Earth and Space Science

RESEARCH ARTICLE
10.1029/2022EA002567

The 2021 European Heat Wave in the Context of Past Major Heat Waves

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Key Points:

- Spatio-temporal characteristics of major heat waves are studied over land and sea combined using the ERA5 reanalysis
- The 2021 heat wave was the longest since 1950 and comparable to the 2003 and 2010 events in terms of magnitude and spatial extent
- The map of the most severe heat waves in individual parts of Europe has been almost completely redrawn in the past two decades

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Lhotka, O., & Kyselý, J. (2022). The 2021 European heat wave in the context of past major heat waves. *Earth and Space Science*, *9*, e2022EA002567. https://doi.org/10.1029/2022EA002567

Received 10 AUG 2022
Accepted 28 OCT 2022

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Abstract

The past two decades in Europe have been characterized by numerous major heat waves, with record-breaking temperatures reported also during the summer of 2021. While most previous studies on heat waves were based on land-only datasets (station or gridded), we use the ERA5 reanalysis to capture also heat wave characteristics over water bodies. An up-to-date list of major European heat waves since 1950 is presented, and the 2021 heat wave is evaluated in this long-term context. This event was record-breaking in length at the European scale, and in many other aspects (spatial extent, magnitude) comparable to the 2003 and 2010 major heat waves. The summer of 2021 was unprecedented over Europe according to the number of hot days (63) and the earliest start of a major heat wave (June 19), while the 2019 heat wave with record-breaking temperatures across Western Europe stands out as to its intensity. Another recent major heat wave in 2018 ranked fourth in terms of magnitude. The spatial pattern in occurrence of the most severe heat wave since 1950 in individual parts of Europe is dominated by the 2003 (Western Europe), 2010 (Eastern Europe), 2018 (Scandinavia), and 2021 (Mediterranean) major heat waves. Overall, 83% of the domain area experienced the most severe heat wave in the past two decades (2002–2021), which demonstrates a rapidly changing summer climate in Europe.

Plain Language Summary

Heat waves, characterized as several days to weeks long periods with excessively hot weather in summer, have negative effects on environment and society. The severity of heat waves has increased in the past two decades and record-breaking temperatures were observed during the recent summer of 2021 over the Mediterranean. We used the climate reanalysis (ERA5) to create an up-to-date list of major European heat waves since 1950 and assess the severity of the 2021 heat wave in the long-term context. The 2021 heat wave was found to be comparable to the 2003 and 2010 major heat waves in terms of magnitude and spatial extent and record-breaking in length. Maps depicting the record-breaking heat waves over European regions differ substantially between the 1950–2001 and 1950–2021 periods. The latter map is dominated by the 2003, 2010, 2018, and 2021 heat waves, demonstrating a rapidly changing summer climate in Europe.

1. Introduction

Heat waves are among the most dangerous natural hazards. Although interest in their studies dates back to the second half of the twentieth century, it has substantially increased following such major and unprecedented events as the 2003 heat wave in Western Europe and the 2010 heat wave in Russia. Marx et al. (2021) showed that the number of scientific papers on heat waves and their impacts has doubled approximately every 5 years since 2003. Major heat waves are associated with negative effects on society and ecosystems, including excess mortality in the population (Robine et al., 2008) and reduced vegetation productivity (Bastos et al., 2014), and often they are linked to rapidly emerging flash droughts (Yuan et al., 2019).

Almost two decades ago, Meehl and Tebaldi (2004) analyzed simulated properties of heat waves analogous to the 2003 heat wave in France and concluded that such events will become more intense, more frequent, and longer lasting in the future climate. Similar findings have been reported in more recent studies (Lhotka, Kyselý, & Farda, 2018; Russo et al., 2014; Wang & Yan, 2021) and the interest in heat waves has further increased due to numerous hot extremes that struck Europe in the 2010s. The 2010 Eastern European (Barriopedro et al., 2011), the 2014 Scandinavian (Baker-Austin et al., 2016), and the 2015 Central European (Lhotka, Kyselý, & Plavcová, 2018) heat waves have been included into the list of "Top 10 European heat waves" (Russo et al., 2015).

Another major heat wave occurred in 2018 mainly over Northern Europe (Yiou et al., 2020) and in the summer of 2019, when many (mostly Western) European countries set new records for all-time high temperatures (Vautard et al., 2020). Rising temperatures have substantially increased the likelihood of occurrence of such major heat waves (Stott et al., 2016); the probability of the aforementioned 2019 event in Western Europe was very low considering the historical 1950–1980 period (>1,000 years return period) but it may become a regular phenomenon at the end of the 21st century (return period between 1.8 and 7.2 years, depending on greenhouse gas concentration scenario; Ma et al., 2020).

The Mediterranean is regarded as one of the most vulnerable European regions in the context of climate change. Observed rates of climate change in this region exceed global trends for most variables, and future summer warming is expected to exceed global rates by 40% (Cramer et al., 2018). Using model ensembles of the newest CORDEX and CMIP6 simulations, Coppola et al. (2021) showed that the projected increment of summertime temperatures is largest in the Mediterranean (plus 4–8°C at the end of the 21st century compared to 1981–2010 under a high greenhouse gas concentration scenario). This region is projected to be also drier in a future climate as the change of precipitation yields a distinct latitudinal pattern over Europe, with increases in the north and decreases in the south. These changes would amplify heat–drought coupling with further implications for society and the environment (Teuling, 2018). Ruffault et al. (2020) found an increase in the frequency of heat-induced fire-weather types in future climate scenarios for the Mediterranean (plus 30% under a high concentration scenario in 2071–2100). Heat-induced fire-weather types are characterized by compound dry and warm conditions occurring during summer heat waves (Rodrigues et al., 2020).

A major heat wave struck the Mediterranean Basin in summer 2021, triggering numerous extraordinary wildfires that attracted also global media attention (e.g., CNN, 2021). The characteristics and driving mechanisms of this recent major heat wave in the context of previous events have not yet been analyzed. Therefore, the main aim of this study is to assess the severity of the 2021 event in the long-term context since 1950 and to study similarities and differences among major European heat waves. We adopt a methodology that takes into account both spatial and temporal characteristics of heat waves. While most previous studies on major heat waves included only land areas in Europe, we present an analysis of the spatial patterns of heat waves over land and sea combined, which allows also capturing their characteristics in coastal regions (e.g., the Mediterranean).

2. Data and Methods

2.1. ERA5 Reanalysis

Heat waves were analyzed using daily maximum temperature at 2 m above the surface (Tmax), obtained from the latest ECMWF ERA5 reanalysis (Hersbach et al., 2020). The reanalysis has a native horizontal resolution of 31 km, but the outputs were interpolated to 0.25° latitude–longitude grid by the data provider. The domain used for the analysis spans 32–72°N and 20°W–45°E and has a total area of 19.64×10^6 km^2. It encompasses the majority of the European (sub)continent and extends across several climatic zones (Kottek et al., 2006). The domain was further divided into nine regions (based on a regular latitude–longitude grid) in order to assess a heat wave's prevailing location (Figure 1a). The whole available 1950–2021 period (72 years) was analyzed, although the data prior to 1979 may be less reliable and were marked preliminary by the data provider. The main issues are, however, related to unrealistically intense tropical cyclones (Bell et al., 2020), which have negligible effect on the domain in our study. The advantage of ERA5 is its data coverage; availability of temperature data in "non-land" grid points was crucial for a proper capture of spatial properties of heat waves in coastal regions, such as the Mediterranean Basin with a plenty of scattered islands. Geopotential height at the 500 hPa level (Z500) was obtained also from the ERA5 reanalysis in order to assess circulation characteristics for individual major heat waves.

2.2. Heat Wave Definition and Indices

Heat waves were delimited based on a sequence of "hot days." A hot day was defined by relative Tmax threshold, that is, the threshold varied among individual grid points (Figure 1b). For each grid point separately, the threshold was calculated as the mean of summertime (June, July, and August) Tmax distribution in 1981–2010 plus doubled standard deviation of the Tmax distribution. The mean summertime Tmax was preferred over daily-adjusted thresholds (e.g., Russo et al., 2014); while the latter approach is suitable for identifying high

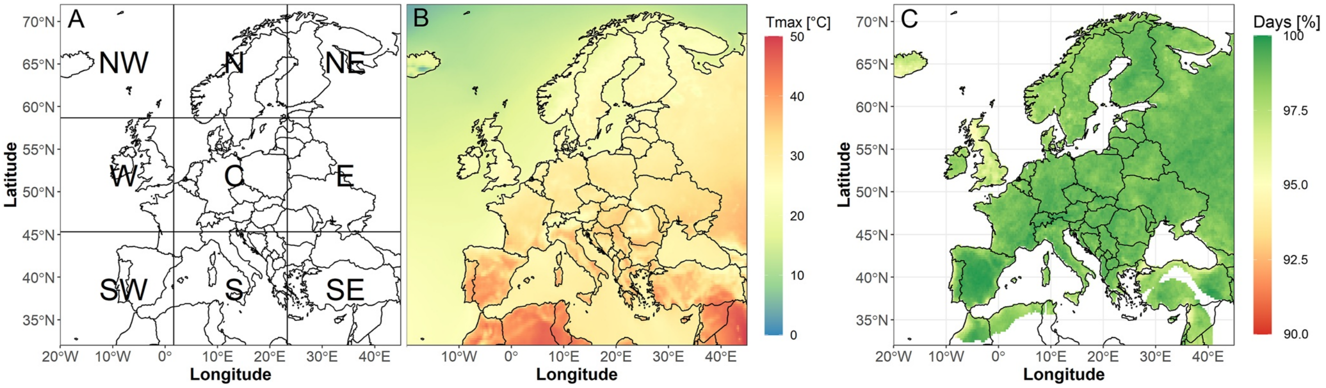

Figure 1. (a) Area of interest with nine regions (C – Central, NW – North-western, etc.), (b) Tmax thresholds used for identification of hot grid points, and (c) ratio of days with Tmax exceeding the threshold simultaneously in both ERA5 and E-OBS to all days above the threshold in ERA5.

temperature anomalies relative to climatology for a given day, the method used in our study captures heat waves in terms of their absolute magnitude, regardless the annual Tmax course, and does not require the season in which heat waves will be analyzed (e.g., June–August) to be predefined.

For each day, those grid points in which Tmax exceeded the threshold were referred to as "hot." Spatio-temporal occurrence of hot grids in ERA5 was evaluated against that calculated from the E-OBS gridded dataset (version 24.0e; Cornes et al., 2018), with thresholds defined separately in the two datasets. This comparison is possible in land areas with E-OBS data, and shows very good agreement between ERA5 and E-OBS in spatio-temporal occurrence of Tmax exceedances above the threshold (Figure 1c); only in a few areas (parts of the UK, Iceland) falls the fraction of days exceeding the threshold simultaneously in ERA5 and E-OBS to all days above the threshold in ERA5 below 97.5%. This suggests good applicability of the ERA5 reanalysis as the source data for studying characteristics of major European heat waves, with only minor differences from E-OBS over land while advantage of providing Tmax also over water bodies. In addition to the Tmax thresholds, a spatial criterion was also employed to define hot days. A hot day occurs when Tmax exceeds its thresholds across at least 625,000 km^2; this area corresponds to the size of domain used for the definition of heat waves in Lhotka, Kyselý, and Plavcová (2018) and takes into account a typical extent of synoptic patterns associated with heat waves in Europe (Zschenderlein et al., 2019).

After a number of preliminary analyses, we define heat waves as sequences of at least 7 consecutive hot days. This relatively long temporal threshold was employed in accordance with Fischer and Schär (2010) in order to capture hazardous long-lasting heat waves. In addition, a relaxation criterion was applied in order to avoid fragmentation of long heat waves into two or more shorter events—a single day during which the hot days' criteria were not met was included into a heat wave if (a) preceded by a hot day, and (b) another hot day followed. We note that this applies to only 20 days in total (over 72 years) and does not substantially affect the heat wave statistics, but it does lead to a more intuitive temporal extent of the events.

The spatial extent of heat waves represents the total area of those grid points that were "hot" for at least 1 day during the given heat wave. Individual heat wave patterns were plotted as composites of hot grid points' values only, which means that sums of positive standard deviations in excess of 2.0 (for days during which a heat wave persists) were visualized. For example, if Tmax was (hypothetically) equal to the mean plus 2.5 standard deviation for 10 consecutive days, that grid point would be assigned the value of 5 in a composite map ((2.5–2.0) × 10). This approach which normalizes Tmax anomalies through standard deviations is more suitable for heat waves' analyses over land areas and water bodies combined compared to quantile-based metrics (e.g., Perkins & Alexander, 2013). Characterizing heat waves using temperature anomalies above a given quantile would result in generally larger anomalies over land areas than water bodies, associated with a distortion of their spatial patterns especially in regions with large radiative forcing (e.g., the Mediterranean).

Using the composite maps of Tmax anomalies, 42,021 grid point values (261 in longitudinal × 161 in latitudinal direction) were multiplied with their respective areas and then summed. This number was divided by 1×10^6 for better readability, resulting in the heat wave magnitude index:

$$Magnitude = \sum_{i=1}^{261\times161} grid\ point\ value \times \frac{area_i}{10^6\ km^2}$$

The heat wave magnitude represents the total severity of a given heat wave, taking into account its duration, affected area, and normalized temperature anomaly. The intensity of a heat wave was calculated as the magnitude divided by length; this characteristic highlights shorter-lived events with large positive Tmax anomalies. In addition, heat wave magnitude was also calculated separately for each of the nine regions (Figure 1a) in order to locate the given heat wave. The heat wave was assigned into those regions wherein the magnitude was larger than its mean calculated from all nine regions. Due to the relatively strict definition of heat waves compared to regionally focused studies, the analyzed heat waves are referred as "major" in this paper.

3. Results

3.1. Heat Waves' Characteristics

In total, 50 major heat waves were identified across Europe in the 1950–2021 period (Table 1), with total duration of 677 days (9.4 per year on average). The mean heat wave length was 13.5 days and reached up to 60 days during the longest event in 2021, which was primarily located in the S, SE, E, and NE regions (Figure 2) and was characterized also by the earliest start date ever (June 19). The 2021 event was in many aspects comparable to the 2003 and 2010 major heat waves, which primarily struck Western and Eastern Europe, respectively, while exceeding them in length. These three major heat waves had the highest magnitude (>200), exceptional length (>6 weeks), and the largest spatial extent, while the intensity was lower in 2021 compared to 2003 and 2010 but still above-average (Table 1). They were related to high pressure ridges and associated positive anomalies in Z500, but the ridge during the 2021 major heat wave was less pronounced, probably also due to its length (Figure 3).

The 2018 major heat wave has a spatial extent (10.8×10^6 km^2) similar to that of the three aforementioned major heat waves but its length (31 days) and magnitude (163.0) were smaller. It persisted mainly over Northern Europe, similarly to the 2014 event, which ranked fifth according to its magnitude (107.2). Both of these major heat waves were linked to large positive Z500 anomalies over Fennoscandia (Figure 3). Another major heat wave that affected mainly the northwestern parts of the domain occurred in 2004. By contrast, the 2015 major heat wave primarily struck continental Europe, especially its central parts where it was the most severe event, and ranked sixth according to its magnitude for the whole domain. The spatial pattern of accumulated temperature anomalies in 2015 was similar to that during the recent 2017 major heat wave that persisted mainly in South-eastern Europe (Figure 2). These two events were related to similar Z500 patterns consisting of positive (negative) Z500 anomalies in south-east (north-west, Figure 3).

Central Europe was affected by a major heat wave also in 2013 (Figure 2), associated with a distinct high pressure ridge extending through continental Europe. A similar Z500 pattern (but with more pronounced positive anomalies) was found for the major heat wave in July 2019, which was shortest among those shown in Figure 3 (9 days) but was characterized as the most intense (alongside with the 2010 major heat wave, Table 1). The majority of the top 16 most severe heat waves (Figure 2) occurred in the past two decades, and only four of them before 2000. While the 1972 and 1994 major heat waves were most pronounced over land areas (Fennoscandia and Central Europe, respectively), the 1955 and 1997 events were rather characterized by the largest accumulated temperature anomalies over water bodies. This is probably related to timing of the given events within a year; the 1955 and 1997 major heat waves occurred in mid-August, when ocean waters tend to be warmer compared to in early summer. The complete list of European major heat waves (including their spatial patterns of accumulated temperature anomalies and Z500 fields) is provided in Figure S1.

Table 1
Characteristics of Major European Heat Waves

Date of start	Length [days]	Spatial extent [10^6 km^2]	Intensity	Magnitude	Regions
1952-07-01	8	2.6	1.8	14.4	W, C
1954-07-05	7	2.3	1.8	12.6	E, NE
1955-08-14	12	4.1	3.9	46.7	W, NW
1957-07-29	8	2.8	2.3	18.6	S, E, NE
1960-07-25	7	3.6	2.7	19.2	E, NE
1963-08-01	8	3.3	2.2	17.5	C, E, NE
1972-06-27	18	3.2	3.0	53.4	N, NE
1972-08-04	9	3.0	2.5	22.1	E, NE
1973-07-02	7	2.7	2.2	15.2	N, NE
1975-08-03	9	3.9	3.7	33.5	W, C, N
1976-06-25	11	1.8	2.1	23.2	W, C
1976-08-20	8	2.6	2.2	17.3	W, NW
1982-08-01	7	1.7	2.0	14.0	C, N
1983-07-25	7	3.4	2.6	18.5	S, C
1987-07-20	8	3.0	2.3	18.3	S, SE
1989-07-19	7	3.2	2.6	18.1	W
1994-07-24	14	5.3	4.0	56.6	C, E, N, NE
1995-08-15	12	3.9	2.9	34.8	W
1997-08-08	15	5.0	3.2	48.1	W, C, NW, N
1998-08-01	12	5.5	2.9	34.4	S, E, C
2000-08-19	7	3.2	2.3	15.9	S, SE, C
2001-07-15	15	5.3	2.4	36.7	SE, E, NE
2002-08-15	10	2.8	2.5	24.5	C, NW, N
2003-07-13	44	12.6	5.2	227.3	C, NW, N
2003-08-29	7	3.3	2.0	13.7	SW, S, NW
2004-07-30	19	6.6	3.9	73.2	SW, NW, N
2006-07-05	8	3.6	2.7	21.8	C, E, NE
2006-07-16	16	4.8	3.0	48.6	S, W, C
2007-07-16	11	4.6	3.5	38.3	S, SE, C, E
2008-07-24	9	3.4	2.2	19.7	C, NW, N
2010-07-08	45	10.9	5.4	243.5	SE, E, NE
2012-07-20	12	6.0	2.8	33.2	SE, E
2012-08-05	7	5.6	3.9	27.5	SW, S, SE, E, NW
2012-08-17	11	5.6	3.2	35.6	SW, S, C
2013-07-27	14	6.9	3.2	44.4	C, N, NE
2014-07-07	8	2.6	1.8	14.0	N, NE
2014-07-18	25	9.2	4.3	107.2	C, E, NW, N, NE
2015-06-30	9	4.4	2.9	25.7	C, E
2015-07-16	32	9.3	3.1	97.6	SW, S, SE, C, E
2016-07-15	10	6.1	3.1	30.9	W, E, N, NE
2016-08-14	14	4.9	1.9	26.8	SW, W, C, NW, NE
2017-08-01	13	6.5	4.4	56.6	S, SE, C, E
2018-06-27	7	2.6	2.0	14.2	W, E, N

Table 1
Continued

Date of start	Length [days]	Spatial extent [10^6 km^2]	Intensity	Magnitude	Regions
2018-07-11	31	10.8	5.3	163.0	C, N, NE
2019-06-25	7	4.0	3.3	23.2	S, C
2019-07-22	9	7.2	5.4	48.6	W, C, NW, N, NE
2020-07-26	8	5.3	3.3	26.7	S, E, C, N, NE
2020-08-06	8	4.2	3.7	29.6	W, C, N
2020-08-16	7	4.6	2.4	16.8	SW, W, C, N
2021-06-19	60	14.0	3.7	224.2	S, SE, E, NE
Average	13.5	5.0	3.0	46.9	

Note. Regions are sorted from south-west to north-east.

3.2. Temporal Variability of Heat Waves

A marked increase in the annual number of hot days, duration of heat waves, and their total magnitude was found since the 1990s. Before 1990, annual numbers of hot days usually ranged from 0 to 10. More than 10 hot days per season were found in 11 out of 40 years, with the largest number of 30 in 1972. In the period since 1990, by contrast, at least 1 hot day per season occurred during 28 consecutive years (1994–2021) and more than 10 hot days per season were observed in the past 12 summers (2010–2021) consecutively, with the record-breaking number (63) in 2021 (Figure 4). The 1960s clearly stand out as a period of cold summers, with only one major heat wave (lasting 8 days) in 1962–1971, while in a period 50 years later (2012–2021), 19 major heat waves occurred with total duration of 292 days (Table 1).

The majority of heat waves occurred in the past two decades (Table 1). In this period, at least one heat wave was found in 17 out of 20 years and in every year since 2012 (Figure 4). In 2021, the heat wave persisted for 60 days, which is considerably longer compared to the total heat wave length in 2003 (51 days) or 2010 (45 days). The total magnitude of heat waves was 224.2 in 2021, which ranked that year third after 2010 (243.5) and 2003 (241.0). The other years with total heat wave magnitude >100 were 2014, 2015, and 2018 (Figure 4), and there were no occurrences of annual heat wave magnitude >100 before 2003. This documents a rapid shift toward warmer summertime conditions in Europe in the past two decades.

Figure 5 shows spatial patterns for occurrence of the most severe heat wave (according to sums of positive standard deviations). In the 1950–2001 period (i.e., excluding the last two decades), the spatial pattern was characterized mainly by the 1955 major heat wave located over the NE Atlantic, 1972 in Scandinavia and Russia, and 1994 spanning Central Europe and the Baltic region. The western Mediterranean was struck by a major heat wave in 1983, while its eastern parts in 1987 and 1998 (Figure 5a).

If the entire 1950–2021 period is considered, the spatial pattern differs substantially (Figure 5b). The area where the 1994 heat wave was the most severe was reduced to a minimum and the 2003, 2010, 2015, and 2018 events became more severe in the majority of its original area. Large reductions were found also for the 1972 (NE Europe) and 1983 (Mediterranean) heat waves. The three most severe major heat waves in 2003, 2010, and 2021 were record-breaking over more than half (55%) of the grid points in the whole area. While the 2021 event set new records in the Eastern Mediterranean, the 2003 heat wave remained as the most severe over its Western basin. Overall, the map has been redrawn for 83% of domain area during the last two decades.

4. Discussion

The present analysis of European major heat waves was not confined to land-only areas and due to this fact, in contrast to studies employing quantile-based definitions (e.g., Guerreiro et al., 2020; Zhang et al., 2020; Zschenderlein et al., 2019), characteristics of major heat waves were analyzed through standard deviations of Tmax distribution in order to address differences in temperature anomalies especially between land and ocean grid points (Schär et al., 2004). This allows capturing the spatial patterns of major heat waves occurring over both land and sea more comprehensively, and might be preferred methodology also in evaluation of heat waves in

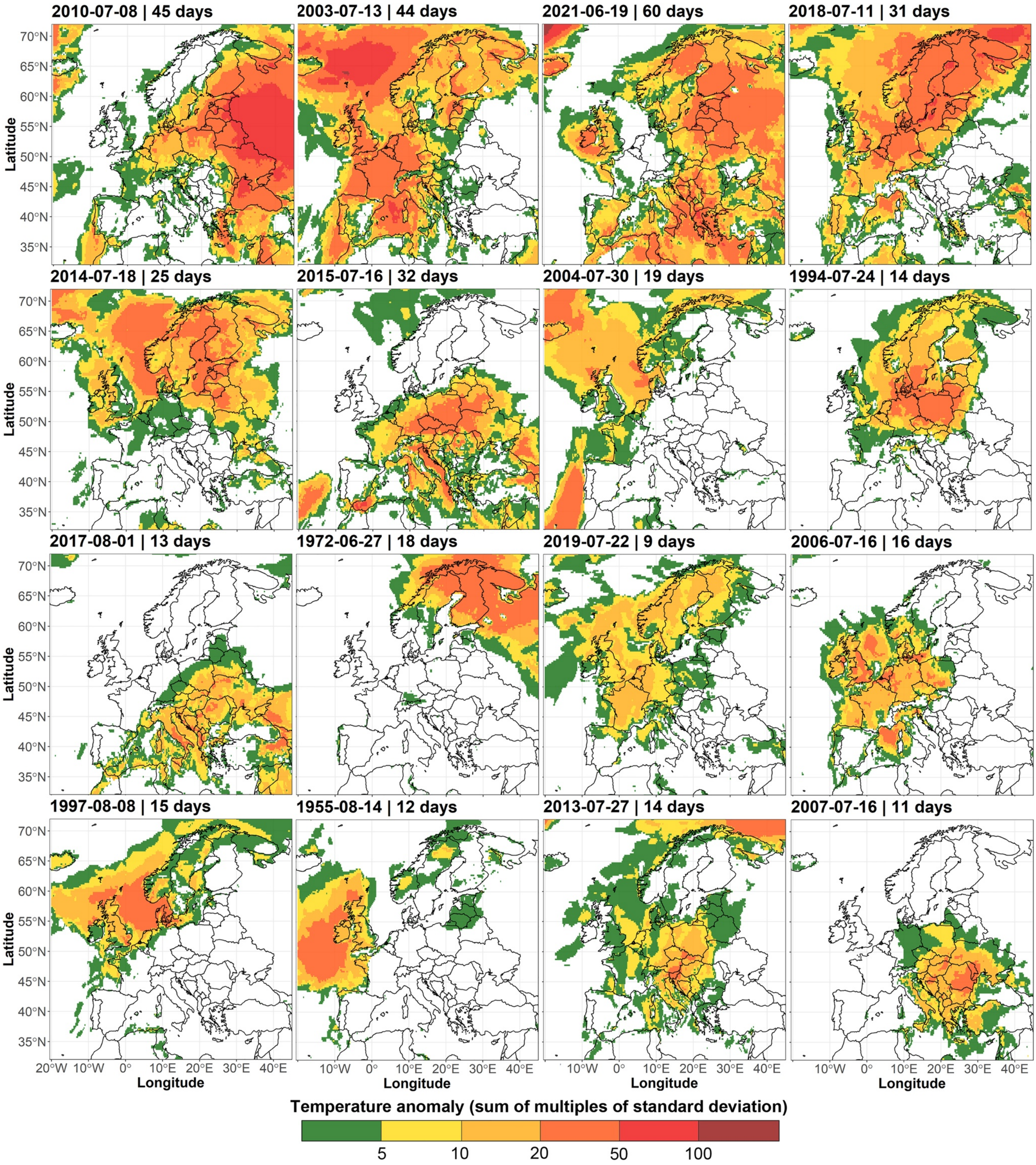

Figure 2. Accumulated temperature anomalies during the 16 most severe heat waves according to heat wave magnitude index. Their date of start and length are indicated above each panel.

climate models when it is not confined to land areas only. The quantile-based definition, by contrast, would have resulted in underestimated magnitude of heat waves over large water bodies.

The most severe heat waves identified in our study (Table 2) are in general agreement with the list of top 10 European heat waves (Russo et al., 2015) defined through a quantile-based method in land-only E-OBS data (Haylock

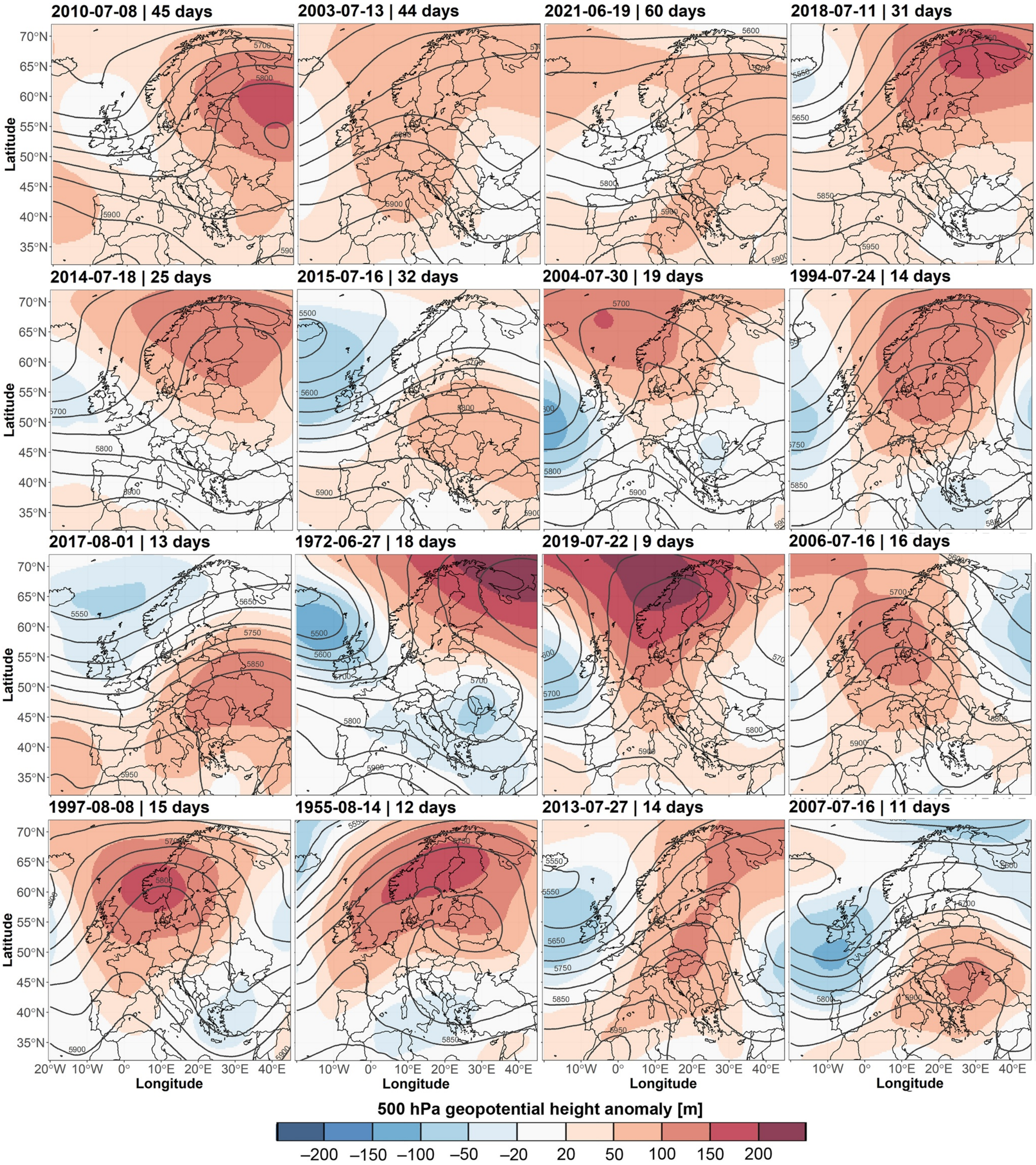

Figure 3. Five-hundred hPa geopotential height (isolines) and its anomalies from summer 1981 to 2010 climatology (color scale) during the 16 most severe heat waves according to heat wave magnitude index. Their date of start and length are indicated above each panel.

et al., 2008) and using daily-adjusted thresholds (Section 2.2). The only exceptions are the 1969 Norway heat wave (not included in our study due to its relatively small spatial extent) and the 2004 major heat wave (not listed in Russo et al., 2015 because it was located mainly over the Atlantic Ocean). The direct evaluation of heat wave patterns over water bodies against observations is challenging, however, due to relatively strong coupling between

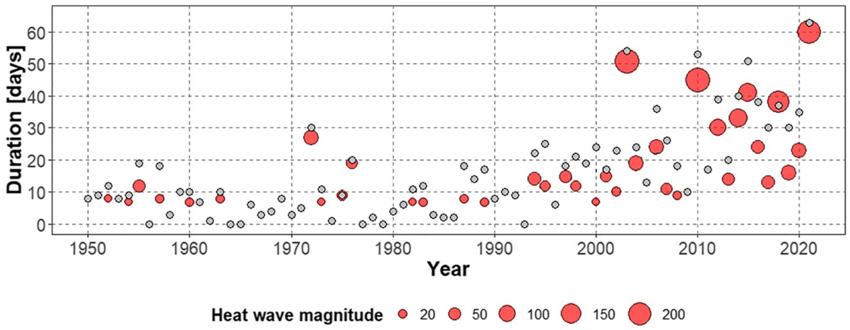

Figure 4. Annual number of hot days (gray circles), total duration of heat waves (y-axis position of red circles), and total heat wave magnitude index (size of red circles).

sea surface and 2 m atmospheric temperatures, it is possible to evaluate the identified major heat waves over water bodies against sea surface temperature anomalies from the NOAA OI SST V2 High Resolution Dataset (1981–present; Reynolds et al., 2007). The 2003, 2018, and 2021 major heat waves were also manifested in respective positive sea surface temperature anomalies in this dataset. In the period prior 1981, such evaluation is not feasible due to the lack of data but for example, the 1955 major heat wave found in our study, which was predominantly located over NE Atlantic, was manifested in severe heat and drought observed in the UK (Fowler & Kilsby, 2002). This indicates good capability of the methodology proposed here to capture spatial patterns of major heat waves and reasonable agreement between the ERA5 and E-OBS.

The key index—magnitude of major heat waves—takes into account their temperature characteristics, spatial extent, and length, analogously to the extremity index introduced in Lhotka and Kyselý (2015). The magnitude of the 2021 major heat wave was comparable to the 2010 event and even surpassed it in characteristics such as length and spatial extent (but had a lower intensity). It should be noted, however, that the core of the 2010 major heat wave had a longitudinal extent approximately between 25 and 55°E (Barriopedro et al., 2011), that is, a part of the heat wave was not within the domain of our study, thereby causing underestimation of its magnitude and spatial extent from a more "global" perspective. On the other hand, because the Mediterranean Basin is located at the southern edge of the domain, these characteristics of the 2021 heat wave may be underestimated as well. Applications of recently proposed event-tracking procedures (Lo et al., 2021) in future updates of the European major heat wave database may reduce uncertainties originating from the fixed domain, and better distinguish between two events taking place at the same time but representing separate heat wave phenomena.

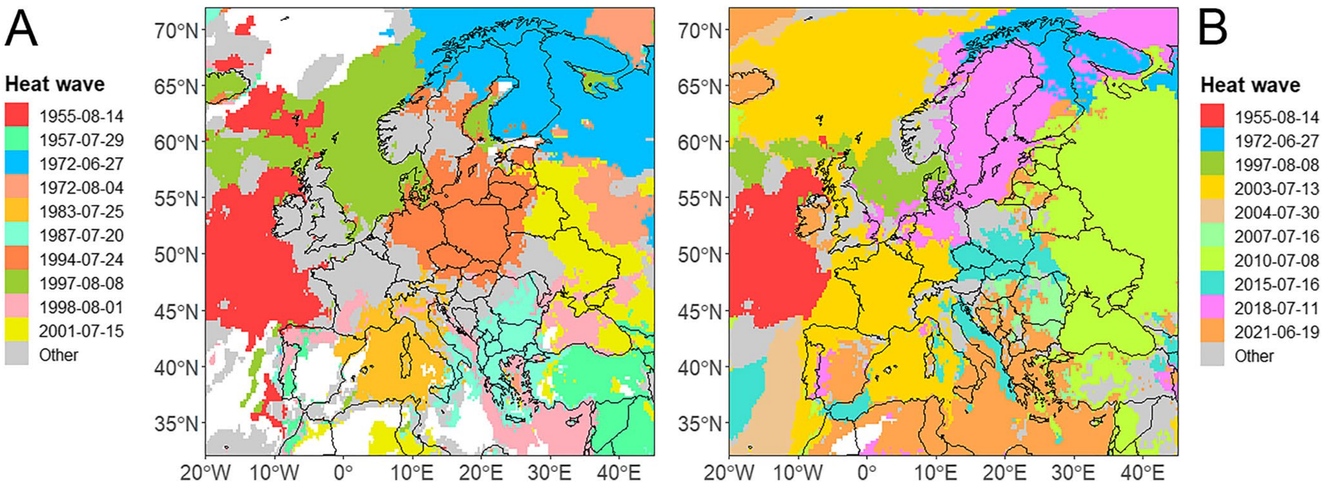

Figure 5. The most severe heat wave in each grid point according to sums of positive standard deviations in (a) 1950–2001 and (b) 1950–2021. White color represents no heat wave in the given period. Top 10 heat waves (according to area) are shown in both maps.

Table 2
Top Ten European Major Heat Waves in the Present Study According to Their Magnitude

Rank	Year	Magnitude	Rank in Russo et al. (2015)
1	2010	243.5	1
2	2003	227.3	2
3	2021	224.2	–
4	2018	163.0	–
5	2014	107.2	×
6	2015	97.6	6
7	2004	73.2	9
8	1994	56.6	8
9	2017	56.6	–
10	1972	53.4	3

Note. "–" stands for events that occurred after publishing the list in Russo et al. (2015), and "×" indicates major heat wave not listed in that publication.

In continental Europe, the 2015 major heat wave (ranked sixth according to its magnitude) was associated with onset of an extremely dry period (Hoy et al., 2017; Ionita et al., 2017) that peaked in 2018 when another heat wave occurred (Dirmeyer et al., 2021; Lhotka et al., 2020), ranked as the fourth most severe since 1950 at the continental scale. The 2017 heat wave is also among the "top 10" in this study (Table 2), highlighting the close link between heat waves and drought development. Many studies showed that soil desiccation before and during hot extremes is linked to altered land–atmosphere coupling and amplification of heat waves (Fischer, 2014; Wehrli et al., 2019).

Heat waves over Europe are related to high latitude blocking anticyclones and/or sub-tropical ridges of high pressure. These high pressure systems are associated with hot conditions through horizontal advection of warm air masses, adiabatic heating during air subsidence, and/or diabatic (solar) heating of the surface and adjacent air. The importance of these processes, however, varies across Europe (Zschenderlein et al., 2019). While the blocking anticyclones are linked to hot extremes mainly in Northern Europe (as seen during the 2014 and 2018 major heat waves), heat waves over Southern Europe are associated with relatively flat high pressure ridges (e.g., the 2007, 2017, and 2021 Southern European heat waves). In Central Europe, heat waves may be linked to both these phenomena (Sousa et al., 2018), which leaves room for further investigation regarding interactions of different large-scale drivers of major heat waves in this region.

By analyzing near-term outputs of 10 CORDEX regional climate model (RCM) simulations, Russo et al. (2015) found that all simulated at least one major heat wave analogous to the 2003 event in the 2011–2040 period. Because only one RCM (out of 10) yielded such a strong event in the 1981–2010 evaluation run, they concluded that return periods of major heat waves will be considerably shortened in near future, which is in line with occurrence of the 2018 and 2021 major heat waves in Europe. It should be noted, however, that climate models tend to have difficulties in reproducing the joint effect of atmospheric circulation and land–atmosphere coupling on the development of heat waves (Knist et al., 2017; Lhotka, Kyselý, & Plavcová, 2018; Ukkola et al., 2018) and this is also linked to relatively large uncertainties in climate change scenarios of heat waves (Lee et al., 2021).

According to Russo et al. (2015), the increased frequency of major heat waves may be regionally masked or amplified by internal variability of the climate. This was shown recently, for example, by Zahradníček et al. (2022), who analyzed observed and simulated seasonal numbers of days in Central Europe with Tmax reaching 30°C. The number of observed hot days in the 2006–2020 period was higher by 40% (27%) compared to an ensemble of model simulations forced by the RCP 4.5 (8.5) concentration scenario. The observed increment of circulation types conducive to summertime hot and dry extremes in Central Europe (Lhotka et al., 2020) probably contributed to that inconsistency, which may be either related to effects of climate change on atmospheric circulation or linked to multidecadal climate variability.

5. Conclusions

Using daily Tmax data from the ECMWF ERA5 reanalysis, we created the list of major heat waves in Europe during 1950–2021, which includes their dates and area of occurrence, length, spatial extent, intensity, magnitude, and spatial patterns of accumulated temperature anomalies. Apart from the majority of previous studies, the analysis was performed over land and sea combined, which better captures the spatial extent and severity of individual heat waves. The main conclusions are as follows:

- The 2021 major heat wave was found to be the longest since 1950 and comparable to 2003 and 2010 events in terms of magnitude and spatial extent but its intensity was lower. By contrast, another recent major heat wave that occurred in 2019 was characterized by large intensity equivalent to the most intense 2010 event.

- A marked increase in the annual number of hot days since the 1990s was shown. Before 1990, only 11 out of 40 years recorded more than 10 hot days per season. By contrast, more than 10 hot days per season were found in the past 12 summers (2010–2021) consecutively, with the record-breaking number (63) in 2021.
- The total magnitude of major European heat waves in the past decade (2012–2021) was roughly 50% larger compared to the previous decade (2002–2011), in spite of the occurrence of the exceptional 2003 and 2010 events, and approximately 10-fold compared to the average for the remaining decades (1950–2001). Similar behavior can be seen in the total number of hot days.
- The map of the most severe heat waves in individual parts of Europe has substantially changed in the past two decades. While in 1950–2001 the spatial pattern was characterized mainly by the 1955, 1972, and 1994 major heat waves, they were surpassed during the past two decades, mainly by the 2003, 2010, 2018, and 2021 major heat waves which became record-breaking over the majority of Europe.

These points document a rapid shift toward warmer summertime conditions in Europe in the past decades. The list of major European heat waves created in this study (including their temporal and spatial characteristics) may serve as a basis for subsequent analyses of their driving mechanisms and future scenarios, and the definition allowing for characterizing heat waves over land and sea combined may be useful also for studying links between marine heat waves (Frölicher et al., 2018) and high temperature extremes over land, including simulations of those events in climate models.

Data Availability Statement

The ERA5 reanalysis used for creating an up-to-date list of major European heat waves can be freely downloaded for research purposes from the Copernicus Climate Change Service (C3S) Climate Data Store (https://doi.org/10.24381/cds.adbb2d47; its preliminary version for the 1950–1978 period was obtained from the same provider through https://cds.climate.copernicus.eu/cdsapp%23%21/dataset/reanalysis%2Dera5%2Dpressure%2Dlevels%2Dpreliminary%2Dback%2Dextension%3Ftab%3Doverview, retrieved November 24, 2021). The E-OBS gridded data set used for ERA5 evaluation is also freely available from C3S (https://doi.org/10.24381/cds.151d3ec6).

Acknowledgments

The study was supported by the Czech Science Foundation, project 20-28560S. OL contribution was carried out also within project SustES – Adaptation strategies for sustainable ecosystem services and food security under adverse environmental conditions (CZ.02.1.01/0.0/0.0/16_019/0000797). We acknowledge the ERA5 reanalysis from European Centre for Medium-Range Weather Forecasts (ECMWF).

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