of the blocking

Corresponding author e-mail: Lisa-Ann Quandt, lisa.ann.quandt@kit.edu

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ridges (e.g., Tibaldi and Molteni 1990; Matsueda 2009). These troughs (hereafter referred to as flanks) have a special role as they are the transition zones from the quasi-stationary persistent core of the block to the environmental flow.

An impressive example of atmospheric blocking is the spatially extensive high pressure system over Russia during summer 2010 (Fig. 1) that blocked the zonal flow from mid-June to mid-August (Trenberth and Fasullo 2012). Favorable large-scale sea surface temperatures and local soil moisture conditions supported the formation of the block (Hong et al. 2011; Lau and Kim 2012; Schneidereit et al. 2012; Trenberth and Fasullo 2012). Two high-impact weather events were associated with this blocking system (Fig. 1): floods in Pakistan and a heat wave in Russia. The heat wave developed as a result of clear-sky conditions created by the blocking anticyclone and the resulting increased downward surface solar radiation (Lau and Kim 2012). High surface temperatures and low relative humidity favored wildfires that affected air quality (Witte et al. 2011; Grumm 2011). In Russia, 55,000 people died from the consequences of the heat wave. It was the worst drought since 1972 and caused economic losses of about 15 billion U.S. dollars (Barriopedro et al. 2011; Grumm 2011). The record-breaking floods in Pakistan resulted from monsoon surges, extratropical disturbances, and topography that caused the extreme rainfall (Hong et al. 2011; Houze et al. 2011; Lau and Kim 2012; Martius et al. 2013). As a consequence, 20 million people were affected by the flooding, with 3000 fatalities (Hong et al. 2011). The predictability of the flooding event in Pakistan and the associated forecast variability of the upper-level controlling trough (being the eastern flank of the block) are not part of this study, as that topic is discussed in Webster et al. (2011).

Matsueda (2011) investigated the predictability of this blocking. Overall, the blocking was associated with high predictability, but drops in predictability occurred in the period from the end of July to mid-August. The forecasts of the block’s western flank were described as critical, especially during the end of July. His studies further revealed that the reduced predictability of the blocking high’s decay influenced the reliability of forecasts for temperature extremes on the surface.

Up to now, the predictability and the impact of a certain weather system on surface conditions were mostly investigated separately. In this paper, we combine both aspects by showing how differences in the representation of the blocking ridge may impact forecasts of surface conditions. This study is a proof of concept, since we show how to get information about surface impacts from available operational ensemble forecasts. We address the following research questions. Does low predictability of the blocking transfer to a low predictability of the associated high-impact weather? What are the main development scenarios of the block in the forecast? Can the scenarios be linked to specific impacts or a lack thereof?

We focus on the three major developmental stages of the block’s life cycle: the onset phase, the mature stage, and the decay phase (Fig. 1). We cluster medium-range multimodel ensemble forecast members at the time of high variability (defined here as a large spread between the forecast members within the ensemble) of the block and investigate the impact of this variability on the intensity of the heat wave and in the precipitation distribution over Europe, where heavy rain events were reported (e.g., in Austria on 2 August 2010). We chose medium-range forecasts, as heat waves may be long-lasting high-impact weather events and the medium-range development is important for emergency managers and their planning. We further quantify the contributions of the ensemble prediction systems (EPSs), used in this study, to the different development stages.
scenarios (corresponding to clusters that resulted from the clustering methodology).

This paper is structured as follows. The data and the methods are presented in section 2, followed by investigations of the onset phase in section 3, the mature stage in section 4, and the decay period of the block in section 5. The summary and conclusions are given in the last section.

2. Data and methods

a. Data

We used data from the THORPEX Interactive Grand Global Ensemble (TIGGE) multimodel EPS. Because one of our blocking identification techniques requires potential temperature on the dynamical tropopause (2-PVU surface, where 1 PVU = 10^{-6} K kg^{-1} m^2 s^{-1}) as an input variable, only 3 of the 10 EPSs in TIGGE could be considered: the European Centre for Medium-Range Weather Forecasts (ECMWF, 51 members), the National Centers for Environmental Prediction (NCEP, 21 members), and the Met Office (UKMO, 24 members). With this selection, each TIGGE forecast contained 96 members. The members were retrieved in 12-h forecast steps at an interpolated grid of 1°. The initial conditions of the three control forecasts at the same spatial resolution as the forecasts were used as analysis data. As these differed only slightly, an unweighted mean of the control runs was used as an analyzed scenario, which is referred to as the analysis mean. Since the minimum and maximum temperature variables of the model are defined over the last 6 h, we used short-term forecasts of 6 h for these variables as pseudo-analysis. For total precipitation, first-guess daily analyses databases based on surface synoptic observation (SYNOP) messages from the Global Precipitation Climatology Centre (GPCC), provided by the Deutscher Wetterdienst (DWD), were used as reference (Schamm et al. 2013).

b. Selection of forecasts

We focused on three different phases of the blocking life cycle: the onset phase, the mature stage, and the decay period.

To select the forecasts best suited to investigating the onset and decay phases of the blocking, we first determined the onset and the decay of the block. We applied the blocking index of Tibaldi and Molteni (1990) to the analysis data, and identified 20 June as the onset date and 17 August as the date of decay. Thus, we chose forecasts initialized prior to 20 June for the onset phase and prior to 17 August for the decay phase (Fig. 2). Matsueda (2011) mentioned the high forecast variability of the western flank at the end of July. Hence, for the

![Hovmöller diagrams](image-url)
mature stage, we chose forecasts with initialization times in mid-July. This selection still provided us with a large amount of data, making a further subselection necessary. We confined ourselves to one highly variable ensemble forecast for each phase, to discuss different main development scenarios of the block in detail.

These forecasts were selected based on maxima in the ensemble spread in the 500-hPa geopotential field, associated with the block, as revealed in Hovmöller diagrams averaged between 40° and 80°N. Selecting the forecasts based on the ensemble spread only works for ensemble forecasts in which some members predict blocking. It is not suitable for forecasts in which all members fail to predict the blocking (Matsueda et al. 2011). The forecast uncertainty associated with the blocking high, identified by the blocking index of Tibaldi and Molteni (1990), could be seen clearly in the chosen ensemble forecasts (between 0° and 120°E; Fig. 2). For the onset phase, a maximum in the ensemble spread in geopotential height at 500 hPa was located at 0°, coinciding with the position of the blocking system. Over the western Atlantic, the ensemble spread was small, indicating only a slight forecast variability upstream of the block around 100°W. During the mature stage, the 500-hPa geopotential height ensemble spread between 20° and 100°E grew continuously until the end of the forecast time, when values of around 75 gpm were reached. Near the center of the blocking system at 60°E, the ensemble spread was at its minimum. Thus, the forecast variability that was investigated for the mature stage corresponded to the flanks of the block, being the upstream and downstream troughs of the blocking ridge. Prior to the decay of the block, the ensemble spread was high in the vicinity of the block, compared to areas downstream (around 140°E) and upstream (around 80°W). No blocking was identified in this index between 12 and 14 August. This noncontinuous blocking signal reflected the limits of blocking identification. The index failed in identifying the block since the block’s structure was not favorable for that (meaning that there were no overturning features), although the ridge was still amplified (not shown but visible in the 500-hPa geopotential height field). In all three ensemble forecasts, forecast uncertainty increased over the Pacific (180°), but we did not focus on that.

c. EOF analysis and fuzzy clustering

Since every forecast contained 96 members, investigating the development in every single member is not expedient. However, if we use an average over all members, we miss important details. Hence, an empirical orthogonal function (EOF) analysis and fuzzy-clustering methodology was employed to group members based on characteristic structural features. In this study, we applied the EOF analysis and fuzzy C-means clustering method (Harr et al. 2008) to the 500-hPa geopotential height. The method was modified by an additional stability criterion, as described in Keller et al. (2011).

For this methodology, it is necessary to determine several parameters: the time at which the EOF should be calculated (hereafter referred to as clustering time), the calculation area, and the number of clusters. See appendix A for details. Table 1 gives an overview of the choice of the EOFs and clustering parameters for our investigations. The clustering times and investigation times are marked in Fig. 2. Since we were interested in medium-range predictability, late clustering times are reasonable. The clustering times are not equal to the investigation times but are linked to the high variability of the block itself, while the investigation times are associated with high variability in the impact-relevant surface variables. For the three phases of the block, different lead times turned out to be suitable as investigation times.

We use the term “main development scenario” for the forecast scenario represented by one cluster. The members with the smallest Euclidean distance to their cluster center in the phase space, spanned by the first and second principle components, are called representative members and were used to compare the main development scenarios. Our results were sensitive to the choice of representative members since they were representative of the clustering time. With increasing lead time, the spread between the forecast members becomes larger, also within one cluster. However, after the clustering time the differences between

<table>
<thead>
<tr>
<th>Clustering parameters</th>
<th>Onset</th>
<th>Mature stage</th>
<th>Decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initialization</td>
<td>1200 UTC 14 Jun 2010</td>
<td>1200 UTC 26 Jul 2010</td>
<td>1200 UTC 10 Aug 2010</td>
</tr>
<tr>
<td>Clustering time</td>
<td>0000 UTC 22 Jun 2010</td>
<td>1200 UTC 31 Jul 2010</td>
<td>1200 UTC 16 Aug 2010</td>
</tr>
<tr>
<td>EOF area</td>
<td>40°–90°N, 40°W–120°E</td>
<td>40°–90°N, 40°W–120°E</td>
<td>40°–90°N, 40°W–120°E</td>
</tr>
<tr>
<td>No. of clusters</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>No. of members per cluster</td>
<td>22, 18, 20, 20 (no cluster: 16)</td>
<td>19, 24, 33 (no cluster: 20)</td>
<td>14, 34, 28 (no cluster: 20)</td>
</tr>
</tbody>
</table>
members of different clusters are stronger than the differences among members of the same cluster. We did not use the cluster mean for the comparison of the development scenarios of the block, in order to omit the neutralizing effects that averaging produces on small-scale structures and on synoptic fields (which is a particular problem at the end of the forecast when forecast variability is high).

d. Identification of atmospheric blocking

We used two blocking indices. The first index is one-dimensional and identifies blocking as overturning of the geopotential height field at 500 hPa (Tibaldi and Molteni 1990). The second index identifies Rossby wave breaking (RWB) in the potential temperature field at 2 PVU as an indicator for atmospheric blocking (Pelly and Hoskins 2003). In its original version, this index is also one-dimensional, as it is calculated along the so-called central blocking latitude. Here, we computed a two-dimensional version of the index following Masato et al. (2013). Since both methods have advantages and disadvantages (e.g., Barnes et al. 2012), we employed two indices to increase the probability of correctly identifying blocking. We considered blocking to be present if the blocking criterion of at least one method was met.

e. Definition of impacts

1) Heat indices and temperature thresholds

Heat waves have a negative impact on human comfort (Robinson 2001). During heat waves, the risk of heat-related illnesses (such as exhaustion or heatstroke) and mortality increases (Koppe et al. 2004).

The World Meteorological Organization offers no unique definition of the term heat wave. In fact, the operational definition differs from country to country (Robinson 2001). Different thresholds of atmospheric variables, like air temperature, relative humidity, and wind speed, are used. In this study, we used two heat indices. These indices represent heat stress in a simplified way but are better suited to capturing the effects of heat on humans than the 2-m temperature. The first index is the heat index (HI) used by NCEP (http://www.wpc.ncep.noaa.gov/html/heatindex_equation.shtml). The critical thresholds of the heat index can be found in Table 2. The second index called Humidex is discussed in Masterton and Richardson (1979) and is operationally used by Environment Canada (EC; information online at http://ec.gc.ca/meteo-weather/default.asp?lang=En&n=6C5D4990-1#humidex). The four warning levels are described in Table 3. A detailed discussion of the two heat indices and their regional suitability can be found in appendix B.

In addition to these heat indices, we also looked at the temporal evolution of the spatially averaged maximum (minimum) temperature during the daytime (at nighttime). We averaged the 2-m temperature over the region with the strongest heat wave intensity centered over Moscow, Russia [50°–60°N, 35°–55°E; see also Figs. 6 and 17 and Dole et al. (2011)]. As 11.92 million people live in Moscow, we also focused on the coordinates of this city, namely 55.75°N and 37.62°E, and averaged the indices over just the four surrounding grid points. We discussed the extreme temperatures using the following thresholds: extremely hot day ($T_{max}$ ≥ 35°C), hot day ($T_{max}$ ≥ 30°C), summer day ($T_{max}$ ≥ 25°C), and tropical night ($T_{min}$ ≤ 20°C).

2) Wildfire potential

Widespread wildfires were one of the most devastating impacts of the Russian heat wave in 2010 (Witte et al. 2011). For our studies, we used the lower-atmosphere severity index (LASI) for wildfire fires of Haines (1988). It is separated into four danger classes (Table 4). See appendix B for definitions and additional information about the applications.

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**Table 2. Ranges of the NCEP heat index and the associated warning levels (adopted from http://www.srh.noaa.gov/ama/?n=heatindex).**

<table>
<thead>
<tr>
<th>Heat index</th>
<th>Degree of danger</th>
</tr>
</thead>
<tbody>
<tr>
<td>27–32</td>
<td>Caution: fatigue possible with prolonged exposure and/or physical activity</td>
</tr>
<tr>
<td>33–41</td>
<td>Extreme caution: sunstroke, muscle cramps, and/or heat exhaustion possible with prolonged exposure and/or physical activity</td>
</tr>
<tr>
<td>41–54</td>
<td>Danger: sunstroke, muscle cramps, and/or heat exhaustion likely; heatstroke possible with prolonged exposure and/or physical activity</td>
</tr>
<tr>
<td>&gt;54</td>
<td>Extreme danger: heatstroke likely</td>
</tr>
</tbody>
</table>

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**Table 3. Ranges of Humidex and the associated warning levels (adopted from: http://ec.gc.ca/meteo-weather/default.asp?lang=En&n=6C5D4990-1#humidex).**

<table>
<thead>
<tr>
<th>Humidex</th>
<th>Degree of comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>20–29</td>
<td>No discomfort</td>
</tr>
<tr>
<td>30–39</td>
<td>Some discomfort</td>
</tr>
<tr>
<td>40–45</td>
<td>Great discomfort; avoid exertion</td>
</tr>
<tr>
<td>&gt;45</td>
<td>Dangerous; possible heatstroke</td>
</tr>
</tbody>
</table>
3. Variability during the onset phase

In the present study, the onset of the block was associated with the beginning of the mega–heat wave. In this section, we will present the main development scenarios for the onset that were extracted from a forecast initialized at 1200 UTC 14 June 2010.

a. Selection and characteristics of forecast scenarios

The spatial EOF patterns indicated those flow features that show largest variability in the 500-hPa geopotential height among the EPS members at +180 forecast hours (cf. section 2c). EOF 1 captured 24.5% of the total variability and resembled an amplitude pattern (Anwender et al. 2008). Positive and negative height anomalies could be found along the blocking ridge between 40° and 80°E (Fig. 3, top).

The second strongest variability pattern (11.8%) was also found along the blocking ridge and resembled a shift pattern (Anwender et al. 2008), with a dipole with a positive signal to the west and a negative signal to the east of the ridge axis (Fig. 3, bottom).

Clustering the first two principle components (PC) following the criteria defined in appendix A resulted in four clusters. All four clusters contained approximately 20 ensemble members (Table 1), indicating their equal probability of occurrence. In the PC phase space the three analysis members were located between clusters 1 and 2 (Fig. 4). The forecast members from the three different EPSs contributed to the four clusters as follows. The ECMWF and the NCEP EPSs were present in all four main scenarios, while UKMO missed one of the development scenarios and had most of its members in cluster 4.

b. Main development scenarios for the onset

At 1200 UTC 23 June (+216-h forecast), the blocking system (between 20° and 80°E) had formed in three of the four scenarios (Fig. 5). The index of Tibaldi and Molteni (1990) identified the block in scenarios 2 and 3, while the index of Pelly and Hoskins (2003) indicated the block in scenarios 1 and 2. The positions of the blocking ridge in scenarios 1 and 2 were quite similar, but their shapes were different. The trough upstream of the block was narrower in scenario 2, while the downstream trough was positioned farther west. The trough downstream was positioned farther east in scenario 1. North of the blocking system at around 80°N, higher potential temperature on the 2-PVU surface was present in scenario 2, indicating a stronger blocking. In scenario 3, the blocking system merged with an upstream ridge. As a result, the blocking complex was
FIG. 5. (left) The 500-hPa geopotential height (color shaded in gpm) and mean sea level pressure (contours in hPa), (right) potential temperature at 2 PVU (color shaded in K) and 300-hPa zonal wind (contours in m s\(^{-1}\)) at +216 h (1200 UTC 23 Jun 2010) for (top to bottom) the four main forecast scenarios and the analysis mean for blocking onset. BL marks the blocking system and P2 marks the position of poleward anticyclonic RWB (Gabriel and Peters 2008).
zonally more extended compared to the blocks in scenarios 1 and 2. In the no-blocking scenario 4, the ridges and troughs over the Atlantic–European sectors were less amplified, leading to more zonal flow conditions. Around 70°N, an area of low pressure stretched from 20°W to 80°E. Scenarios 1 and 2 coincided best with the analysis mean, despite differences in the area of low pressure north of the block (between 70° and 80°N) and in the pressure field just below the blocking ridge.

c. Forecast variability of impact-related parameters

We will now focus on the influence of the blocking system on surface variables. At 1200 UTC 23 June (+216-h forecast), the surface temperatures over Moscow became uncomfortable (Fig. 6). In scenario 1, hot temperatures could be found in the region east of Moscow, and HI as well as Humidex indicated no warning for Moscow itself. This was different in scenario 2. The 2-m temperatures were higher near Moscow and the first warning level of the two heat indices was reached. Scenario 3 showed the city in a border area with higher temperatures to the south. In scenario 4, the extreme heat was confined to the south of 50°N.

In three of four scenarios, the blocking ridge was forecast; however, the details varied significantly. Accordingly, the surface temperature distribution differed in all main development scenarios, leading to varying heat intensities for different areas (Fig. 6). Interestingly,
the scenarios that captured the upper-level flow best exhibited remarkable differences in their representation of the surface temperature compared to the analysis mean. In section 3b, we found for the wave pattern that scenarios 1 and 2 coincided best with the analysis mean. However, scenarios 1 and 2 overestimated the temperature, especially for the area southeast of Moscow.

The spatially averaged temperatures increased with time from 19 June onward in all scenarios except scenario 4 (Fig. 7). This increase coincided with the blocking onset. In scenario 2, the increase was most prominent, and the threshold for a hot day was reached. The maximum temperatures of scenarios 1 and 3, as well as of the short-term forecast (corresponding to the analysis mean), only reached the threshold for a summer day. Thus, the temperatures in scenario 2 were overestimated. Moreover, in scenarios 1–3, the threshold for a summer day was reached at least 1 day too early compared to the short-term forecast. In scenario 4, which did not contain blocking, the temperature decreased until 21 June. During the nighttime, the minimum temperatures did not reach the threshold for a tropical night. The second warning level of the Humidex, representing some discomfort, was reached in scenario 2 on 21 June. However, this was an overestimation compared to the analysis mean, which reached this level on 24 June. The HI of scenario 2 was overestimated, also approaching the threshold for extreme caution. Scenarios 2 and 3 had already reached the caution level around 21 June. In scenario 1, this level was reached 1 day later, in agreement with the analysis mean.

The spatially averaged LASI (averaging area: 51°–57°N and 37°–49°E) was in line with the findings above. In scenario 2, the increase could be observed in scenario 1 also, but in accordance with the temperature there was a decrease after 21 June. In scenarios 1–3, the

**Fig. 7.** Time series of (top left) 2-m minimum temperature (°C) during the nighttime (long dashed) and 2-m maximum temperature during the daytime (solid), (top right) HI and (bottom left) Humidex during the daytime averaged over an area from 50° to 60°N and from 35° to 55°E, and (bottom right) LASI averaged over an area from 51° to 57°N and from 37° to 49°E. Colors mark the different scenarios for blocking onset. Horizontal lines show impact relevant thresholds; for the temperature extremes, TN20 stands for tropical night, TX25 for summer day, TX30 for hot day, and TX35 for extremely hot day.
threshold for low fire potential was reached 1 day too early compared to the analysis mean. The LASI for scenario 4 indicated a very low potential for large fires. On 23 June, the LASI in all forecast scenarios was below the analysis mean. For scenarios 2–4 and for the analysis mean, the LASI increased with blocking onset. However, this was not the case in scenario 1. One possible explanation may be in the differences in the representation of the western flank of the blocking system (Fig. 5). The trough at 30°E was deeper in scenario 1, compared to the troughs in scenarios 2 and 3 as well as in the analysis mean. This has relevance, as parts of the block’s western flank were inside the averaging area for the LASI.

For Moscow, the temperature increased in all scenarios (Fig. 8), but the threshold for a summer day (25°C) was not reached in scenarios 1 and 4. In scenarios 2 and 3, 25°C was reached 1 day too early compared to the short-term forecast. After 20 June, the date of the block’s onset, the HI increased continuously. In scenario 4, this increase was too fast, so that even the extreme caution level was reached. Scenario 2 agreed best with the analysis mean, although the caution level was reached 2 days too early. For the Humidex, scenario 2 also fit best to the analysis mean. The threshold for some discomfort was reached 2 days before it was reached in the analysis mean. Using a spatial average over a larger area (Fig. 7), the shapes of the Humidex curves were quite similar. For Moscow, the heat indices and the temperatures were lower compared to the spatial mean. Moreover, the spread between the scenarios and the amplitude of the fluctuations were larger in the gridpoint investigation, indicating a challenge for accurate predictions on surface conditions over Moscow.

4. Variability during the mature stage

During the mature stage, the block’s western flank was subject to forecast uncertainty (Matsueda 2011). We used a forecast initialized at 1200 UTC 26 July 2010 to investigate the influences of the variability along the western flank on the rainfall pattern over Europe, and in the blocking anticyclone itself on the heat distribution.

a. Selection and characteristics of forecast scenarios

The forecast variability was investigated with the help of the first two EOFs at 1200 UTC 31 July 2010 (cf. Table 1).
EOF 1 represented 21.4% of the total variability. The highest values of EOF 1 were located north of the block between 70° and 90°N, capturing variability in the amplitude of the blocking ridge (around 50°E). Furthermore, EOF 1 showed a meridional dipole within the trough around 10°E (Fig. 9, top). This signal could be interpreted as being the variability in the amplitude of the trough, forming the block’s western flank.

The second strongest variability (20.2%) appeared as a strong dipole with negative values to the west of the block and positive values to the east (Fig. 9, bottom). Thus, EOF 2 captured the variability in the zonal position of the ridge.

Here, the three-cluster solution was most suitable. Every EPS contained all three of the scenarios. Members of the ECMWF ensemble were mostly part of cluster 3 (Fig. 10). The UKMO ensemble had the equivalent number of members in clusters 2 and 3, whereas only one member was part of cluster 1. Members of the NCEP ensemble were mostly part of cluster 1. The analysis members were closest to the center of cluster 3. Given the number of members (Table 1), this scenario was the most probable one.

b. Main development scenarios for the mature stage

At 1200 UTC 2 August (+168-h forecast), the amplitude of the blocking ridge was forecast similarly in all scenarios (Fig. 11). However, the block’s western flank (0°–20°E) differed strongly between the scenarios. In scenario 1, the trough was tilted to the southeast and was less amplified, compared to scenarios 2 and 3. In scenario 2, the trough axis had no tilt of note, but its zonal extension was the largest. A cutoff of the trough occurred in scenario 3. Here, the trough axis was tilted to the southwest. Moreover, the western flank was positioned farther to the west in comparison to scenarios 1 and 2, leading to a more zonally extended blocking complex. Thus, the variability of the block’s western flank was clearly visible in the mature stage of the block.

The differences in the representation of the surface pressure below the western side of the blocking ridge (around 30°E) were also remarkable.

c. Forecast variability of impact-related parameters

For the mature stage, we investigated the impact of the variability of the blocking anticyclone on the heat intensity, and of the block’s western flank on precipitation. We compared the forecast precipitation with the first-guess daily analysis data from the GPCC (cf. section 2a). The reports about high-impact weather events were taken from the European Severe Weather Database (ESWD; Dotzek et al. 2009).

At 1200 UTC 2 August 2010, temperatures over Russia varied between the scenarios (Fig. 12). In scenario 1, temperatures exceeded 30°C in Moscow and the surrounding area. For Moscow itself, the HI indicated caution. The Humidex level indicating some discomfort was reached in the area surrounding Moscow. In scenario 2, temperatures above 35°C and HI values indicating extreme caution extended farther north and affected a larger area. In scenario 3, Moscow did not experience extreme temperatures; only the southeastern areas were affected. By comparing all three scenarios, it could be seen that the western side of the heat-affected area was represented more differently than the eastern side. We hypothesized that this
was linked directly to the variability of the western flank of the blocking complex. A comparison revealed that the heat distribution in scenario 1 was closest to the analysis, whereas it was overestimated in scenario 2 and underestimated in scenario 3.

Substantial differences in the precipitation field over Europe can be seen in Fig. 13. In the analysis, one precipitation area covered from $45^\circ$N−$0^\circ$ to $55^\circ$N−$20^\circ$E and another one was located over Scandinavia. On 2 August 2010, 10 heavy rain events and 4 large hail events were reported in Europe (ESWD). Most of these events occurred in Austria. In scenario 1, it rained in areas around the Gulf of Venice and from $50^\circ$N−$20^\circ$E to $65^\circ$N−$35^\circ$E. In both precipitation areas, amounts over 30 mm were reached. In scenario 2, it rained in Austria, Croatia, Slovenia, and Hungary. Another difference to scenario 1 was the precipitation center over Scandinavia. In scenario 3, it rained over Germany, France, and Scandinavia. Here, a larger area was affected by rain amounts over 30 mm, in comparison to scenarios 1 and 2. Another precipitation center could be found over Great Britain. The position of the western flank of the block was closely linked to the

FIG. 11. As in Fig. 5, but at $+168$ h (1200 UTC 2 Aug 2010) for the three main forecast scenarios and the analysis mean for the mature stage of the block.

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precipitation distribution, since in all scenarios, the rainbands were located ahead of the western trough of the block and the smaller precipitation centers underneath the trough. Compared to the first-guess daily analysis, the precipitation amount was overestimated and the position of the rainband was displaced in all forecast scenarios.

5. Variability during the decay phase

This section discusses the main development scenarios of the decay phase, extracted from a forecast initialized at 1200 UTC 10 August 2010, and shows how the variability of the block’s decay influenced the predictability of the final stage of the heat wave.

a. Selection and characteristics of forecast scenarios

The distributions of the first two EOFs reflected the forecast variability of the flow features at +144 forecast hours. The strongest variability (EOF 1 with 25.6%) could be found as a dipole along the blocking ridge around 0° and 60°E (Fig. 14, top). Thus, EOF 1 described the variability of the amplitude of the short-wave ridges within the long-wave blocking ridge and also a meridional shift of the low at 80°N, 60°E.

The second strongest variability (16.8%) was found as a tripole pattern along the ridge (Fig. 14, bottom). EOF 2 also represented the variability of an area of low geopotential height northeast of the blocking system. Thus, EOF 2 represented the variability in the block’s amplitude.

The clustering procedure resulted in the three-cluster solution. The members from the three individual EPSs were distributed between the clusters as follows (Fig. 15). The ECMWF and the NCEP EPSs contributed to all three clusters. In contrast, none of the UKMO members was found in cluster 1. The three analysis members were located close to the center of cluster 2, which meant that at clustering time, the 500-hPa geopotential height scenario of cluster 2 closely resembled the analysis. Based on this forecast, the occurrences of the scenario represented in clusters 2 and 3 were more probable than in the scenario for cluster 1 (Table 1).
b. Main development scenarios for the decay

At 1200 UTC 18 August (+192-h forecast), the decay of the block was forecast only in scenario 1. Blocking was still identified in scenarios 2 and 3. In scenario 1, a deep trough was located between 20° and 100°E (Fig. 16). At 500 hPa, the trough created zonal flow conditions between 0° and 60°E. In scenario 3, the blocking ridge broke cyclonically. This was different in scenario 2, in which a cutoff system was apparent at 50°N, 20°E. In the analysis mean, the low at 60°E was much smaller than in the forecast scenarios. Thus, scenario 1 was most similar to the analysis mean; however, the forecast overestimated the extension of the low and the amplitude of the ridge upstream.

c. Forecast variability of impact-related parameters

At 1200 UTC 18 August (+192-h forecast), the blocking was still identified in scenarios 2 and 3. The surface temperature evolution was closest to the analysis in scenario 2 despite the fact that in scenario 2 the block was still present while it has already decayed in the analysis (Fig. 17). Scenario 1, which had forecast the decay correctly, underestimated the temperature values around Moscow. Hence, for the decay phase, the forecast of the heat intensity did not depend on the blocking prediction.

This was also visible in the temporal evolution of the minimum and maximum temperatures, and of the heat...
In all of the scenarios, the temperatures, the heat indices, and the LASI decreased with time. On 11 August, the maximum temperature of the short-term forecast corresponded to an extremely hot day. Ten days later, the maximum temperature dropped below 25°C. Scenarios 1 and 2 captured this trend. In scenario 3, the drop in temperature after 16 August was stronger. The drop in temperature below the hot day level occurred later in scenarios 1 and 3 than in scenario 2. Scenario 2 agreed with the short-term forecast. In all scenarios, the minimum temperature dropped below the threshold for a tropical night after 14 August; in the short-term forecast, this had already happened after 12 August. After 19 August, HI and Humidex decreased strongly in all scenarios. In scenario 1, the HI fell below the extreme caution level too early, compared to the analysis mean, whereas scenarios 2 and 3 forecast this decrease too late. For the Humidex, the drop below the two caution levels occurred up to 2 days earlier, except for scenario 3, which fell below the extreme caution threshold 1 day after the observed decrease in HI. A similar evolution was found for the Humidex results (Fig. 19).

All scenarios predicted the end of the heat wave, although the blocking system still existed in scenarios 2 and 3. Heat waves have a spatial dependence. Thus, a shift of the controlling upper-level wave pattern leads to the end of or to an interruption of the heat wave. Interruption means here that a heat wave possibly redevelops, as long as the surface and upper-level weather systems are again favorable. In our scenarios, the blocking system was either dissolved or shifted to the west. In both cases this led to the end of the heat wave in the region around Moscow.

6. Summary and conclusions

We investigated the forecast variability of the blocking anticyclone that caused the 2010 Russian heat wave and its impact on surface conditions. For three periods in the block’s life cycle, we extracted main forecast scenarios from a single TIGGE forecast and compared the development of the block using these forecasts.

The onset of a blocking system is associated with the transition from a zonal to a meridional flow pattern. In indices and the LASI (Fig. 18). In all of the scenarios, the temperatures, the heat indices, and the LASI decreased with time. On 11 August, the maximum temperature of the short-term forecast corresponded to an extremely hot day. Ten days later, the maximum temperature dropped below 25°C. Scenarios 1 and 2 captured this trend. In scenario 3, the drop in temperature after 16 August was stronger. The drop in temperature below the hot day level occurred later in scenarios 1 and 3 than in scenario 2. Scenario 2 agreed with the short-term forecast. In all scenarios, the minimum temperature dropped below the threshold for a tropical night after 14 August; in the short-term forecast, this had already happened after 12 August. After 19 August, HI and Humidex decreased strongly in all scenarios. In scenario 1, the HI fell below the extreme caution level too early, compared to the analysis mean, whereas scenarios 2 and 3 forecast this decrease too late. For the Humidex, the drop below the some discomfort level was forecast too late in all scenarios. According to LASI, the risk for large fires decreased in all scenarios from a moderate to a low level. However, the drop below the low fire potential level occurred 2 days earlier than in the analysis mean. At the end of forecast time, the LASI in the analysis mean was significantly lower than in the forecast scenarios.

For Moscow, the heat-relevant variables decreased over time (Fig. 19). Up to 15 August, the trend in the maximum temperature was similar in the short-term forecast and the scenarios, except for scenario 2, in which the temperature was underestimated. The drop in temperature below 25°C occurred more than 2 days too early in scenario 3. The period during which tropical nights were detected was 3 days longer in scenarios 2 and 3, and even 6 days longer in scenario 1, compared to the short-term forecast. The HI continuously decreased in the analysis mean. The drop below the two caution levels occurred up to 2 days earlier, expect for scenario 3, which fell below the extreme caution threshold 1 day after the observed decrease in HI. A similar evolution was found for the Humidex results (Fig. 19).
our case, the onset was forecast in three of four scenarios for the analyzed onset time. This result indicates high predictability, confirming the previous literature (Matsueda 2011). However, the variability in the representation of the blocking anticyclone was still big enough to generate significant differences in the surface conditions. After blocking onset, the heat wave developed, resulting in increases in the temperature, heat intensity, and wildfire potential. This could be quantified by using two heat indices (HI and Humidex) and a fire potential index (LASI).

Matsueda (2011) indicated that the predictability of the western flank of the Russian heat wave block was lower than the predictability on the eastern flank. This may be connected with the dynamics occurring in the vicinity of the western flank, which are often affected by synoptic-scale disturbances arriving from the west, whereas the eastern flank could be seen as the part of the system that is protected by the amplified ridge upstream from the arriving disturbances. In our three forecast scenarios for the mature stage, the tilts and amplitudes of the western flank differed significantly, corroborating
the findings of Matsueda (2011). We hypothesize that these differences had a strong impact on the intense precipitation that developed over Europe, since the precipitation fell mainly just ahead of the trough axis. In comparison to the first-guess daily analysis, the precipitation areas in the ensemble members were in the wrong position and the amount of precipitation was overestimated. The poor precipitation forecast is a result of the forecast variability along the block’s western flank. Moreover, the variability of the western flank also influenced the surface heat distribution farther east, as the western side of the heat-affected area below the block was more variable among the EPS members than the eastern side.

The decay of a blocking system corresponds to the transition from meridional to zonal flow conditions. In the analyzed forecast, the decay of the blocking system over Russia during the summer of 2010 was only captured in one of three forecast scenarios. Thus, in two scenarios, the flow was still meridional. However, the end of the heat wave was manifested in temperature drops in all scenarios, regardless of whether the blocking still existed. Without blocking, the upper-level conditions are no longer suitable for supporting the existence of the heat wave. In our case, the heat wave ended because the blocking system was shifted.

In our case, the predictability of the block’s decay was lower than that of the block’s onset. During the mature stage, the block was forecast in all development scenarios; however, there was a remarkable uncertainty in the representation of the block’s western flank. These results agree with further studies, in which TIGGE ensemble forecasts were also investigated; however, other EPSs such as those of ECMWF, NCEP, and UKMO were also included (Matsueda 2011). We hypothesize that the forecast variability of the heat wave (as well as the precipitation over Europe during the mature stage) resulted from the forecast variability of the blocking system. We could show that already slight differences in the representation of the block had a strong influence on the surface variables. Since we used 10-day forecasts, we assume in our case that other variables like soil moisture
For our case, the beginning and end of the heat wave could be identified with both heat indices. Thus, it seems to be a promising tool to use these indices with TIGGE data for heat warnings. However, the particular dates, when a specific warning threshold was reached, differed between forecast scenarios by up to 6 days. Such differences are highly relevant for the population that is affected by heat, since long-lasting heat periods can stress the metabolic system. Furthermore, our comparison for the onset and the decay phase of the block between a gridpoint forecast for Moscow and a forecast for a spatial mean (averaging area: 50°–60°N and 35°–55°E) showed that, following expectations, the spread between the scenarios and the amplitude of the fluctuations (e.g., maximum temperature) within one scenario were larger in the gridpoint forecast. In addition to the smoothing effect on the averaged variables, this points to the spatial limitations on forecast quality, as well as the challenges involved with issuing gridpoint-based warnings.

Keller et al. (2011) investigated the forecast variability of synoptic patterns associated with extratropical transition in TIGGE and tried to specify the role of the ECMWF EPS within TIGGE. They found that TIGGE offered a broader range of possible scenarios, in particular if ECMWF members were included in the multimodel ensemble. Regarding our investigations of the atmospheric blocking event, for the three investigation periods of the block, the ECMWF EPS, as well as the NCEP EPS, contained members in all development scenarios. For both the onset and the decay phases of the block, the UKMO ensemble missed one development scenario.

In conclusion, our results indicate that the low predictability of the blocking transfers to a low predictability of surface conditions relevant for human comfort. However, even if much has been done to understand the Russian heat wave in summer 2010 (e.g., Schneidereit et al. 2012), some questions are still unanswered. Up to now, it is unclear why the blocking high lasted for such a long time. More studies about the dynamical aspects will be necessary to shed light on this topic. Another open question is which processes were responsible for the forecast uncertainty discussed in this paper. We will address precisely this question in follow-up studies.

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APPENDIX A

EOF and Fuzzy Clustering Methodology

The following list gives an overview on the criteria that have to be considered for the EOF calculation and the clustering routine.

- Clustering time: The lead time for which the EOFs and the clusters were calculated is defined as the clustering time. At this time, the ensemble spread associated with the block should have been remarkable. Thus, we were looking for the strongest variability. This differs from other studies (Anwender et al. 2008; Keller et al. 2011), in which lead times showing the strongest increase in variability were used as clustering times. Hovmöller plots (Fig. 2) and/or spaghetti plots showing the isolines of, for example, a characteristic 500-hPa geopotential height value of all ensemble members (not shown) helped to identify a suitable clustering time. We checked if a shift of the clustering time to 6–12 h had an impact on the cluster solutions. We found that the cluster membership was quite similar for 12-hourly varying clustering times that we quantified by calculating the similarly index of Rand (1971) (not shown). With increasing differences between the clustering times (more than 12 h), the members were distributed more differently from the clusters, resulting in small values of the Rand index.

- Calculation area: After choosing the clustering time, it is also necessary to determine the area over which the EOFs should be calculated. The calculation area covered the important flow features at the clustering time. We determined the area using plots of the

Fig. 19. As in Fig. 18, but for Moscow and without the LASI plot.
ensemble mean 500-hPa geopotential height field (not shown).

- Number of clusters: To find the best cluster solution, we ran the clustering procedure for 2 to \( n \) clusters (here \( n = 10 \)). With an additional stability criterion (Keller et al. 2011), the number of cluster solutions was limited. This criterion helped us to identify solutions for which the clustering did not depend on initial seed points. For each number of clusters, the algorithm was run 100 times, each time with varying and randomly chosen seed points. Only if the cluster centers were identical in all 100 cluster runs was the solution declared to be stable. The number of clusters has been chosen from those stable solutions so that they showed most of the different synoptic developments, but still contained a reasonable number of members, meaning that, for example, one cluster should not have only two members.

### APPENDIX B

#### Definition of Impacts

##### a. Heat indices

It is reasonable to take more than one heat index into account, because the dependence of human comfort on temperature and humidity differs from region to region (Robinson 2001; Koppe et al. 2004; Gasparrini et al. 2015).

The heat index (HI) is defined as follows:

\[
HI = c_1 + (c_2 T) + (c_3 RH) - (c_4 T \times RH) - (c_5 T^2)
- (c_6 RH^2) + (c_7 T^2 \times RH) + (c_8 T \times RH^2)
- (c_9 T^2 \times RH^3),
\]

where \( T \) is the temperature (°F) at 2 m and RH is the surface relative humidity (%). The equation of the HI used here and the \( c \) values\(^\text{b1} \) are an approximation to a heat stress model presented by Steadman (1979).

The Humidex is defined as

\[
\text{Humidex} = \vartheta + \frac{5}{9} (e - 10),
\]

where \( \vartheta \) is the temperature (°C) at 2 m and \( e \) is the vapor pressure (hPa). The Humidex can be understood as air temperature plus a value that considers the impact of moisture.

For the Humidex, temperature has a stronger impact than humidity. Thus, in general, Humidex decreases as latitude increases, following the annual mean surface temperature (http://ec.gc.ca/meteo-weather/default.asp?lang=En&n=6C5D4990-1#humidex). For the HI, temperature as well as humidity contribute similarly. Nevertheless, for example, above 50°N, a portion of the high-HI values are only artifacts of high humidity, since the temperature does not reach values over 20°C. Consequently, it is necessary to filter the HI (taking account of the temperature range). As both indices are dependent on latitude and as Russia is located at approximately the same latitudes as Canada, the Canadian Humidex seemed to be more suitable for investigating a heat wave in Russia. In this study, we compared the heat intensity represented in one forecast scenario to that represented by another forecast scenario; thus, it is more of a relative consideration. For investigations that aim for absolute results, it could be necessary to adapt the danger thresholds.

##### b. Wildfire potential

We used the lower atmosphere severity index (LASI) for wildlife fires (Haines 1988):

\[
\text{LASI} = (\theta_{p1} - \theta_{p2}) + (\vartheta_{p2} - \tau_{p2}),
\]

where \( \theta \) is the temperature and \( \tau \) the dewpoint (both in °C). Both \( p1 \) and \( p2 \) are pressure levels in the lower troposphere, with \( p1 < p2 \) in height. The first term describes the stability of the atmosphere, whereas the second part of the index is the moisture term. The resulting values of both terms are assigned to factor values between 1 and 3. These factor values are then added. This sum is the effective LASI with a range between 2 and 6. There are three configurations of LASI that are adjusted to the different elevation levels (low, mid-, and high) of the United States. We confined the computation of the LASI to a region from 51° to 57°N and from 37° to 49°E, where active fires were observed (Witte et al. 2011). The geographical height of this region varies from 130 to 200 m above sea level, requiring use of the low-elevation index. The stability is calculated between 950 and 850 hPa and the moisture term is defined for 850 hPa (corresponding to \( p2 \)). As the required input variables from TIGGE are not available at 950 hPa, we used the variables at 925 hPa (corresponding to \( p1 \)). This results in an overestimation of the stability term, leading to an overestimation of the LASI itself (Potter et al. 2008).

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\(^\text{b1}\) The \( c \) values are \( c_1 = 42.379 \), \( c_2 = 2.04901523 \), \( c_3 = 10.14333127 \), \( c_4 = 0.22475541 \), \( c_5 = 6.83783 \times 10^{-3} \), \( c_6 = 5.481717 \times 10^{-2} \), \( c_7 = 1.22874 \times 10^{-3} \), \( c_8 = 8.5282 \times 10^{-4} \), and \( c_9 = 1.99 \times 10^{-6} \).
LASI does not consider surface conditions, like soil moisture; however, it represents atmospheric conditions that influence fire behavior as well (Brotak 1994). Thus, it can be interpreted as an indicator if the vertical lapse rate and the amount of moisture in the air are favorable for the fire evolution or not (Brotak 1994). Although LASI was developed for predicting the fire risk in the United States, it has also been employed successfully outside the United States, for example, in South Korea (Choi et al. 2006) and Australia (McCaw et al. 2007).

REFERENCES


