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HIGH IMPACT HEAT WAVES OVER THE EURO-MEDITERRANEAN REGION AND TURKEY - IN CONCERT WITH ATMOSPHERIC BLOCKING AND LARGE DYNAMICAL AND PHYSICAL ANOMALIES

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ABSTRACT

The increase in high impact heat waves in the Euro-Mediterranean region and Turkey is related to a number of *concurring* factors that include persistent anticyclonic weather regimes. The present study investigates the June-July-August (JJA) of 2000, 2007 and 2010 heat wave events *in concert* with some meteorological anomalies (500 hPa geopotential height, 850 hPa temperature, sea surface temperature and soil wetness) and blocking anticyclones, focusing on heat wave occurrences on a grid point base. Detection methods for atmospheric blocking and heat wave are introduced and applied on study cases. During the 2000 JJA very high temperatures were recorded over the Balkan Peninsula and over Turkey where 42 cities had breaking all time highest temperature records for June, but the duration of heat wave was short. The 2007 summer was also abnormally hot for the region and record breaking temperatures were observed in Greece, Romania, Bulgaria and Turkey where 34 cities had highest temperature records for June and July, and the highest total heat wave duration was 60-70 days. The 2010 JJA period was extremely hot over Russia and nearby countries including Turkey where 9 cities had highest temperature records for August. The 2010 case was marked for; large meteorological anomalies, the longest heat wave duration and the highest heat wave intensity. In all cases, heat wave occurrences found to be particularly high over the western part of Turkey. The extremely hot summers of 2000, 2007 and 2010 could reflect summers to come. The results indicate that summer climate might experience a pronounced increase in year-to-year variability. Increase in variability might be able to explain the high impact heat waves, and would strongly affect their incidence in the future. The results may also contribute to a better understanding of heat waves in context of climate variability.

Key words: Heat waves, atmospheric blocking, climate variability, Euro-Mediterranean, Turkey

1. INTRODUCTION

High impact heat wave events (HIHWE) refer to discernible impacts on human health, wellbeing, efficiency, rise in mortality and morbidity [1], an increased demand on energy and water supply [2], agricultural resources, the retail industry, ecology and tourism [3], increased air pollution [4], and consequences on economy due to crop shortfall and wild forest fires [5].

Many HIHWE hit parts of Europe in the last decade or so [6]: the 2003 European heat wave [7], the 2006 heat wave of Central Europe [8], the 2007 summer heat wave of South–Eastern Europe [9], and the 2010 heat wave of Russia [10]. The HIHWE of 2003 led to about 70,000 deaths, and the HIHWE of 2010 caused a death toll of 55,000 due to high heat and poor air quality caused by wildfires, an annual crop failure of about 25%, around 1 million ha of burned areas, and ~US$15 billion of total economic loss [10]. Research studies [5, 11-14] indicate that heat wave events are expected to be more frequent and intense in the next decades.

An observed increase of summer air temperatures of around 4°C is noted in a region stretching from the Atlantic across the Central Europe to the Black Sea [15]. According to a recent report by the Intergovernmental Panel on Climate Change [5], the 1983-2012 period was the warmest 30-yr period of the past 1400 years in the Northern Hemisphere. It was also noted that in the period of 2016-2025 air temperatures are expected to rise by 0.3-0.7°C compared to the1985-2005 period. Considering various

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climate projection scenarios, the report notes that air temperatures may rise by 2.6-4.8°C. Global anthropogenic greenhouse gas (GHG) emissions have been on increase since the pre-industrial era. Studies on the impact of continued emissions of GHG indicate that the Mediterranean region is among the sensitive and positively responsive regions; rise in temperature, large decrease in precipitation and increases in inter-annual warm-season variability [13, 16].

The high variations in summer temperature are related to the meridional pattern, suggesting a northward shift of existing climate zones. Dynamical factors depend on pole ward shifts of storm tracks and associated cyclones and anticyclones, baroclinic zones, and jets as descending Hadley cell branches and subtropical dry zones enlarge pole ward, and as midlatitude flows adjust to a less pronounced equator-to-pole temperature gradient [17]. Future climate projection studies suggest an increase in the number of hot days in the Mediterranean zone and the Eastern Europe, with an additional 60 days or more above 30°C than under current climatic conditions [15].

Climate variability is not spatially and temporally uniform. The modes of climate variability can affect weather and climate on many spatial and temporal scales. The well-known and most periodic climate variability mode is the seasonal cycle. Modes of climate variability and their influence on regional climates are usually diagnosed through spatial teleconnections. Climate variability modes can also force other modes of climate variability. For example, a pronounced sea surface temperature anomaly, relative to the global mean, can affect duration and intensity of heat waves [18].

Prominent ingredients conducive to HIHWE can serve as fingerprint and yield insights into their most important triggering and driving mechanisms. A succinct summary of the manner in which the common dynamical and physical factors work *in concert* are outlined below:

i. *Persistent anticyclones at the surface.* Heat waves mainly depend on large-scale atmospheric circulation patterns. Persistent anticyclones are considered to be the major dynamical factor [19-21]. The interaction between persistent anticyclones and land-surface might be the reason why persistent anticyclones are so important for warm extremes over land. Quasi-stationary anticyclonic atmospheric circulation patterns are usually characterized by the persistent 500 hPa geopotential height anomalies that dynamically cause subsidence which leads to clear-sky, adiabatic warming and inhibits cloud formation which, in turn, increases incoming solar radiation, warm-air advection and prolonged hot weather conditions at the surface. The absence of clouds causes strong radiative anomalies. These anomalies enhance surface evaporation, and cause a gradual depletion of soil moisture, which, in turn, leads to larger sensible heat (SH) fluxes from the ground in to the atmospheric boundary layer and thus increasing surface air temperature [22]. Persistent anticyclones may also directly be responsible for establishing and maintaining warm Mediterranean Sea surface temperature anomalies [19]. The duration of the persistent anticyclone is a key factor for heat waves contributing dynamical and physical processes work in concert; the following gives a descriptive account of role played by persistent anticyclones in the factors outlined below.

ii. *Atmospheric boundary layer (ABL).* The surface plays a very important role in severe heat waves by accumulating heat during the day. The warmed ABL may persist throughout the night [21]. This situation can offset night time cooling which is driven by upward radiation under clear sky conditions, keeping the nocturnal ABL warm, thus slowing the decrease in surface air temperature before sunrise [19, 21, 22]. Therefore, the following day starts off in a warmer state than the previous day and, as this positive feedback cycle repeats, the heat continues to build up in ABL. In response to these progressive processes, ABL becomes much warmer and deeper [23]. 2003 and 2010 heat wave studies showed how ABL changed from 500 m to 4 km in some places [19, 21]. The heat built-up during prolonged intensive heat waves is the key mechanism for the escalation of surface air temperature throughout the event. These progressive processes shed light on why temperatures continue to increase from one day to the next. The warmed-up ABL interact strongly with the underlying soil, which continuously dries out. As a result, cooling of the land surface by evaporation decreases and the land surface is further warmed-up, which, in turn, causes increased SH flux from the surface into ABL. The progressive cycle of pronounced heat storage and soil desiccation were found in both 2003 and 2010 mega HIHWE and increased temperatures to record-breaking levels [21, 23].

iii. *Soil moisture (SM).* It varies very slowly, on the time scale of weeks to months [13, 24] and thus carries potential of the previous months/season's storage until summertime. Precipitation deficit in winter and/or in early spring leads to SM deficit. The anomalous clear skies and very strong radiative anomalies contribute to loss of SM reservoirs, and in subsequent days, SM depletion and soil desiccation take place. The early phenology green-up caused by spring time warmness, together with dry weather regimes, can result in early season moisture depletion too [25]. Under persistent anticyclonic conditions, exposed to sunnier and drier air, plants evaporate more water. In the subsequent period, dried soils emit more SH flux and less latent heat (LH) flux, then this leads to reduced cloudiness and hence further increasing diurnal surface air temperature. An increase of temperature is further amplified when the inability of LH fluxes to transfer heat upwards due to the depleted SM. The land radiation budget and water resources are interrelated via the LH flux associated with evaporation [26]. In SM poor areas, the surface radiation budget is dominated by SH [13] which is strongly determined by SM. Dry soils inhibit cloud formation, increasing incoming solar radiation, and thus amplifying evaporation. Lack of SM enhances diurnal hot air entrainment and causes the formation of persistent residual layers that produce the heat built-up [21]. Modeling studies of HIHWE 2003 revealed a high sensitivity to SM conditions [21, 22, 24, 27].

iv. *Sea surface temperature (SST).* It is well-known that SST is a critical component which influences the exchange of energy between the atmosphere and ocean. A warm SST anomaly can modify air temperature which, in turn, can cause a reduction of the meridional temperature gradient. This may shift the polar jet and the sub-tropical jet –which brings warm and dry air from subtropics- further north than its climatological position, allowing the expansion of the anticyclone; in turn, this atmospheric circulation can induce SST anomalies [28]. When the anticyclone persists over the area, it can block and divert the transient weather coming from the Atlantic Ocean and thus prevent cooling of the Mediterranean SST. Since anticyclones are characterized with downward motion, they can suppress convection and thus increase solar radiation over the Mediterranean Sea. The positive feedback processes between the atmospheric circulation and land-sea can establish and sustain very warm Mediterranean SST for some weeks. High SSTs also have the potential to generate and sustain anticyclones. The 2003 heat wave period was found to be associated with record breaking warm SST of the Mediterranean Sea [19, 28, 29].

Atmospheric models have limitations in simulating some of the key heat wave triggering and driving mechanisms, such as the persistence of anticyclonic circulations, variability of SM and related positive feedback mechanisms between the atmosphere and land-surface [23]. Comprehensive treatments of land-surface hydrology, radiation and convection play a vital role in predicting heat waves well [30].

Previous studies addressed change in temperature and heat wave trends in the Euro-Mediterranean region and Turkey. The western Balkans, southwestern and western Turkey, and along the Turkish Black Sea coastline are referred as “hot spots” of heat wave changes [31]. A heat wave classification study of the region identified clusters of heat waves, and placed Turkey as a second heat wave center within the Iberian Cluster [32]. Studies focusing on Turkey highlight a rise in temperature [33-35] and rising trend in heat wave occurrences over the western part of Turkey [36]. Regional climate projection studies also identify the Mediterranean region as the most responsive hotspots for increasing heat stress [13, 16].

Heat waves over the Balkans and Turkey were noted to be associated with persistent anticyclones by previous studies [9, 35, 36], but this relationship has not yet been investigated explicitly. This study is tailored to associate high impact heat wave episodes and atmospheric dynamics in an event-based approach on a grid point basis. Heat waves occur under the influence of large scale atmospheric circulation factors, and they are not localized events, therefore this study examines heat waves in spatial context not on certain observational points or cities unlike previous studies [9, 35, 36].

The purpose of this current study is twofold: On the dynamical side; it aims to synthesize the underlying triggering and driving mechanisms that pave a way to heat waves, in particular, to examine relationship between heat waves and the associated atmospheric flow such as atmospheric blocking, in an event-based manner and on a grid point basis. On the heat wave analysis side; it aims to explore duration, number of heat wave occurrences and intensity on a grid point basis for the June-July-August (JJA) periods of 2000, 2007 and 2010.

2. DATA AND METHODS

The dataset used in this study is from the European Centre for Medium Range Weather Forecasts ERA-Interim (ECMWF-EI) reanalysis [37]. The ECMWF-EI period employed in this study is 1979-2009, and related meteorological parameters are interpolated on to 1°x1° longitude-latitude grids.

In order to analyze the heat waves of JJA summer period from a dynamical and physical point of view, anomalies (with respect to JJA of 1979-2009) of geopotential height at 500 hPa, temperature at 850hPa, sea surface temperature and soil wetness were computed. The temperature at 850hPa is considered as a good tracer of air mass type because it is less influenced by surface conditions. The positive anomalies of 500hPa geopotential height are a good indication of anticyclonic conditions at the surface. Sea surface temperature anomalies give insight into role played by surrounding sea. Soil wetness is also very important as outlined in section 1.

2.1. Two Dimensional Atmospheric Blocking Detection Method

Blocking anticyclones are related to the blocking of the mid-latitude westerly atmospheric flow. They act to divert the eastward travelling cyclones to its north or south. Blocking may cause anomalous hot and dry weather underneath the block and increased storm activity and precipitation around the block [38]. Weather and climate models have been reported to have difficulties in the initiation and maintenance of atmospheric blocking [39]. The role played by strong blocking anticyclones in some heat wave events such as the 2003 European heat wave [19] and the 2010 Russian heat wave [40,41], and with climatological studies on circulation anomalies during warm summers [12] revealed their importance. In order to objectively diagnose atmospheric blocking, it is vital to employ an objective blocking detection technique. Detection techniques are based on certain meteorological parameters:

i. The 500hPa geopotential height based detection techniques [42-44]

ii. The potential vorticity [45, 46] based detection techniques [47-49]

In this study, the 500hPa geopotential height based detection technique of [43] is considered. The very basics of one-dimensional TM90 blocking detection technique are given below:

$$GHGS = \frac{Z(\lambda,\phi_c) - Z(\lambda,\phi_s)}{\phi_c - \phi_s} \quad \text{and} \quad GHGN = \frac{Z(\lambda,\phi_n) - Z(\lambda,\phi_c)}{\phi_n - \phi_c} \tag{1}$$

where $Z(\lambda,\phi)$ is the 500hPa geopotential height at longitude (λ) and latitude (ϕ). More specifically:

$$\begin{aligned} \phi_c &= 60^\circ N + \Delta \\ \phi_n &= 80^\circ + \Delta \\ \phi_s &= 40^\circ N + \Delta \\ \Delta &= -3.0^\circ, 0^\circ, 3.0^\circ \end{aligned} \tag{2}$$

where ϕ_c is the central latitude, ϕ_n is the northern latitude, ϕ_s is the southern latitude, and Δ represents limits of variability.

A given longitude is considered as blocked on a given date, if both of the following conditions are satisfied for one of the latitudes in consideration.

GHGS > 0 and GHGN < -10m per degree latitude (3)

In the two-dimensional version [44]; the central latitude concept is not used, *GHGS* and *GHGN* are calculated for all the longitudes and latitudes from 30°N to 70°N. The threshold value for GHGN is taken as < -5m for the JJA period. If a given latitude and longitude satisfy the above defined conditions, the local instantaneous blocking is assigned for that location. Following to the work of [43], a temporal-scale of four days is considered for a blocking episode.

2.2. Heat Wave Detection Method

Record breaking temperatures should not be misled for heat waves, although when they occur over a large area give a good signal of heat wave. The definition of heat waves is not straightforward [50], and there is no objective and uniform heat wave definition [12]. One of approaches to identify heat wave is based on daily maximum temperature being above a fixed absolute threshold. A detection based on the exceeding an absolute temperature threshold cannot be applied to all regions, because each region is often characterized by different micro-climatic conditions. For example, in cooler areas absolute thresholds may not be achieved, and temperatures may have to be even higher in hotter areas. In order to reduce the degree of arbitrariness involved in the selection of a threshold temperature for heat wave and to provide a dynamic definition, which may also be easily transferable to other regions, percentiles turns out to be more suitable. Percentile-based studies can differ in considered percentiles: 90^{th} [15, 26, 36, 51, 52], 95^{th} [9, 31, 32], and 99^{th} [20]. They also differ in the way a chosen percentile is computed: (i) the respective calendar day threshold is computed on a single day [9, 15, 36], (ii) the respective calendar threshold day is computed at the center of a given time-window; 31-day [52], 21-day [32], 15-day [31, 51], and 5-day [26].

Since this study deals with spatial distributions, it uses a nonparametric method to determine a threshold value, which is based on the 95^{th} percentile that uses a 7-day time window. Only those days at which temperature exceeds the 95^{th} percentile are considered and checked for three consecutive days. For each June-July-August (JJA) day, the 95^{th} percentile is computed on a grid point basis using air temperature at 2 m from 1979 to 2009. Details of criteria employed and parameters are outlined below:

i. ***Spatially and temporally varying temperature threshold:*** It is computed for each grid point with respect to the climatology (1979–2009). The 95^{th} percentile temperature threshold is computed for the respective calendar day (rcd), using a 7-day time window, between D-3 days and D+3 days –which are based on heat wave temporal scale. For example, to compute the 95th percentile on 7 June at a given grid point, temperature values between 4 and 10 June of 1979-1999 are used. For each JJA day, a threshold temperature, based on 95th percentile, is defined from a sample of seven days (three days on each side of the respective calendar day):

$$T_{(i,j,t)threshold,95^{th}} = \bigcup_{y=1979}^{2009} \bigcup_{rcd=d-3}^{d+3} T_{y,rcd} \tag{4}$$

where ⋃ denotes the union of data time-sets, and $T_{y,\,rcd}$ is the daily maximum temperature of the respective calendar day (*rcd*) in the year (*y*). The indices *i*, *j*, *t* represent latitude, longitude and time (in this application the respective calendar day) respectively.

ii. ***Temporal threshold:*** The above described temperature threshold is to be satisfied on three consecutive days.

iii. ***Heat wave detection:*** A hot spell that satisfies (i) and (ii) is considered as heat wave.

iv. ***Total number of heat waves (TNHW):*** A given JJA period may consist of several individual sub-heat waves. The sum of total number of heat waves is computed as follows:

$$\mathrm{TNHW} = \sum \mathrm{HW} \tag{5}$$

v. ***Duration of heat wave episodes (DHWE):*** DHWE refers to duration of each heat wave episode.

vi. ***Total heat wave duration:*** It is the sum of all DHWE.

$$\mathrm{THWD} = \sum \mathrm{DHWE} \tag{6}$$

vii. ***Magnitude:*** It is computed as the sum of the differences between grid point temperature value and the corresponding threshold temperature (i) for a given heat wave episode and for JJA period.

Magnitude of heat wave episode (MHWE): It is computed for each heat wave episode:

$$\mathrm{MHWE} = \sum_{\mathrm{n}=1}^{\mathrm{dhwe}} (\mathrm{T_{max}} - T_{threshold,95^{th}}) \tag{7}$$

Magnitude of total heat wave episodes (MTHWE): It is the sum of all MHWE.

$$\mathrm{MTHWE} = \sum \mathrm{MHWE} \tag{8}$$

viii. ***Intensity:*** it refers to the ratio between magnitude and duration.

Intensity of heat wave episode (IHWE): It is the ratio between MHWE and DHWE:

$$\mathrm{IHWE} = \frac{\mathrm{MHWE}}{\mathrm{DHWE}} \tag{9}$$

Intensity of total heat wave period (ITHW): It is the sum of all IHWE.

$$\mathrm{ITHW} = \sum \mathrm{IHWE} \tag{10}$$

3. SELECTED HIGH IMPACT HEAT WAVE PERIODS

This study addresses the exceptionally hot JJA of 2000, 2007 and 2010 from a dynamical and physical point of view to shed some light on how exceptional these heat waves were in the context of pronounced anomalies, and also examine occurrences of atmospheric blocking and heat wave characteristics. The rationales behind the chosen cases are: (i) Heat waves that caused large impacts, (ii) Large anomalies of selected meteorological parameters, (iii) Having affected the Euro-Mediterranean region and Turkey.

3.1. The 2000 Summer Heat Waves

A ridge of high pressure from Saharan Africa brought a scorching heat wave to southeast Europe breaking century-old records in various parts of the Balkans, Turkey and Italy with some locations in Sardinia and the Greek Islands exceeding 48°C. The heat wave period affected Turkey to the extent that previous records of maximum temperatures observed in previous decades were broken in many locations, according to observations of the Turkish Meteorological Service: 42 cities had breaking all time highest temperature records, 33 of which had daily maximum temperature over 40°C, exceedances over the 65-year average daily maximum reached more than 10°C in 26 cities. The Turkish government declared holidays for state offices on 13-14 July 2000. On 13 July, the heat abated across parts of Europe but Turkey was hot into the weekend of 15-16 July 2000. Media reported that the heat wave claimed lives: 11 in Turkey, 31 in Greece, 30 in Serbia, 5 in Romania, 5 in Bulgaria. The hot and dry conditions led to various wildfires which spanned from Italy to the Balkans: in Bulgaria, 1400 wildfires consumed more than 58000 ha; in Greece, particularly on Samos, fire consumed one-fifth of the island [53, 54]. Over Turkey, the burned out forest area was 26,353 ha, which is the highest amount recorded since 1994 [36].

Anticyclonic conditions dominated in the most part of JJA period, in particular in July. At the surface, there was over all persistence of anticyclonic conditions (not shown in here), with positive anomalies in the 500 hPa geopotential height (Figure 1a). The high anomaly was located over the northern part of Turkey and Greece, another anomaly was located between the north-west tip of Africa and the southern end of Spain. At the 850 hPa level, the highest temperature anomaly (2-2.5°C) is over north-west edge of Africa, and another anomaly is over Greece, Turkey (0.8-1.8°C) and extending down over Middle-East (Figure 1b). The distribution of SST anomalies show that over the Eastern Mediterranean, the SST anomalies of 2000 JJA are 0.8-1.2°C higher than averages, but over all anomalies are not so large (Figure 1d). As for soil wetness, some parts of Spain, the north of Italy, the southern Europe, the north-west and north-east of Turkey are dry (Figure 1e). The prevalence of anticyclonic conditions might have caused soil moisture depletion, which usually generates high air temperatures by enhancing the surface sensible heat flux and substantially reducing latent heat flux.

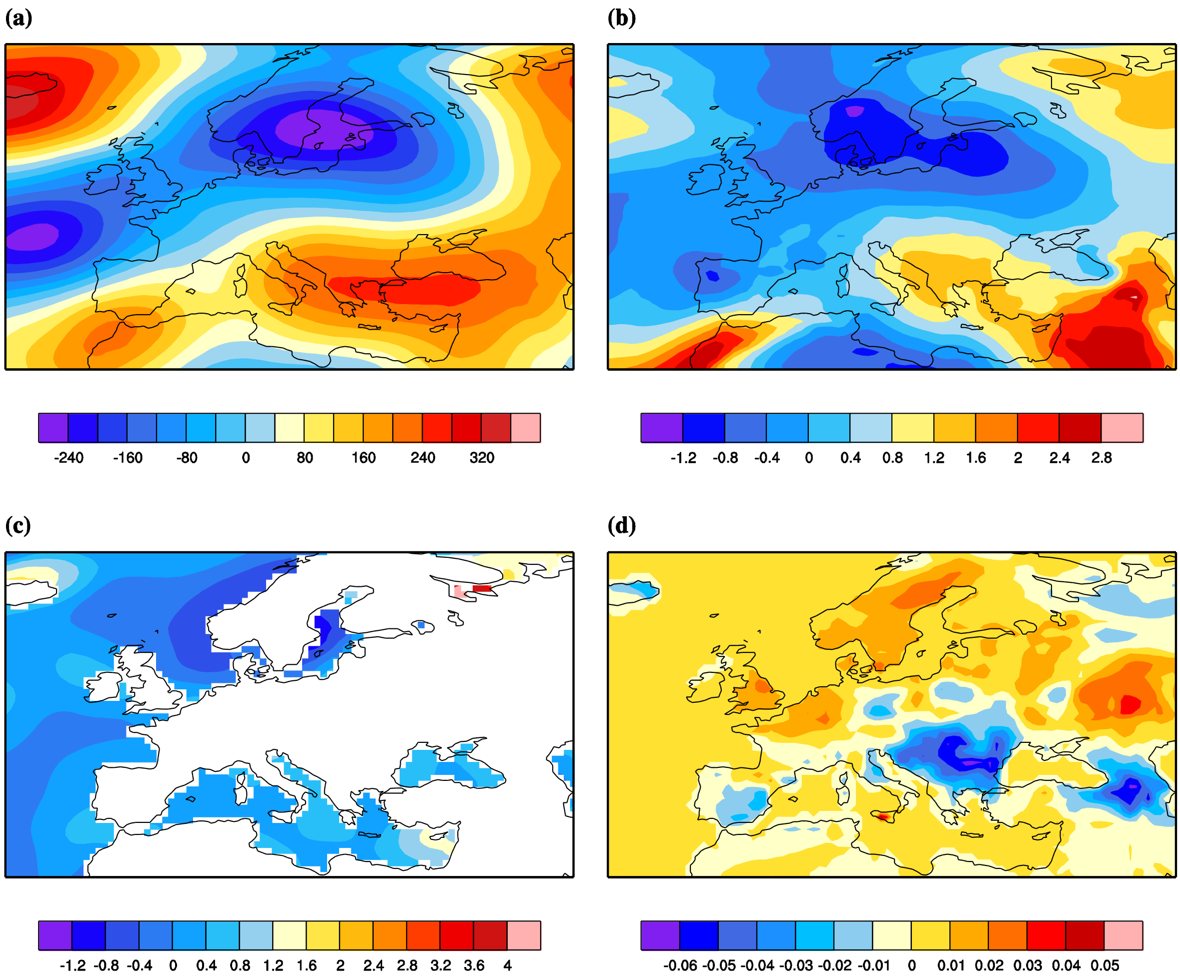

Figure 1. 2000 JJA anomalies for: a) 500hPa geopotential height (m^2/s^2); b) 850hPa temperature (°C); c) Sea surface temperature (°C); d) Soil wetness m (water equivalent).

Atmospheric blocking studies show the area from the Western Mediterranean to over the western part of Turkey and also the north-west of Black Sea having blocking days of 4-40 days (Figure 2a). There is no one-to-one correspondence between total atmospheric blocking days and total heat wave duration, since there are other reasons and contributing factors on heat wave occurrences and their sustainability. It is normal to have more heat wave days than atmospheric blocking days. Distributions of total heat wave days indicate that there are 40-60 days over the Eastern Europe, the Balkans and over the western part of Turkey (Figure 2b). As for total number of heat wave occurrences during the JJA period, it varies from 4 to 7 over the area just mentioned (Figure 2c). The intensity of the total heat wave period is also computed, and results show that the Eastern European area has the highest intensity (4-6°C), over Turkey it is around 2-3°C over the coastal parts and 3-4°C in other parts (Figure 2d).

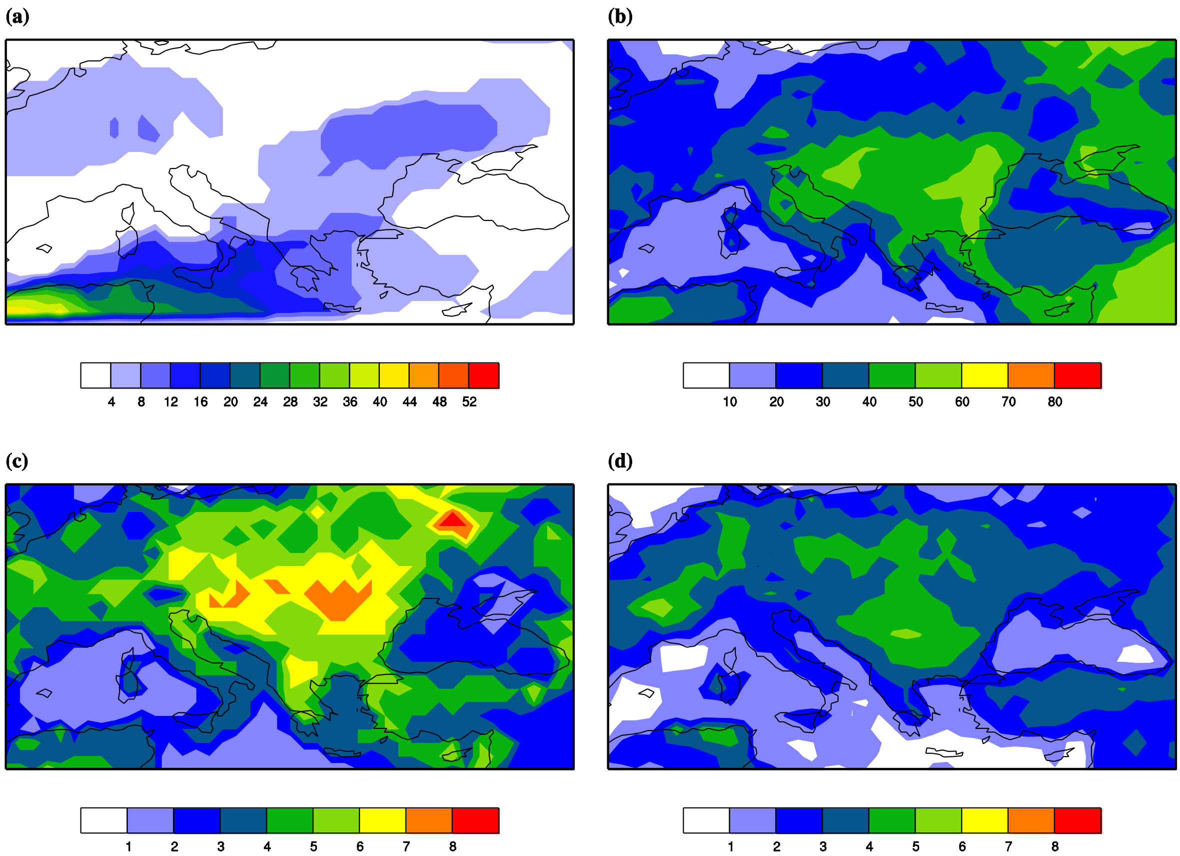

Figure 2. For the 2000 JJA period: a) Total atmospheric blocking days; b) Total heat wave days; c) Total number of heat waves; d) Total heat wave intensity (°C).

3.2. The 2007 Summer Heat Waves

Many heat wave events took place in 2007 JJA; breaking all-time high temperature records in some places [for details see 55]. The summer of 2007 was extraordinarily warm for the southeastern Europe [60, 61], the Balkan Peninsula [9, 57] and for Turkey where several locations, mostly on the west, historical daily maximum temperature records for June and July took place: 34 cities had breaking all time highest temperature records, 16 of which had daily maximum temperature over 40°C, exceedances over the long period average daily maximum reached more than 10°C in 26 cities. Heat wave period prompted record levels of electricity demand and over 130 fires in the south-eastern Europe and the Mediterranean area [56]. In Greece, a large number of fires were observed in the region of Peloponnesus where 177,265 ha of the forest, urban and agricultural areas were burnt [57]. In Turkey, the total burnt area reported for 2007 was 11,664 ha. In the top ten World natural disasters of 2007 by number of casualties, the heat wave period of 2007 ranks the 5th causing 567 deaths in the southern Europe and the Balkans [58]. The poor air quality conditions (high concentrations of surface level O_3, NO_2 and SO_2) were also reported [59].

The analysis of meteorological anomalies computed for this period highlighted higher values compare to anomalies reported for the 2000 JJA period. The 500 hPa positive geopotential height anomaly's south-western edge is located over Turkey and Greece (Figure 3a), this is indicative of strong anticyclonic conditions at the surface level. The 850 hPa large positive temperature anomalies (over 3°C) are located in the central part of Turkey and also over the north-east of Black Sea (Figure 3b). Perhaps, not surprisingly, the highest SST anomaly (2-3°C) is over the Black Sea (Figure 3c), as for the

Mediterranean Sea area, 2°C SST anomalies are noted near the Turkish coastal area which are very close to previous study of the same region [62], and lower values in the other parts. Soil moisture was not high; soil wetness is below 0 in the most affected areas, over Turkey the most pronounced dry soil area was noted around the Black Sea coastal area (Figure 3d). Amplified temperature anomalies and soil moisture deficits may be due to negative precipitation anomalies during the winter of 2007. The period from September 2006 to February 2007 was the warmest in Europe for more than 500-years with the highest air temperatures anomalies over the most part of Europe and the Balkans, and pronounced negative precipitation anomalies over the entire Mediterranean [63].

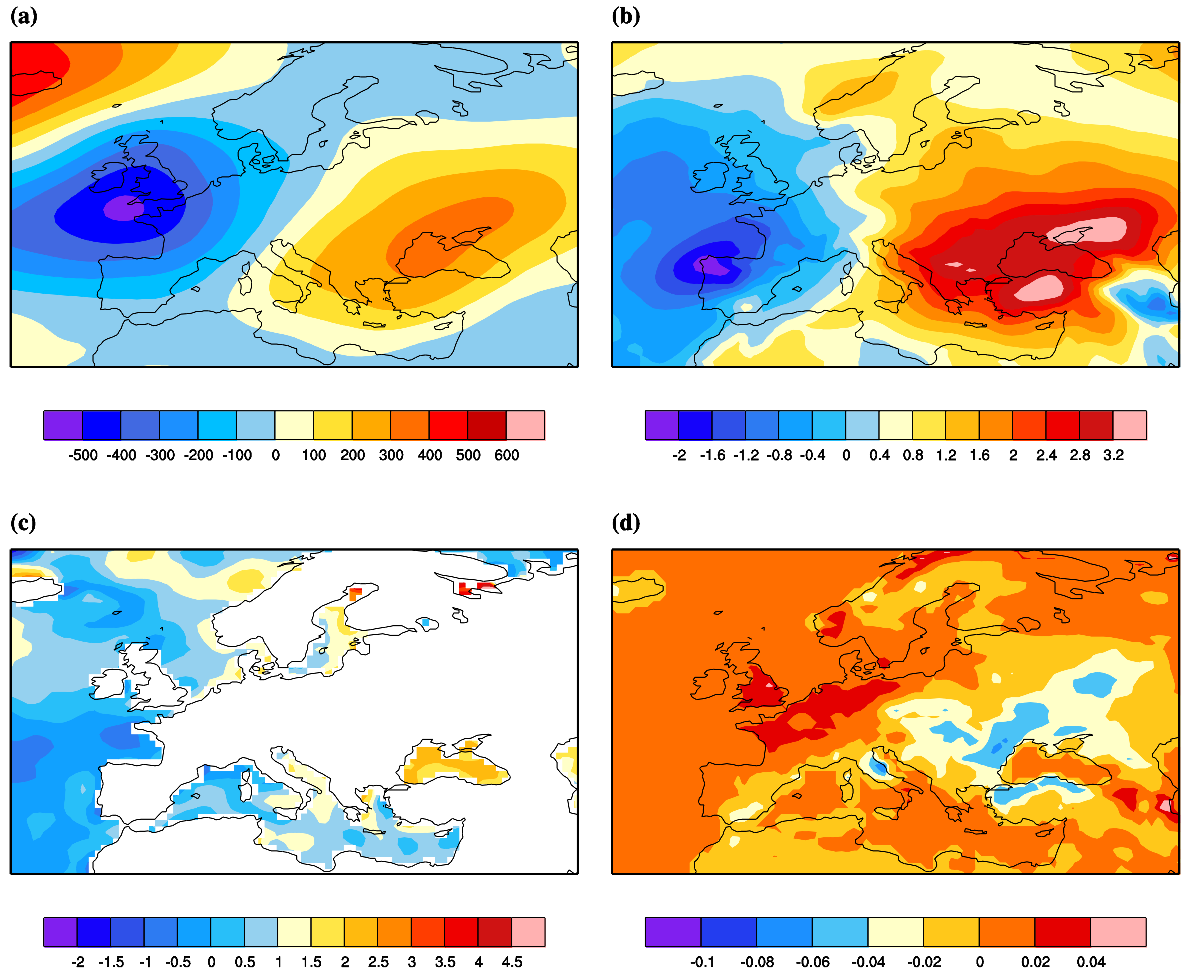

Figure 3. 2007 JJA anomalies for: a) 500hPa geopotential height (m^2/s^2); b) 850hPa temperature (°C); c) Sea surface temperature (°C); d) Soil wetness (m) (water equivalent).

Atmospheric blocking analysis of the period indicates that the blocking area extends from south-west of the Mediterranean to the north-west of Black Sea (Figure 4a). The highest duration of blocking is 20-30 days on the south-west part, and 6-12 days on its north-west part (Figure 4a). The blocking area implies two important points: (i) Hot air temperatures are advected from the hot and dry North Africa, (ii) Cooler circulation patterns (Figure 3a-b) are kept on the west (in particular the area near the south west of the UK) and not allowed to enter over the area where strong anticyclonic conditions maintain hot air temperatures. The heat wave studies of 2007 JJA period clearly shows 60-70 days of total heat wave days being located over the Aegean coastal part of Turkey, the eastern part of Greece and the north-west of the Black Sea (Figure 4b). As for number of total heat waves, over the western Black Sea part of Turkey, there are 5-7 heat waves, but the highest number of heat waves (7-8) is noted to the north west of Turkey (Figure 4c). The intensity of heat wave period is also analyzed, and results are similar to the 2000 JJA, although there are some spots on the north east indicating as high as 4-5°C. Areas to the north of Turkey have values around 4-6°C (Figure 4d). The summer 2007 heat wave period was considered to be the most severe in some other studies too [9, 51, 57, 60, 61].

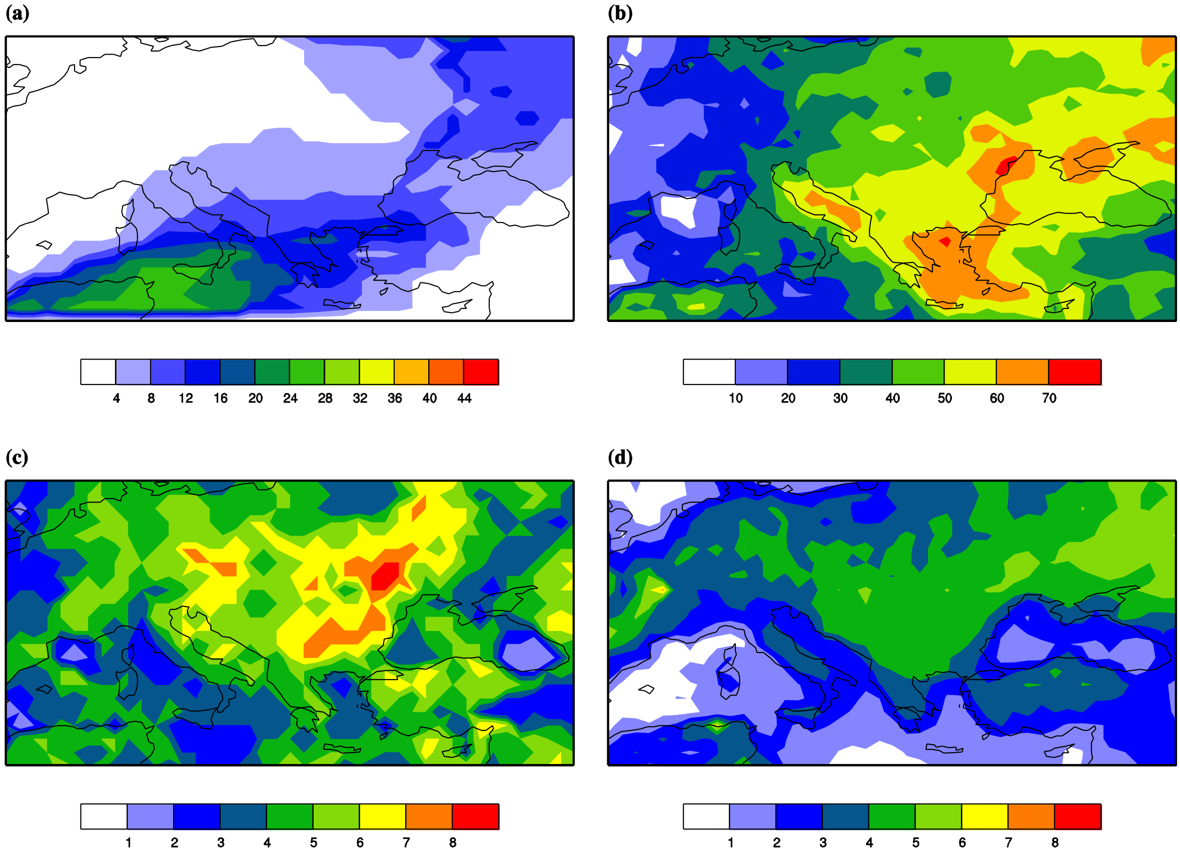

Figure 4. For the 2007 JJA period: a) Total atmospheric blocking days; b) Total heat wave days; c) Total number of heat waves; d) Total heat wave intensity (°C).

3.3. The 2010 Summer Heat Waves

The 2010 heat wave period over the western Russia was extraordinary, with the region experiencing the warmest July since at least 1880 and many places reaching all-time maximum temperature records [10, 41]. Extreme temperatures and very poor air quality due to wildfires caused to large increases in deaths in Moscow and elsewhere in western Russia [64]. The Eastern Europe and western Russia experienced HIHWE in the summer of 2010: Maximum temperatures were over 40°C resulting in over 15,000 deaths, more than 600 wildfires which also led to severe smog levels and poor air quality [41, 64, 65], inflicting large economic losses due to damage to crops such as wheat. The heat wave period resulted from strong and extensive atmospheric blocking that persisted over the Euro-Russian region from late June to early August [40]. Over Turkey, 9 cities had breaking all time highest temperature records for August, 4 of which had daily maximum temperature over 40°C, exceedances over the long period average daily maximum reached more than 10°C in 4 cities. Other studies of the 2010 summer period [35] also remarked very high temperatures over Turkey.

The societal and environmental impact of the 2010 JJA heat wave episodes were very extensive as noted above. Usually unprecedented events result from very large anomalies. In this regard, the 500 hPa positive geopotential height anomaly is the highest compared to 2000 and 2007 cases, it is almost twice as previously noted cases, and it is located further east and its southern edge extends over the north-east of Turkey (Figure 5a). At the 850 hPa level; positive temperature anomaly is also very high (above 5.5°C) over the Russia, and around 4°C over Turkey (Figure 5b). As it might be expected, the highest positive SST anomalies (2.5-3.5°C) are located over the Black Sea and over Caspian Sea, and the Mediterranean SST anomalies are within the range of 0.5-1.5°C (Figure 5c). Negative soil wetness anomalies are located over Russia and over the north-west part of Turkey (Figure 5d).

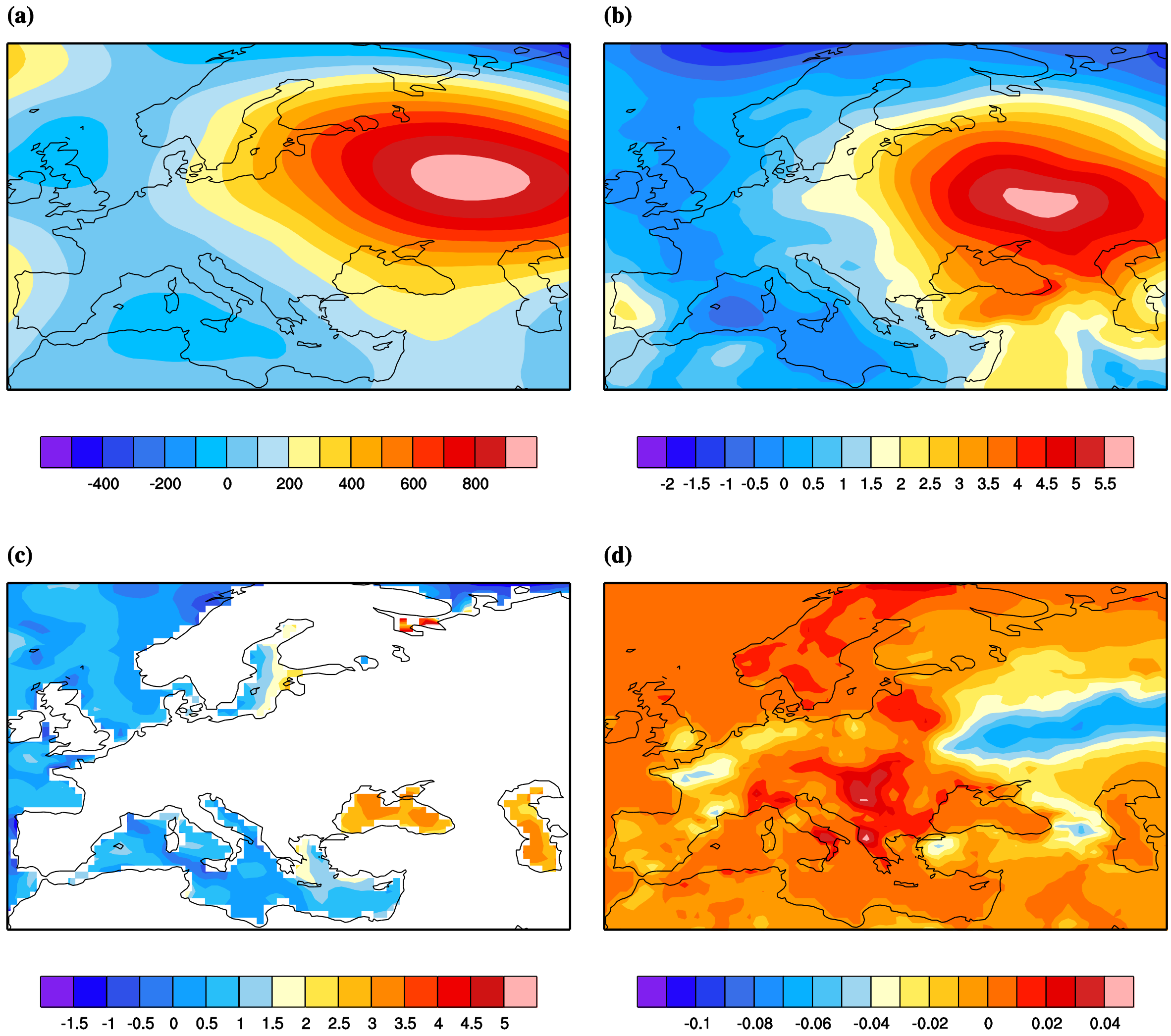

Figure 5. 2010 JJA anomalies for: a) 500hPa geopotential height (m^2/s^2); b) 850hPa temperature (°C); c) Sea surface temperature (°C); d) Soil wetness m (water equivalent).

The 2010 HIHWE occurred due to internal atmospheric dynamical processes that triggered and maintained a strong and long-lived blocking event. A persistent anticyclonic flow regime (an omega block) caused an exceptionally extensive and heat wave period that affected the Eastern Europe and Western Russia [18, 41]. The blocking lasted from late June to early August, and new records of daily maximum temperature were recorded in many places. The results of current study show that the duration of atmospheric blocking is the highest (more than 40 days) over Russia. The study also takes into account blocking at lower latitudes, and these blocking areas show 4-24 days of blocking (Figure 6a). Heat wave analyses of the 2010 JJA period highlight that the highest total heat wave days are 70-80 days over Russia (Figure 6b). Since Turkey is positioned between the two major blocking areas, the total heat wave distribution depends on closeness to the blocking areas; on the west, it is 50-60 days, in the midland, it is 40-50 days (Figure 6b). Number of heat waves is highest (6-7) over the central Europe, 4-6 over Russia and Turkey (Figure 6c). As for intensity of the 2010 heat wave period, it is above 10°C over Russia which is the highest compared to 2000 and 2007 cases, and over Turkey, it is 2-4°C (Figure 6d).

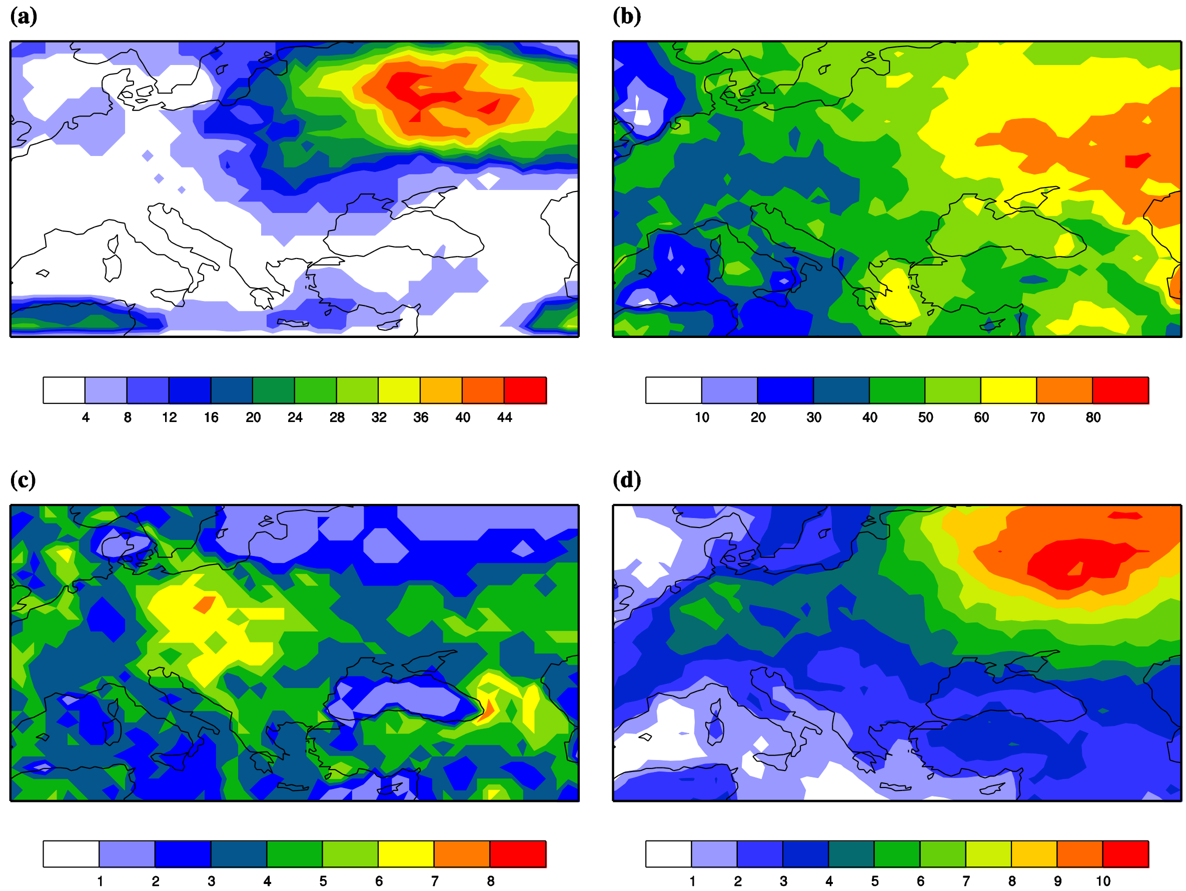

Figure 6. For the 2010 JJA period: a) Total atmospheric blocking days; b) Total heat wave days; c) Total number of heat waves; d) Total heat wave intensity (°C).

4. CONCLUDING REMARKS

This paper has provided a brief account of the anomalously hot JJA periods of 2000, 2007 and 2010 that have broken records in the Euro-Mediterranean region and Turkey. Several inferences can be drawn from the results: (i) the summer of 2000 caused many record breaking daily temperatures but in terms of heat wave duration it was the shortest compared to others; (ii) the 2007 JJA period caused very intense heat waves over the Balkans and Turkey; (iii) the 2010 is by large the most long lasting and intense heat wave period of 2000s; (iv) The record heat waves that affected many countries during the course of 2000, 2007 and 2010 summers have been considered as high impact weather conditions to come; (v) the results demonstrate that summer climate might experience a pronounced increase in year-to-year variability. Increase in variability might be able to explain the unusual heat waves, and would strongly affect the incidence of heat waves in the future. The results may also contribute to a better understanding of heat waves in context of climate variability.

The findings also have the following implications: (i) Large positive anomalies of 500 hPa geopotential height play a key role in maintaining prolonged heat wave events; (ii) Pronounced positive temperatures anomalies at the 850 hPa give a good indication about high air temperatures of heat wave periods; (iii) Anomalous sea surface temperature anomalies can serve as additional contributor on maintaining surface anticyclones and heat waves; (iv) Negative soil wetness anomalies shed light on dryness of the JJA period and also give hint on their role in escalating sensible heat flux which can increase air temperature; (v) Atmospheric blocking is important for maintaining heat wave duration and intensity since it blocks cooler weather events to move over the heat wave affected region, and also maintains dynamics effects of anticyclonic circulation; (vi) Using spatially and temporally varying dynamic daily temperature threshold serves conveniently for JJA period and over a large area that have very different climatic features in different regions.

The high impact heat wave events that affected the Euro-Mediterranean region and Turkey broke records across the area. Although these events were unprecedented from a historical point of view, they may become common place by the end of the century. Future climatic projection aspects have not been addressed explicitly in this research; a deeper investigation should be sought in coming studies.

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