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Heat wave changes in the eastern Mediterranean since 1960

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[1] A new data set of high-quality homogenized daily maximum and minimum summer air temperature series from 246 stations in the eastern Mediterranean region (including Albania, Bosnia-Herzegovina, Bulgaria, Croatia, Cyprus, Greece, Israel, Romania, Serbia, Slovenia, Turkey) is developed and used to quantify changes in heat wave number, length and intensity between 1960 and 2006. Daily temperature homogeneity analyses suggest that many instrumental measurements in the 1960s are warm-biased, correcting for these biases regionally averaged heat wave trends are up to 8% higher. We find significant changes across the western Balkans, southwestern and western Turkey, and along the southern Black Sea coastline. Since the 1960s, the mean heat wave intensity, heat wave length and heat wave number across the eastern Mediterranean region have increased by a factor of 7.6 ± 1.3, 7.5 ± 1.3 and 6.2 ± 1.1, respectively. These findings suggest that the heat wave increase in this region is higher than previously reported. **Citation:** Kuglitsch, F. G., A. Toreti, E. Xoplaki, P. M. Della-Marta, C. S. Zerefos, M. Türkeş, and J. Luterbacher (2010), Heat wave changes in the eastern Mediterranean since 1960, *Geophys. Res. Lett.*, *37*, L04802, doi:10.1029/2009GL041841.

1. Introduction

[2] Heat waves have discernible impacts including rise in mortality and morbidity [e.g., *Knowlton et al.*, 2009], an increased strain on infrastructure (power generation, water supply, transportation) [e.g., *Smoyer-Tomic et al.*, 2003] and consequent impacts on society. Further impacts may include effects on agricultural resources, the retail industry, ecosystem services and tourism [*Ferris et al.*, 1998; *Ciais et al.*, 2005]. Large financial losses due to crop shortfall, forest fires or increased mortality highlight the strong impact potential of heat waves on our environment, society and economy [e.g., *Kovats and Koppe*, 2005; *Poumadère et al.*, 2005; *Intergovernmental Panel on Climate Change*, 2007]. In the 21st century the Mediterranean area is expected to be one of the prominent and vulnerable climate change "hot spots" [*Giorgi*, 2006; *Diffenbaugh et al.*, 2007] that will experience a large number of extremely hot temperature events, an increase of summer heat wave frequency and duration [e.g., *Türkeş et al.*, 2002; *Founda et al.*, 2004; *Kostopoulou and Jones*, 2005; *Della-Marta et al.*, 2007] and increasing summer temperature variability [*Xoplaki et al.*, 2003; *Jones et al.*, 2008]. These studies focus either on changes in mean monthly maximum temperatures [*Türkeş et al.*, 2002], dirunal temperature ranges [*Türkeş and Sümer*, 2004], temperature percentiles [*Diffenbaugh et al.*, 2007], count series above absolute or percentile based thresholds [*Founda et al.*, 2004; *Kostopoulou and Jones*, 2005], and do not specifically focus on changes in heat wave number, length and intensity. Moreover, previous studies often lack a rigorous application of inhomogeneity detection and correction techniques of station data. In order to make our heat wave analyses applicable to the assessment of climate impacts (e.g., human health and the economy) we use (1) a combination of daily maximum (TX) and minimum air temperatures (TN) and (2) define temperature thresholds to estimate the beginning and the end of heat waves [*Karl and Knight*, 1997; *Hémon and Jougla*, 2003; *Grize et al.*, 2005; *Gosling et al.*, 2008]. The importance of considering TN was highlighted by *Karl and Knight* [1997] who concluded that three or more consecutive nights with no relief from very warm nighttime (minimum) temperatures may be most important for human health impacts. However, they focused on absolute values i.e. the "annual worst heat" event and did not study periods when temperature exceeds long-term and location-specific temperature percentiles which were identified to have crucial impacts [*Meehl and Tebaldi*, 2004; *Diáz et al.*, 2006; *Della-Marta et al.*, 2007; *Gershunov et al.*, 2009]. This study uses a combination of the heat wave definitions (see Chapter 2 for details) and consequently focuses on heat events when both TX and TN exceed location specific temperature percentiles for three or more days. This allows (1) a better and more reliable comparison of heat waves, and (2) a better identification of the spatial extent of long-term heat wave trends. The detection and analyses of heat waves require high quality and homogenized instrumental daily data [*Kuglitsch et al.*, 2009]. Here we use for the first time quality controlled and homogenized TX and TN series of 246 stations across the eastern Mediterranean covering the period 1960–2006. Temperature adjustments due to data homogenization are usually smaller than 1°C but are crucial for any reliable heat

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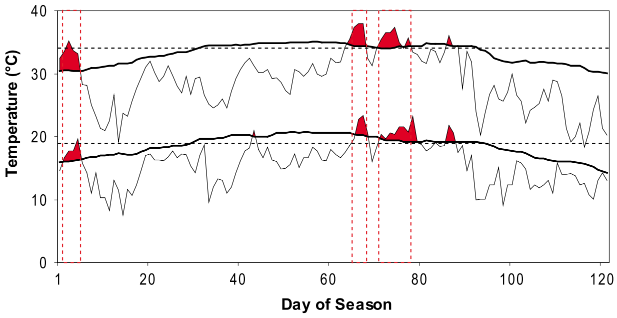

Figure 1. Schematic overview of heat wave detection. The thick black lines (thin dashed black lines) indicate the daily (seasonal) 95th percentile and daily values of 2006 (thin black lines) for TX and TN for the station of Ankara, Turkey. Red areas characterize hot days and nights. Red dotted frames indicate the three 2006 heat waves.

wave study [cf. *Kuglitsch et al.*, 2009] (see auxiliary material).[1] The analyses of trends of shorter and smaller scale events give results that differ significantly depending on the use of homogenized or raw data [*Della-Marta et al.*, 2007; *Kuglitsch et al.*, 2009]. The present study investigates the evolution of summer heat waves in the eastern Mediterranean since 1960s focusing on the number, length and intensity of the heat waves based on new high-quality and homogenized TX and TN datasets.

2. Data and Methods

[3] Homogenized daily extended summertime (JJAS) TX and TN series recorded at 246 stations in the eastern Mediterranean region are used. Most of the series cover the period 1960 to 2006. The data set contains data from the European Climate Assessment and Dataset (ECA&D) [*Klein Tank et al.*, 2002], the Turkish State Meteorological Service and the Hellenic National Meteorological Service. The most complete time period is identified between 1969 and 1998 and used as the reference period in the data homogenization and the heat wave analyses. The full data set is quality controlled (see *Kuglitsch et al.* [2009] for details) and homogenized using highly correlated neighbouring series (see Figure S1 for the stations used, the length of the time series and the detected break points). Based on the new homogenized TX and TN data sets, summer heat wave numbers, lengths and intensities are calculated. As there is no universal definition to quantify heat waves based on both TX and TN, we developed a new characterization (based on work by *Meehl and Tebaldi* [2004] and *Della-Marta et al.* [2007]) considering only periods of three or more consecutive hot days and nights. A hot day/night is defined as a day/night when the daily TX/TN exceeds the long-term (1969–1998) daily 95th percentile within the June–September season (122 days). For each June–September day, a 95th percentile is calculated from a sample of 15 days (seven days on either side of the respective day [*Della-Marta et al.*, 2007]) using data over the 1969 to 1998 period. A heat wave (HW) is defined as a period of three or more consecutive hot days and nights not interrupted by more than one non-hot day or night. Figure 1 provides a schematic overview of heat waves detected for the station of Ankara (Turkey) for the summer of 2006. For estimating the heat wave intensity we compute the local TX exceedances (i.e. degree days in °C). Since TX and TN are highly correlated we replace TN with TN conditional (TNc) on TX (TNc = TN|TX) and sum the TX exceedances with TNc exceedances, obtaining the local summertime heat wave intensity index, $HWI_{95} = \sum_i \max(TX_i - TX_{95,i}, 0) + \sum_i \max(TNc_i - TNc_{95,i}, 0)$, for i ranging from June 1 to September 30, resulting in an annually resolved time series at each station. The new variable TNc is derived from estimating the relationship between TN and TX, i.e. $TN = f(TX) + \varepsilon$. A penalized spline smoothing with a restricted maximum likelihood parameter estimate [*Krivobokova and Kauermann*, 2007] is applied to each series. Moreover the maximum heat wave intensity index ($HWMAXI_{95}$, in °C), of the longest heat wave per summer is calculated. We also focus on changes in heat wave number (HWN_{95}) characterizing the number of summer heat waves per year, and the heat wave length (HWL_{95}, in days) of all summer heat waves, and maximum heat wave length ($HWMAXL_{95}$, in days) per summer season. For comparison purposes, the 95th percentile for TX (*TX95perc*) and TN (*TN95perc*) are calculated for the entire summer season as shown in Figure 1 (thin black dashed line). Linear trends of *TX95perc*, *TN95perc*, HWN_{95}, HWL_{95} and HWI_{95} and their significance are estimated using the ordinary least square technique (OLS) and the Mann-Kendall rank correlation test for the period 1960 to 2006.

3. Results and Discussion

[4] In the eastern Mediterranean region 61% and 74% of the TX and TN time series are affected by artificial break points caused by site displacements, new instrumentation or land-use changes. This underlines the importance of data homogenization for analyzing extreme events (cf. Figure S1). Results from the daily temperature homogeneity analysis suggest that many instrumental measurements in the 1960s are warm-biased and agree with findings by *Della-Marta et al.* [2007] and *Kuglitsch et al.* [2009] for other European and Mediterranean regions. The mean correction (°C ± standard error) of these biases results in an overall reduction in TX95perc (−0.05°C ± 0.03°C), TN95perc (−0.07°C ± 0.02°C), HWN_{95} (−0.2 ± 0.01), HWL_{95} (−0.5 days ± 0.02 days) and HWI_{95} (−2.0°C ± 0.11°C) in the 1960s compared to the raw data. The corrections made to the series in this period have a substantial influence on the overall heat wave trends. Figure 2 summarizes the impact of data homogenization on long-term HWN_{95} trends and indicates that 24% of the series show a significant change in trend when using homogenized data. During the 1960s many station screens were changed in terms of type, size and ventilation, the latter making measured temperatures closer to the ambient temperature [e.g., *Aguilar et al.*, 2003]. Since the 1960s the temperature of hot summer days and nights (expressed as the seasonal TX and TN 95th percentile) and the number, length and intensity of heat waves have increased significantly. Year-to-year variability of HWN_{95}, HWL_{95} and HWI_{95} are highly correlated with each other ($r^2 > 0.97$). However, since 2000 the increase of HWI_{95} proceeds stronger than those of HWL_{95} and HWN_{95} (compare Figure S2). The reduced increase of HWL_{95} and HWN_{95} can be explained by longer

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[1] Auxillary materials are available in the HTML. doi:10.1029/2009GL041841.

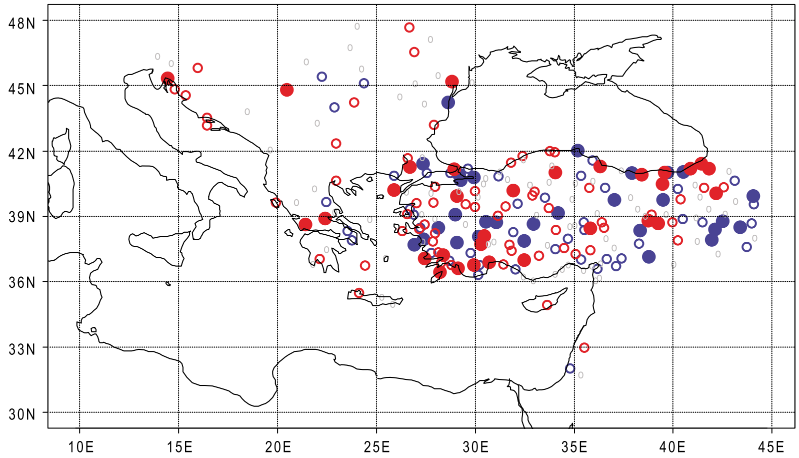

Figure 2. Differences in linear trends of HWN_{95} (homogenized data minus non-homogenized data) from 1960 to 2006 using the OLS method. Red- (blue-) colored dots indicate a significant increase (decrease) of HWN_{95} trends at the 5% significance level (Mann-Kendall test) after the data homogenization. Red- (blue-) colored open circles characterize non-significant positive (negative) trends. Grey colored open circles indicate stations with no change in trend.

and merging heat wave events. Moreover, TX95perc has increased stronger than TN95perc since 1990 (not shown) [*Moberg et al.*, 2006]. This trend is expected to continue in the SRES A2 emission scenario until the end of the 21st century [*Diffenbaugh et al.*, 2007]. Regional climate model (RCM) projections [e.g., *Meehl and Tebaldi*, 2004; *Diffenbaugh et al.*, 2007; *Founda and Giannakopoulos*, 2009; *Zanis et al.*, 2009] agree on the intensification, higher frequency and longer duration of heat waves by the end of the 21st century for Mediterranean regions. However, their assumptions are only based on TX95perc and TN95perc, two parameters which in our case explain heat wave number, length and intensity by only 63% and 60%. Therefore a projection of future heat waves using only these parameters might not give a full description of changes in number, length and intensity.

[5] Linear trends (°C/decade ± mean standard error of the trend of the mean TX95perc; OLS method) of the seasonal TX and TN 95th percentile (TX95perc, TN95perc) show a significant (Mann-Kendall test) increase for most of the series analyzed (Figure S3). The mean estimated trend in TX95perc (+0.38 ± 0.04°C/decade) over all stations is higher than in TN95perc (+0.30 ± 0.02°C/decade). These trends agree with findings for other European regions and the western Mediterranean [*Moberg et al.*, 2006]. While the TX95perc increase is highest in continental areas, the maximum increase of TN95perc is found generally in coastal areas. Only along the Turkish Mediterranean coastline and in parts of southeastern Anatolia TN95perc increased more than TX95perc. Overall, the strongest increase (>+0.63°C decade) of TX95perc and TN95perc are found across the western Balkans, southwestern and western Turkey, and along the eastern parts of the Turkish Black Sea coastline (Figure S3, dark red dots). The smallest changes in both, TX95perc and TN95perc are prevalent around the western Aegean, eastern and southeastern Anatolia. A significant decrease in TX95perc is found at Anamur (−0.27 ± 0.05°C/decade) and Finike (−0.20 ± 0.04°C/decade) along the south coast of Turkey. A significant decrease (−0.19 ± 0.04 to −0.58 ± 0.14°C/decade) in TN95perc is detected in Kjustendil (Bulgaria), Tanagra, Tripoli (Greece), Egirdir, Erzincan, Sariz and Urgup (Turkey). These stations show 0.6–1.6°C higher temperatures in the 1960s compared to the last 10 years and are either located in higher altitudes (900–1,500 amsl) or very close to sea level. Significant differences in temperature and heat wave trends in terms of altitude are not found. It is notable that stations showing negative temperature trends are highly exposed and strongly influenced by topography driven local climate effects. This might increase the uncertainty of the homogenization procedure and cause underestimated temperature adjustments in the 1960s [*Kuglitsch et al.*, 2009]. Between 1960 and 2006 a significant increase in regional mean HWI_{95} (+1.33 ± 0.06°C/decade), HWN_{95} (+0.17 ± 0.01/decade) and HWL_{95} (+0.85 ± 0.02 days/decade) is found for 56%, 47% and 37% of all stations, respectively (Figure 3). A significant increase in $HWMAXI_{95}$ (+1.42 ± 0.03°C/decade) and $HWMAXL_{95}$ (+0.70 ± 0.01 days/decade) is found for 46% and 19% of all stations, respectively. We identify "hot spots" of heat wave change across the western Balkans, southwestern and western Turkey, and along the Turkish Black Sea coastline. There, trends of HWI_{95}, HWN_{95} and HWL_{95} exceed +2.0°C/decade, +0.4/decade and +2.0 days/decade, respectively. Stations that show non-significant heat wave changes cluster in continental parts of the Balkan Peninsula, Greece, parts of western Turkey, eastern Anatolia and higher altitudes. Areas with strongest heat wave trends generally agree with areas affected by largest TX95perc and TN95perc trends, however many stations across the Balkan Peninsula and eastern Anatolia show a significant increase of daytime and nighttime temperatures but do not show significant changes in heat wave trends (Figures S3 and 3). The eastern Mediterranean has experienced an increase of HWI_{95}, HWL_{95} and HWN_{95} by a factor 7.6 ± 1.3, 7.5 ± 1.3 and 6.2 ± 1.1, respectively, by comparing the 1960s with the period 1997–2006 (compare Figure S1). $HWMAXI_{95}$ and $HWMAXL_{95}$ have increased by factor 5.6 ± 1.1 and 5.4 ± 1.0. We are aware that heat wave trends can be biased by one extreme event and OLS method is not most suitable to model variations of heat waves over time since there is little variability in the period 1960–1985. However, the linear trends give an indication of the heat wave change. As we use

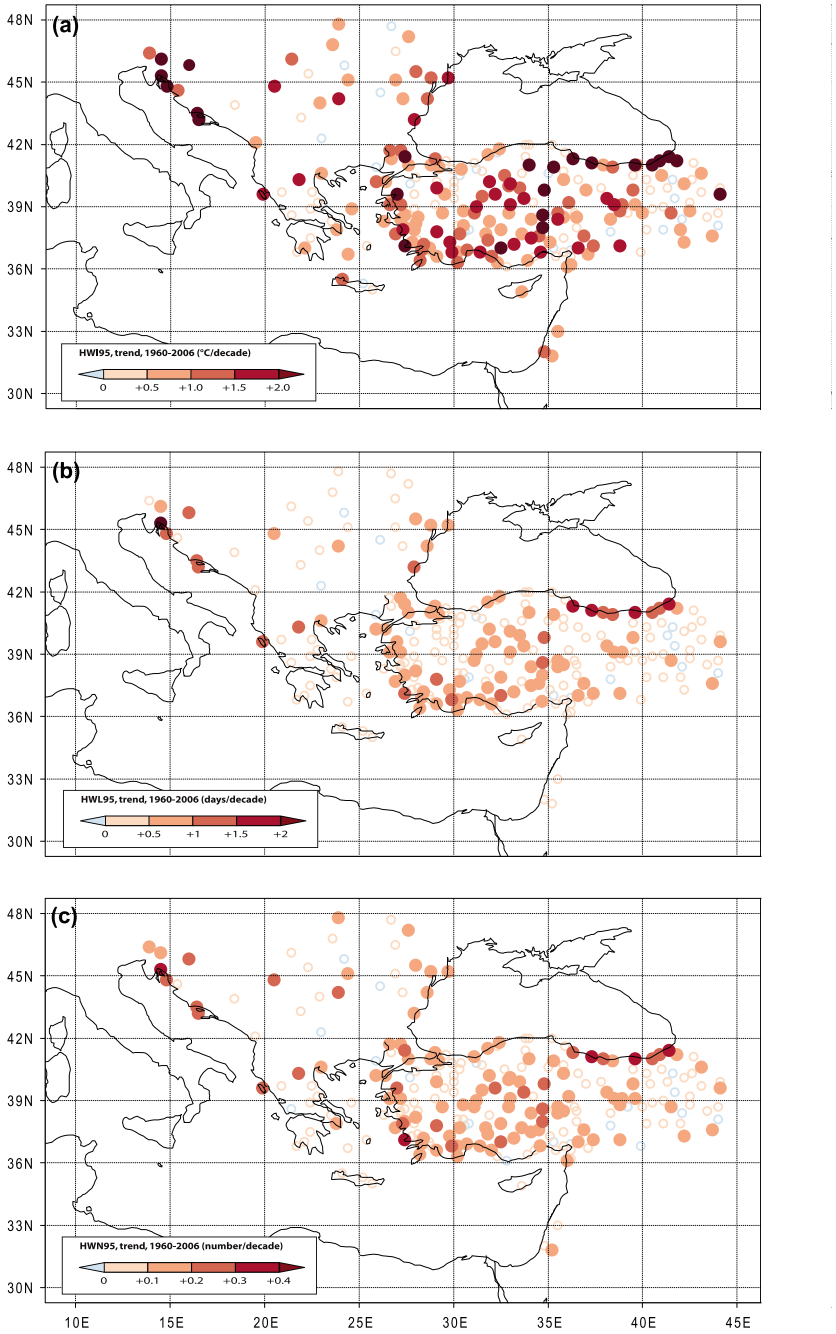

Figure 3. Linear trends of (a) HWI_{95} (°C/decade), (b) HWL_{95} (days/decade) and (c) HWN_{95} (number/decade) from 1960 to 2006 using the OLS method. Red-(blue-) colored dots indicate significant positive (negative) linear trends at the 5% significance level (Mann-Kendall test). Open circles characterize non-significant trends.

a combined heat wave definition based on TX and TN a comparison with other studies is not possible.

4. Conclusions and Outlook

[6] TX and TN series of 246 stations across the eastern Mediterranean region have been homogenized and used for estimating changes in heat wave number, length and intensity. After data homogenization, the increase of temperature and heat wave indices is significantly enhanced due to overall negative temperature adjustments in the 1960s. Averaged over the whole area, hot summer daytime (TX95perc) and nighttime temperature (TN95perc) have increased by +0.38 ± 0.04°C/decade and +0.30 ± 0.02°C/decade, respectively since the 1960s. The mean heat wave intensity (HWI_{95}), heat wave length (HWL_{95}) and heat wave number (HWN_{95}) across the whole eastern Mediterranean region have increased by a factor of 7.6 ± 1.3, 7.5 ± 1.3 and 6.2 ± 1.1, respectively. “Hot spots” of heat wave changes are identified along the eastern parts of the Turkish Black Sea coastline, in western, southwestern and central Turkey, and across the western Balkans. The increase in HWI_{95} and

HWL_{95} is much more pronounced than changes in the longest heat wave intensity (HWMAXI_{95}) and length (HWMAXL_{95}). This implies that the eastern Mediterranean is more affected by an accumulation of short (<6 days) but more intense heat wave events compared to past decades. At many stations the longest heat wave event per year has not lengthened and intensified, yet, however a trend of merging i.e. longer lasting and more intense events have been detected since 2000. Further investigations will focus on single heat wave events, their relation to large scale atmospheric circulation, land-use-atmosphere interactions, and impacts on human health, livestock, ecosystem vitality, agricultural production, water supply, power generation and the comparison with RCMs at daily time scales.

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