The record-breaking heat wave of June 2019 in Central Europe

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Abstract
After being hit by several devastating heat waves in recent years, Europe experienced an exceptionally hot June in 2019 again. This June is the hottest one on record over Central Europe both in a monthly-mean sense and in terms of the number of extremely hot days. The above-normal hot condition is caused by an anomalous long-lasting anticyclone in the upper troposphere, which advects warm air from the Sahel and Mediterranean region and enhances incoming solar radiation and surface turbulent fluxes. The anomalous anticyclone results from an unusually-intensified British-Baikal Corridor (BBC) pattern and a synoptic Rossby wave breaking (RWB) event over Europe. Three sub-monthly heat waves are observed in the month. The first two are associated with the BBC pattern, and the third is related to the combination of the previous BBC pattern activity and the RWB event.

KEYWORDS
heat wave, teleconnection, wave breaking

1 | INTRODUCTION

Heat waves are extreme weather events featured by abnormally high temperatures (Meehl and Tebaldi, 2004; Schär et al., 2004; Barriopedro et al., 2011). It has severe impacts on the air quality, economy, and ecosystem (Clais et al., 2005; Vautard et al., 2005; Grumm, 2011), and it is listed as the leading cause of weather-related mortality (Changnon et al., 1996; Robine et al., 2008; World Health Organization, 2009). The physical reasons behind the heat waves are complicated, and many factors can potentially lead to the occurrence of heat wave event. Generally speaking, two types of mechanisms are primarily responsible for the occurrence of heat waves (Deng et al., 2018). First is the anomalous atmospheric circulation forcing (Dole et al., 2011). The anomalous anticyclonic forcing in the above can induce warm temperature advection and reduce the cloud cover, which favors the occurrence of heat waves. Second is the soil moisture-surface temperature feedback (Fischer et al., 2007). Deficit soil moisture in preceding periods can suppress the surface evaporation and reduce the latent cooling, which can also help to increase the occurrence probability of heat waves. In the context of global warming, numerical models predict that both surface temperature and surface temperature variabilities will increase in response to the anthropogenic greenhouse gas warming (Ballester et al., 2009; Fischer et al., 2012), implying the heat waves will become more intense, more frequent and last longer in the future (Meehl and Tebaldi, 2004), thus posing a tough challenge for the adaptation of human society to the changing climate.

After being hit by several deadly heat waves in recent years, many countries in Europe again experienced
sweating temperatures in June 2019. Record highs were set in France, Germany, Poland, Spain, and Switzerland. According to the OGIMET website (www.ogimet.com), which reports information from the Belgium SYNOP weather stations, France experienced temperatures exceeding 45°C for the first time in recorded history and even issued its first-ever red weather alert. Thousands of schools were closed, and hot weather-related deaths and wildfires were reported in many countries during the heat wave. Since the high-temperature extremes can exert devastating impacts on society, investigating its related mechanism is not only an important issue for academia but also the public. In this study, the basic characteristics and related mechanism for the June 2019 heat wave are examined preliminarily in both monthly-mean and sub-monthly timescales. Evidence suggests that June 2019 is the hottest June for Central Europe on record. A persistent anomalous anticyclone, which is caused by an unusually-intensified teleconnection pattern propagated across Eurasia and a strong Rossby breaking event above Europe, is responsible for this scorching and record-breaking June.

2 | DATA AND METHODS

This study is based on the daily and monthly mean Japanese 55-year Reanalysis (JRA-55) data with 1.25° latitude by 1.25° longitude resolution (Kobayashi et al., 2015) for the period 1958–2019. Besides, National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis data with 2.5° latitude by 2.5° longitude resolution (Kalnay et al., 1996) are also used to validate and confirm the results based on JRA-55 data. A high spatial resolution daily gridded dataset E-OBS version 20.0e is also employed in this study for comparison (Klein Tank et al., 2002). The dataset has 0.25° latitude by 0.25° longitude resolution, and it is based on the station data and covers the European region from 1950 onward. The climatology is defined as the average over the period 1979–2018, and monthly and daily anomalies are calculated as the departures from the climatology in a particular month or particular day. The rainfall data are from the Climate Prediction Center Merged Analysis of Precipitation (CMAP) dataset (Xie and Arkin, 1997). The hot days are defined as the days with the daily mean surface air temperature above its 90th percentile, and the number of hot days (NHDs) can be used to indicate the climate extremes. In addition, a quantity α, defined as the ratio between the NHDs in a particular month and its corresponding climatological value, is used to reflect the fractional change in the NHDs (Wang and Chen, 2010). For example, if α = 1.5, NHDs are 50% more than normal.

3 | RESULTS

Figure 1a shows the surface air temperature (Ts) anomalies in June 2019. A wave-like anomalous temperature pattern can be observed across the Eurasian continent, with the anomalous warm-core over Europe and Northeast Asia and cool core over the Central Siberia and Yakutsk. The warm Ts anomalies over Europe and Northeast Asia are remarkable, with the positive amplitude exceeding 5°C around (50°N, 15°E) and (70°N, 110°E). The temperature anomalies derived from E-OBS also show a similar pattern in Europe (Figure 2), confirming the reliability of the JRA-55 dataset in this case study. An average of Ts over Central Europe (indicated by the blue box in Figure 1a) suggests that the region...
averaged $T_s$ in June 2019 has surpassed the record-breaking temperature of June 2003 for almost 1°C, making the June 2019 as the hottest June for Central Europe since 1958 (Figure 3a). This conclusion also holds in the E-OBS dataset when the same period is considered (Figure 3b) and the NCEP/NCAR dataset when the starting year extends back to 1948 (not shown). Although Figure 1a shows the temperature anomalies are most intense over Central Europe, the domain-averaged high temperature is still unprecedented if we select a larger domain that covers almost the entire European continent (Figure S1). As reported by recently-released news issued by Copernicus Climate Change Service (2019), June 2019 is the hottest June for Central Europe than any other June on record, confirming the extraordinary warming condition in this year. The distribution of $\alpha$ indicates the hot region across Eurasia is also featured with more NHDs (Figure 1b), and Central Europe is the most seriously impacted region. Many places suffered from extremely hot days eight times and even 16 times than normal (Figure 1b). The domain averaged NHDs over Central Europe in this June is also the highest than any other June since 1958 (Figure 3c, also the highest one if the starting period is extended to 1948 using NCEP/NCAR dataset). These results indicate the June in 2019 is exceptional for Central Europe in terms of not only the enhanced monthly mean $T_s$ but also the most extreme hot days on record.

Figure 1c shows that the exceptional June 2019 is associated with a persist wave-like pattern across the Eurasian continent in the upper troposphere. Positive (negative) geopotential height anomalies are observed over Europe and Northeast Asia (central Siberia), corresponding to the local high (low) $T_s$ anomalies underneath. This wave-like pattern is quite similar to the negative phase of a recently identified teleconnection pattern along the summertime polar front jet, the British-Baikal Corridor (BBC) pattern (Xu et al., 2019; 2020) (Text S1). Figure 3d indicates that the index of the BBC pattern is the second-lowest since 1958, suggesting the unusual activity of the BBC pattern this year. The anomalous anticyclonic center of the BBC pattern over Europe leads to a classic “omega” blocking circulation in the middle troposphere (Dole and Gordon, 2019).
This configuration will impede the eastward movement of frontal systems and induce land warming through anomalous horizontal temperature advection and diabatic heating (Xoplaki et al., 2003; Cassou et al., 2005). Diagnose of 1,000–850 hPa-integrated temperature tendency equation indicates that the warming over the European continent is primarily resulted from the northward advection of warm air masses from the Sahel and Mediterranean region (Figure S2a), while the anomalous zonal temperature advection only plays a minor role (Figure S2b). In contrast, the diabatic heating, which implicitly include the radiations and turbulent heat flux, acts to cool the continent as a whole in this June (Figure S2c). Further diagnose about the surface radiations and turbulent heat flux indicates that the upper-tropospheric "omega" blocking circulation can enhance the incoming shortwave radiation and sensible heat flux, which also contributes to the warming in Central Europe (Figure S3). In fact, similar blocking-like circulation patterns were also found to be the main synoptic features during the 2003 and 2010 European heat waves (Trigo et al., 2005; Dole et al., 2011). It implies that the European heat waves are likely to happen during some specific summertime atmospheric circulation regimes (Cassou et al., 2005; Wolf et al., 2018).

After revealing the monthly mean situations, the temporal evolutions of the heat wave on the sub-monthly time scale are examined. Figure 4a shows the daily time series of the historical maximum of Ts (pink shading) and Ts in June 2019 (red line) averaged over Central Europe (i.e., the blue box in Figure 1a). The Ts of Central Europe experienced a stable upward trend towards the end of the month. The Ts on 14–16 and 25–27 June are distinct because they exceed the historical maximum on the counterpart day. The Ts on 26 June is particularly notable because it exceeds the historical maximum by almost two degrees. The time series of the daily Ts anomalies (Figure 4b, red bar with the right y-axis) suggests that every day in June 2019 is at least 1°C warmer than its corresponding climatology and that there are primarily three heat waves in this month: 3–10 June, 11–22 June, and 23–28 June. Each event is more intense than the preceding one, with the last event attains its unprecedented peak that is almost 5°C warmer relative to the climatology. This result suggests that the stable upward trend of Ts shown in Figure 4a is not only a reflection of the seasonal cycle but also caused by the anomalous heat waves in this month.

Figure 4b also shows the daily time series of the BBC pattern in June 2019, which has been in the negative phase for almost the entire month. Two peaks are observed on 6 June and 17 June, respectively, with the BBC index exceeding the historical lowest value during 14–18 June and 19–20 June (Figure 4b). A third peak is observed on 25 June, but it is much weaker than the previous two. The sub-monthly evolution of the BBC index agrees quite well with that of the Ts over Central Europe during the first two heat waves (i.e., 3–10 June and 11–22 June). Meanwhile, the geopotential height anomalies averaged during the two heat waves (Figure S4a and b) quite resemble the BBC pattern (e.g., Figure 3a in Xu et al., 2020). These results suggest that the BBC pattern contributes not only to the monthly mean Ts in June 2019 but also to the sub-monthly fluctuations of Ts during the first two heat waves (3–22 June). Nevertheless, the BBC pattern fails to explain the occurrence of the strong heat wave at the end of June because the pattern begins to be attenuated at this time (Figures 4b and S4c).

To reveal the essential dynamical process of the third strongest heat wave, the evolutions of the isentropic potential vorticity at the 350 K level are examined (Figure 5). Two ridges are located above the Atlantic and Europe, respectively, on 23 June (Figure 5a), and they begin to amplify, merge and break anticyclonically...
between 24 and 28 June (Figure 5b-5f). The ridge over Europe persists almost in situ during the entire process, facilitating the massive poleward intrusion of the warm air into Europe and thereby the heat wave. These results indicate that the severe heat wave event that happened at the end of June 2019 is caused by a combination of the previous BBC pattern and a synoptic Rossby wave breaking event above Europe. The former sets the warm and dry land preconditions that favor the occurrence of a serious heat wave (Figure S5), and the latter directly leads to the heat wave through advecting the warm air into Europe and enhancing the incoming solar radiations and turbulent sensible heat fluxes.

4 | CONCLUSION AND DISCUSSION

After being hit by several devastating heat waves in recent years, Europe experienced a severe heat wave in June 2019 again. This study analyzes the causes of this heat wave preliminarily. It reveals that the June 2019 is the hottest June on record not only in a monthly-mean sense but also in terms of the number of extremely hot days. The above-normal Ts over Central Europe can be related to a massive anomalous long-lasting anticyclone above, which is part of a wave-like teleconnection pattern across entire Eurasia, known as the BBC pattern (Xu et al., 2019). On the sub-monthly timescale, there are primarily three heat waves during 3–10 June, 11–22 June, and 23–28 June, respectively. Each event is stronger than the preceding one with the last two events exceeding the historical maximum daily mean temperature on record. The occurrence of the first two heat waves is closely associated with the intraseasonal behavior of BBC pattern. In contrast, the occurrence of the exceptional heat wave at the end of the month is related to the strong Rossby wave breaking event under the warm and dry context preconditioned by the previous two heat waves.

One question is why the BBC pattern is so intense in June 2019. Since the variability of BBC pattern is

| PVU | 4 | 6 | 8 | 10 | 12 |

**FIGURE 5** The daily evolutions of the isentropic potential vorticity at the 350 K level on (a) 23 June, (b) 24 June, (c) 25 June, (d) 26 June, (e) 27 June, and (f) 28 June of 2019 (unit: PVU, and 1 PVU is $10^{-6}$ K m$^2$ kg$^{-1}$ s$^{-1}$)
primarily determined by the atmospheric internal dynamics (Xu et al., 2019; 2020; Figure S6), the wave-mean flow interactions over the North Atlantic may play an important role in amplifying the BBC pattern. On the other hand, other external forcing such as anomalous tropical convections (Figure S7) may also favor the excitation of the BBC pattern through tropical–extratropical connection (Cassou et al., 2005; Ding and Wang, 2005). These issues remain to be explored in the future.

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**CONFLICT OF INTEREST**

The authors declare no conflict of interest.

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**REFERENCES**

Ballester, J., Giorgi, F. and Rodó, X. (2009) Changes in European temperature extremes can be predicted from changes in PDF central statistics. *Climatic Change*, 98, 277.

Barriopedro, D., Fischer, E.M., Luterbacher, J., Trigo, R.M. and García-Herrera, R. (2011) The hot summer of 2010: redrawing the temperature record map of Europe. *Science*, 332, 220–224.

Benedict, J.J., Lee, S. and Feldstein, S.B. (2004) Synoptic view of the North Atlantic Oscillation. *Journal of the Atmospheric Sciences*, 61, 121–144.

Cassou, C., Terray, L., and Phillips, A.S. (2005). Tropical Atlantic Influence on European Heat Waves. *Journal of Climate*, 18(15), 2805–2811. https://doi.org/10.1175/jcli3506.1

Changnon, S.A., Kunkel, K.E. and Reinke, B.C. (1996) Impacts and responses to the 1995 heat wave: a call to action. *Bulletin of the American Meteorological Society*, 77, 1497–1506.

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., Chevallier, F., de Noblet, N., Friend, A.D., Friedlingstein, P., Grünwald, T., Heinesch, B., Keronen, P., Knoll, H., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J.M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J.F., Sanz, M.J., Schulze, E.D., Vesala, T. and Valentini, R. (2005) Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature*, 437, 529–533.

Copernicus Climate Change Service. (2019). Record-breaking temperatures for June. (https://climate.copernicus.eu/record-breaking-temperatures-june).

Deng, K., Yang, S., Ting, M., Lin, A. and Wang, Z. (2018) An intensified mode of variability modulating the summer heat waves in Eastern Europe and northern China. *Geophysical Research Letters*, 45, 11,361–11,369.

Ding, Q.H. and Wang, B. (2005) Circumglobal teleconnection in the Northern Hemisphere summer. *Journal of Climate*, 18, 3483–3505.

Dole, R.M., and Gordon, N.D. (1983). Persistent Anomalies of the Extratropical Northern Hemisphere Wintertime Circulation: Geographical Distribution and Regional Persistence Characteristics. *Monthly Weather Review*, 111(8), 1567–1586. https://doi.org/10.1175/1520-0493(1983)112.0.co;2

Dole, R., Hoerling, M., Perlwitz, J., Eischeid, J., Pegion, P., Zhang, T., Quan, X.-W., Xu, T. and Murray, D. (2011) Was there a basis for anticipating the 2010 Russian heat wave? *Geophysical Research Letters*, 38, L06702.

Fischer, E.M., Rajczak, J. and Schär, C. (2012) Changes in European summer temperature variability revisited. *Geophysical Research Letters*, 39, L19702.

Fischer, E.M., Seneviratne, S.I., Vidale, P.L., Lüthi, D. and Schär, C. (2007) Soil moisture–atmosphere interactions during the 2003 European summer heat wave. *Journal of Climate*, 20, 5081–5099.

Grumm, R.H. (2011) The central European and Russian heat event of July–August 2010. *Bulletin of the American Meteorological Society*, 92, 1285–1296.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Jenne, R. and Joseph, D. (1996) The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society*, 77, 437–471.

Klein Tank, A.M.G., Wijngaard, J.B., Können, G.P., Böhm, R., Demarée, G., Gocheva, A., Mileta, M., Pashiaris, S., Hejkrlik, L., Kern-Hansen, C., Heino, R., Bessemoulin, P., Müller-Westermeier, G., Tzanakou, M., Szalai, S., Pålæöttir, T., Fitzgerald, D., Rubin, S., Capaldo, M., Maugeri, M. Leitaass, A., Bukantis, A., Aberfeld, R., van Engelen, A.F.V., Forland, E., Mietus, M., Coelho, F., Mares, C., Razuvav, V., Nieplova, E., Cegnar, T., Antonio López, J., Dahlström, B., Moberg, A., Kirchhofer, W., Ceylan, A., Pachaliuk, O., Alexander, L.V., and Petrovic, P. (2002). Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment. *International Journal of Climatology*, 22(12), 1441–1453. https://doi.org/10.1002/joc.773

Kobayashi, S., Ota, Y., Harada, Y., Ebita, A., Moriya, M., Onoda, H., Onogi, K., Kamahori, H., Kobayashi, C., Endo, H., Miyaoaka, K. and Takahashi, K. (2015). The JRA-55 Reanalysis: General Specifications and Basic Characteristics. *Journal of the Meteorological Society of Japan. Ser. II*, 93(1), 5–48. https://doi.org/10.2151/jmsj.2015-001

Meehl, G.A. and Tebaldi, C. (2004) More intense, more frequent, and longer lasting heat waves in the 21st century. *Science*, 305, 994–997.

Robine, J.-M., Cheung, S.L.K., Le Roy, S., Van Oyen, H., Griffiths, C., Michel, J.-P., and Herrmann, F. R. (2008). Death toll exceeded 70,000 in Europe during the summer of 2003. *Comptes Rendus Biologies*, 331(2), 171–178. https://doi.org/10.1016/j.crvi.2007.12.001
Schär, C., Vidale, P.L., Lüthi, D., Frei, C., Häberl, C., Liniger, M.A.
and Appenzeller, C. (2004) The role of increasing temperature
variability in European summer heatwaves. Nature, 427, 332–336.

Swanson, K.L., Kushner, P.J. and Held, I.M. (1997) Dynamics of
barotropic storm tracks. Journal of the Atmospheric Sciences, 54, 791–810.

Thorncroft, C.D., Hoskins, B.J. and McIntyre, M.F. (1993) Two par-
adigms of baroclinic-wave life-cycle behavior. Quarterly Journal
of the Royal Meteorological Society, 119, 17–55.

Trigo, R.M., García-Herrera, R., Díaz, J., Trigo, I.F. and Valente, M. A. (2005) How exceptional was the early August
2003 heatwave in France? Geophysical Research Letters, 32, L10701.

Vautard, R., Honore, C., Beekmann, M. and Roulil, L. (2005)
Simulation of ozone during the august 2003 heat wave and
emission control scenarios. Atmospheric Environment, 39, 2957–2967.

Wang, L. and Chen, W. (2010) Downward Arctic Oscillation signal
associated with moderate weak stratospheric polar vortex and
the cold December 2009. Geophysical Research Letters, 37, L09707.

Wolf, G., Brayshaw, D.J., Klingaman, N.P. and Czaja, A. (2018)
Quasi-stationary waves and their impact on European weather
and extreme events. Quarterly Journal of the Royal Meteorologi-
cal Society, 144, 2431–2448.

World Health Organization. (2009) Improving Public Health
Responses to Extreme Weather/heatwaves–EuroHEAT. Copenhagen,
Denmark: WHO Regional Office for Europe.

Xie, P.P. and Arkin, P.A. (1997) Global precipitation: a
17-year monthly analysis based on gauge observations,
satellite estimates, and numerical model outputs. Bulletin of the American Meteorological Society, 78, 2539–2558.

Xoplaki, E., González-Rouco, J.F., Luterbacher, J. and Wanner, H.
(2003) Mediterranean summer air temperature variability and
its connection to the large-scale atmospheric circulation and
SSTs. Climate Dynamics, 20, 723–739.

Xu, P., Wang, L. and Chen, W. (2019) The British-Baikal corridor: a
teleconnection pattern along the summertime polar front jet
over Eurasia. Journal of Climate, 32, 877–896.

Xu, P., Wang, L., Chen, W., Chen, G. and Kang, I.-S. (2020) Intra-
seasonal variations of the British-Baikal corridor pattern. Jour-
nal of Climate, 33, 2183–2200.

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