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Heat Waves in Finland: Present and Projected Summertime Extreme Temperatures and Their Associated Circulation Patterns

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Abstract

The number and intensity of individual hot days affecting Finland in the current and future climate is investigated together with the circulation patterns associated with the hot days. In addition, the number, length, and intensity of heat waves lasting at least 3 days is also considered. ERA-Interim reanalysis data and both direct model output and bias-corrected data for historical and future climate (RCP4.5 scenario) simulations from 17 global climate models are analysed. Three intensities of heat waves and hot days are defined based on daily mean temperature thresholds of 20, 24 and 28°C. The percentage of summertime days which exceed these temperature thresholds is shown to increase in the future. In ERA-Interim, 24%

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of summertime days in southern Finland exceed the lowest temperature threshold while none exceed the highest temperature threshold. Under the RCP4.5 scenario these values increase to 47% and 1% respectively. Larger relative changes occur in northern Finland. Heat waves are also longer in the RCP4.5 simulations than in the historical simulations. In southern Finland, the mean length of a heat wave where the 20°C daily mean temperature is exceeded is 6.1 days in the historical simulations but increases to 9.4 days in the RCP4.5 simulations. The hot days in both northern and southern Finland are associated with a statistically significant positive pressure anomaly over Finland and to the east to Finland and a statistically significant negative pressure anomaly over Russia between 90 and 120°E. These pressure anomalies were evident for all intensities of hot days in the current climate and the future climate. The magnitude of the pressure anomalies increases as the daily mean temperature threshold increases. However, for hot days which exceed the same daily mean temperature threshold, the pressure anomalies are weaker in the RCP4.5 simulations than in the historical or ERA-Interim data.

Keywords: circulation patterns, climate change, CMIP5, Finland, heat waves

1 Introduction

Heat waves do not have a uniform definition (Perkins and Alexander, 2013) but, in general, they can be considered as a prolonged period of abnormally hot weather. Heat waves have negative impacts on many aspects of society, the economy and the environment. For example, anomalously high temperatures can effect vegetation growth (Jolly *et al.*, 2005), which in turn can affect the carbon cycle (Ciais *et al.*, 2005). However, the most commonly discussed impact of heat waves is the adverse effects they have on human health.

In the United States, excessive heat is responsible for more weather-related deaths than

any other weather phenomenon such as hurricanes or tornadoes (Borden and Cutter, 2008). Recently in Europe, two major heat waves have occurred: the heat wave of 2003 which affected primarily central and western Europe and the 2010 Russian heat wave. The 2003 heat wave in central and western Europe caused about 70,000 extra deaths (Robine *et al.*, 2008) and consequently this extreme event boosted development of heat-health warning systems. The 2010 Russian heat wave, which also affected eastern Europe and Nordic countries such as Finland, caused approximately 55,000 deaths in Russia (Barriopedro *et al.*, 2011).

Despite its high latitude, ranging from 60 to 70°N, Finland can experience high temperatures during summer due to its relatively continental climate. In almost all areas, temperatures can exceed 30°C, with the highest ever recorded temperature in Finland being 37.2°C in Joensuu in Eastern Finland in July 2010. Both recent European heat waves (2003 and 2010) had impacts in Finland. In summer 2003, 200 non-accidental extra deaths were reported in Finland and in 2010 more than 300 heat-related deaths occurred (Kollanus and Lanki, 2013). According to Kollanus and Lanki (2013), mortality increased significantly among elderly people aged 75 and older due to various causes of death. Sensitivity and adaptive capacity to heat stress vary according to many socio-economic factors such as age, pre-existing heat-sensitive illnesses, especially cardiovascular and respiratory diseases, type of housing and health care. The most severe heat wave that has been studied in Finland took place in 1972 and caused about 800 extra deaths. Since then, remarkable heat waves with increased mortality also occurred in 1973, 1978, 1988, 1995 and 1997 (Näyhä, 2005). Thus, it is important to understand the meteorological characteristics and dynamics of heat waves which affect Finland in our current climate so that adequate forecasts and warnings can be issued.

Many previous studies have attempted to understand the atmospheric circulation pat-

terns which result in heat waves. Meehl and Tebaldi (2004) showed that both the 2003 European heat wave and the 1995 Chicago heat wave were associated with semi-stationary positive 500-hPa geopotential height anomalies. Taking a composite approach, Tomczyk and Bednorz (2016) combined station observations with NCEP/NCAR reanalysis data and found that central European heat waves are associated with positive sea level pressure and 500-hPa height anomalies located over the Baltic Sea. Della-Marta *et al.* (2007b) identified two circulation patterns that are important for the formation of European heat waves. The first pattern had anomalously high sea level pressure centered over Scandinavia and low sea level pressure south of Greenland, the Mediterranean and North Africa, resulting in heat waves in northern and central western Europe. The second pattern, which resulted in heat waves over the Iberian Peninsula, shows a distinct wave pattern with anomalously low sea level pressure in the central North Atlantic, high sea level pressure over central western Europe and low sea level pressure over northeast Europe. All of these studies demonstrate that heat waves in the current climate develop when high surface pressure and an upper level ridge is present. However, none of these earlier studies have focused on circulation patterns that lead to heat waves specifically in Finland.

It is well known that the mean near surface temperature is increasing and that warm extremes are becoming more common (Hartmann *et al.*, 2013). Specific to heat waves, many studies have shown that heat waves in many parts of the world have already started lengthening and intensifying. Della-Marta *et al.* (2007a) analyzed observations from 54 stations across Europe and concluded that over the period 1880 - 2005 the length of summer heat waves had doubled and that the number of hot days (defined in their study as a day where the daily maximum temperature exceeds its long-term 95th percentile) had almost tripled. Other studies have used climate model simulations to examine the occurrence and characteristics of heat waves in the future. Meehl and Tebaldi (2004) and

Fischer and Schär (2010) concluded that Europe can expect more, longer and stronger heat waves in the future, but neither of these studies focused in any detail on Finland. Considering the impact of heat waves on society and the environment, it is vital that the frequency of occurrence, intensity and typical duration of heat waves in the future can be estimated, to enable adaptation measures to be implemented.

There are three objectives to this study. Firstly, the atmospheric circulation patterns that lead to summertime extreme temperatures in northern and southern Finland in the current climate are determined by examining reanalysis data. Secondly, the ability of the current generation of climate models (i.e. those participating in the Coupled Model Intercomparison Project 5 (CMIP5)) to correctly simulate the frequency of hot days and the associated circulation patterns is ascertained by analyzing historical simulations. Finally, the projected frequency of occurrence and characteristics of hot days and heat waves in Finland in the future are quantified using CMIP5 data.

The structure of this paper is as follows. In Section 2, the reanalysis and climate model data sets are described along with the definitions of hot days and heat waves used in this study and an overview of data analysis methods. The characteristics and circulation patterns associated with hot days in the current and future climates are discussed in sections 3 and 4 respectively. Projected future changes to the number and length of heat waves are discussed in section 5. Conclusions are presented in Section 6.

2 Methods

2.1 Data Sets

In this study, both reanalysis data and model simulation output from the Coupled Model Intercomparison Project 5 (CMIP5, Taylor *et al.* (2012)) are analyzed. Specifically, 36

years (1979 – 2014) of ERA-Interim data (Dee *et al.*, 2011), which has a spatial resolution
 of approximately 80 km (T255 spectral resolution) and a temporal resolution of 6 hours
 are analyzed. From CMIP5 simulations, historical runs are used for 1900-2005 (106 years)
 and RCP4.5 (Representative Concentration Pathway 4.5) runs are used for 2006-2100 (95
 years). The forcing in the CMIP5 historical simulations is based on observational data
 for changes in atmospheric greenhouse gas concentrations, anthropogenic and volcanic
 aerosols, land use and solar variability (Taylor *et al.*, 2012). RCP4.5 is the second lowest
 of the four Representative Concentration Pathways Scenarios documented by van Vuuren
et al. (2011). Under this scenario, the global mean anthropogenic radiative forcing stabi-
 lizes at $+4.5 \text{ W m}^{-2}$ relative to pre-industrial values in the year 2100, following a decline
 in carbon dioxide emissions beginning around the year 2050. The CMIP5 multi-model
 projection indicates that the global mean temperature is likely to increase by 1.1°C to
 2.6°C from 1986-2005 to 2081-2100 under RCP4.5 (Stocker *et al.*, 2013). RCP4.5 is one
 of the more realistic scenarios considering the recent Paris Agreement, which aspires to
 cut global greenhouse gas emissions to zero by 2050 and keep global temperature increase
 to under 2°C (UNFCCC (2015)).

RCP4.5 output from seventeen models, which have varying spatial resolutions (see Table
 1), is analyzed. Output from all models is re-gridded to a uniform 2.5° by 2.5° latitude-
 longitude grid to allow the multi-model ensemble mean to be calculated. In both ERA-
 Interim and CMIP5, only data from the summer (June, July, August - JJA) is considered.
 From ERA-Interim, daily mean values of mean sea level pressure (MSLP) and 2-meter
 temperature were calculated from the 6-hourly output. The variables extracted from the
 CMIP5 archives were daily MSLP and near surface air temperature, which is defined to
 be the temperature at 2 meters above surface.

2.2 Bias Correction

Climate model simulations contain systematic errors relative to the observed climate, often referred to as biases (Flato *et al.*, 2013). Even in the ideal case that the biases in basic variables such as temperature remain constant with time, they will affect both the absolute values and the changes in statistics that depend nonlinearly on the basic variables, such as the number of hot days. Therefore, a large variety of bias correction techniques have been developed for refining climate scenarios (Maraun, 2016). In this study as well, analysis of the direct model output is complemented by analysis of bias-corrected 2-m temperature data.

We used method M7 of Räisänen and Rätty (2013), which corrects the biases in the mean and standard deviation of daily mean temperature, but makes no attempt to correct for any biases in the shape of the distribution. First, the mean and standard deviation of the daily mean temperature from both ERA-Interim and the CMIP5 model simulations were calculated, separately for each of June, July and August in the years 1979-2014. From this, we calculated the difference (D) in the mean temperatures ($D = \text{reanalysis} - \text{model}$) and the ratio of the standard deviations ($R = \text{reanalysis} / \text{model}$) for each model. The simulated (historical and RCP4.5) daily temperatures were then corrected treating each month and decade separately, to ensure that long-term temperature trends are not altered by the correction. Denoting the mean value of the model-simulated temperature in the given decade and month as M , the bias-corrected values are

$$T_{corr} = M + D + R * (T - M) \quad (1)$$

where T is the original daily temperature and D and R are the correction constants defined above.

This correction does not eliminate all differences in hot day statistics between ERA-Interim and the historical simulations because the shape of the temperature distributions and the autocorrelation of the time series were not corrected. Nevertheless, the agreement with ERA-Interim is generally improved and the differences between the individual CMIP5 models are substantially reduced. The bias corrections are only applied for refining the projections of future hot days and heat wave statistics. Our analysis on the relationship between hot days and atmospheric circulation is based on the original model data.

2.3 Definitions for hot days and heat waves

In this study we consider both hot days and heat waves. A hot day is one individual day exceeding a temperature threshold whereas a heat wave is 3 or more consecutive days exceeding a temperature threshold.

Heat stress depends on several meteorological parameters – temperature, humidity, wind speed and solar radiation – but in heat warning systems simpler criteria are often used (McGregor *et al.*, 2015). As the focus of this study is on extreme warmth in Finland, we base our definition of hot days on the definition used by the Finnish Meteorological Institute (FMI) to issue heat warnings. FMI started to issue heat warnings in 2011, using three risk levels according to the severity of the heat stress and impact on human health.

The FMI warning thresholds are based on daily maximum and minimum temperatures, or equivalent daily mean temperatures. When communicating to public only the daily maximum temperature criteria of the three risk levels are used: 27, 30, 35°C, corresponding to hot, very hot and extremely hot conditions respectively. In this study, however, we follow Ruosteenoja *et al.* (2013) by using the approximately equivalent daily mean temperature criteria of 20, 24, and 28°C, because in climate models the daily mean tem-

perature tends to be better simulated than daily maximum and minimum temperatures.

In the Finnish population, mortality begins to increase rapidly once the daily mean temperature exceeds 14°C (Näyhä, 2005). Daily maximum temperature relates to heat stress experienced during the day. High minimum temperature is related to high humidity and indicates there is a limited possibility to recover from the heat stress during the night. The strength of daily mean temperature criteria is that they can describe both daytime heat stress and ability to recover during night. The consequences of heat stress become more severe the longer the heat wave lasts (Anderson and Bell, 2011). Therefore, in addition to studying individual hot days, we also studied the changes in characteristics of heat waves lasting three or more consecutive days. We define three intensities of heat waves using the same daily mean temperature thresholds (20, 24 and 28°C) that were used to define hot days.

2.4 Composites

MSLP composites are created for the first two hot day thresholds (a daily mean temperature exceeding 20 and 24°C), separately for hot days that affect southern and northern Finland. Thus, in total four MSLP composites are created. A MSLP composite is not created for the 28°C threshold as this highest threshold was never exceeded in ERA-Interim. In this study, southern Finland is defined as the geographic area within 21.5-30.0°E, 60.0-65.0°N and northern Finland the area bounded by 24.0-30.0°E, 65.5-70.0°N (red boxed areas in Figure 1a). Southern and northern Finland are considered separately as these two regions experience a clear difference in the frequency of hot days. For ERA Interim's resolution (~80 km), northern Finland consists of a 7x10 grid (70 grid points) and southern Finland of a 8x13 grid (104 grid points). Individual days where the daily mean temperature in at least one grid point in the respective geographic area (i.e. southern or northern Finland) exceeds the temperature threshold (either 20 or 24°C) are

identified to be included in the MSLP composite. The MSLP anomaly associated with these hot days is then calculated by subtracting the mean MSLP as calculated over all JJA days from the hot day composite MSLP.

The same basic procedure is applied to the CMIP5 model output. Individual days exceeding the temperature thresholds are identified using data from each model’s own native grid (see Table 1 for the resolution of the different models). However, the MSLP composites were created using CMIP5 data re-gridded to the 2.5° by 2.5° latitude-longitude grid. For the CMIP5 regridded data, northern Finland consists of a 2×3 grid (6 grid points) and southern Finland of a 3×4 grid (12 grid points). First, a MSLP composite anomaly was created for each individual model and then an ensemble mean was taken from the 17 individual model composites.

2.5 Statistical testing

The statistical significance of the MSLP anomalies in the composites described above is determined using a block-bootstrapping method with one-year block length. For clarity, the ERA Interim process has been broken down.

1. For each year from 1979–2014, days exceeding the temperature thresholds in the north and south are identified from the 2-m temperature field if any grid points in the respective geographic areas of study exceed the 20°C or 24°C threshold. The two thresholds are done separately. This results in an ordered list of Julian days for each year which exceed either threshold.
2. The entire 1979–2014 surface pressure data are randomly sampled by year. The result is a scrambled list of years from 1979–2014. We do this for 1000 iterations.
3. For each of the 1000 scrambled lists of years, a composite of MSLP anomalies is generated using the ordered list of temperature-threshold-exceeding Julian days for

each year from 1979–2014.

4. The anomalies in the original, actual pressure composites are identified as significant if they are either more negative than the 5th percentile or more positive than the 95th percentile of the 1000 random realizations.

5. A separate mask for significant positive and negative pressure anomalies is created for southern Finland at the 20°C and 24°C threshold and likewise for northern Finland.

For the CMIP5 ensemble simulations, the aforementioned process was repeated for each individual model for both the historical and RCP4.5 data sets. If at least 9 of the 17 models in the ensemble exhibited significance at a particular grid (over 50% of the ensemble), the pressure anomaly in that grid was considered significant for the ensemble.

3 Current Climate

3.1 ERA Interim 1979–2014

The frequency of summer (JJA) days exceeding the first two FMI hot day temperature thresholds (daily mean temperature of 20°C and 24°C) was examined with ERA Interim data from 1979–2014 (Figure 1). During the period 1979–2014, the 20°C and 24°C thresholds are exceeded with maximum frequencies of 15% and 1% respectively. These values are equivalent to 14 and 0.9 days per JJA season exceeding the 20°C and 24°C daily mean temperature threshold respectively. These maximum values occur in south-eastern Finland near the Finnish-Russian border whereas the lowest frequencies occur in northern Finland north of 65°N. The spatial pattern evident in Figure 1 reflects the distribution of summertime average temperatures in Finland which are the warmest in southern Finland and the coolest north of 65°N, and in particular in north-west Finland.

In the ERA-interim data set, daily mean temperatures never exceeded the 24°C threshold in north-west Finland (Figure 1b). The third temperature threshold (daily mean temperature of 28°C) was never exceeded in ERA-Interim during the period 1979-2014 anywhere in Finland and is thus not included.

All composites of the MSLP anomaly during hot weather days from ERA Interim express statistically significant positive pressure anomalies over Finland and to the east of Finland with a maximum magnitude of 5 hPa (Figure 2). The anomalous high pressure centered east of Finland in all of the composites results in anomalous south-easterly winds over Finland and thus advection of warm air towards Finland. All composites also have a statistically significant positive pressure anomaly over the Atlantic Ocean which is weaker than the anomaly east of Finland. Climatologically, the Azores high is located at 30°N, 40°W in July (Davis *et al.*, 1997). Thus, the positive MSLP anomaly in the Atlantic is north and west of the climatological Azores high suggesting that when hot days occur in Finland, the Azores high is displaced west and north. All of the MSLP anomaly composites have negative MSLP anomalies over a large area of Russia between 90°E and 120°E yet not all of these are statistically significant. In the 20°C composites (Figures 2a,c) statistically significant negative pressure anomalies with magnitudes of 1-2 hPa are present between 90°E and 120°E indicating that when Finland experiences warm weather, anomalously low pressure occurs downstream. This negative MSLP anomaly is approximately 60° longitude downstream from the positive MSLP east of Finland which corresponds well with the length-scale of a Rossby wave.

Comparing the 20°C MSLP composites (Figures 2a,c) to the 24°C MSLP composites (Figures 2b,d), it is evident that the magnitude of the MSLP anomaly increases when the temperature threshold increases. Thus, the most intense and harmful hot days occur when stronger circulation anomalies are present. When the MSLP composites for

northern (Figures 2c,d) and southern Finland (Figures 2a,b) hot days are compared, differences are evident. Firstly, the positive pressure anomaly centered east of Finland is shifted towards the pole approximately 5° and eastward 10° in the northern Finland composite relative to the southern Finland composite. Secondly, the statistically significant negative MSLP anomaly over the eastern Mediterranean has a larger magnitude in the northern Finland composites (Figures 2c,d) than in the southern Finland composites (Figure 2a,b). Thirdly, the spatial extent of the statistically significant negative MSLP anomaly over northern Russia between 90° and 120° E is smaller, or non-existent, in the northern Finland composite than in the southern Finland composite. Finally, notable differences exist over North America. For the 20° C threshold composite there is a statistically significant negative MSLP anomaly at 90° W and 45° N in the northern Finland composite (Figure 2c) which is not present in the southern Finland composite (Figure 2a). The 24° C MSLP composite for northern Finland (Figure 2d) has a positive MSLP anomaly over large parts of Canada which is absent in the 20° C composite (Figure 2b).

It should be noted that the sample size differs for each of these four MSLP composites. The MSLP composites for the 20° C threshold (Figures 2a,c) represent a much larger sample than the equivalent composites for the 24° C threshold (Figures 2b, d) as the 20° C threshold is surpassed much more frequently than the 24° C threshold. For example, the 20° C and 24° C thresholds are surpassed at a frequency of 23.9% and 3.0% respectively in southern Finland (Table 2). Partly related to this is that there are more grid cells with a statistically significant pressure anomaly in the 20° C threshold (Figures 2a,c) than in the 24° C threshold composites (Figures 2b,d). This is particularly true for the northern Finland composite as the 24° C threshold is only exceeded in northern Finland with a frequency of 0.4% or 12 days of the 3312 days in the data set (Table 2). Hence Figure 2d is also noisier than the other MSLP composites.

3.2 CMIP5 Historical 1900-2005

The frequency of summer (JJA) days exceeding the first two FMI hot day temperature thresholds (daily mean temperatures of 20°C and 24°C) in the CMIP5 historical simulations for 1900-2005 were calculated using both the direct model output (Figure 3a,b) and the bias-corrected data (Figure 3c,d). When the multi-model ensemble mean from the direct model output (Figure 3a,b) is compared to the results from ERA-Interim (Figure 1), reasonable agreement is found in terms of the basic spatial pattern.

The highest frequencies near the southern part of the Finnish-Russian border and the lowest frequencies in northern Finland above the 65°N latitude are reproduced in the CMIP5 historical ensemble created from the direct model output. The smoother distribution of the CMIP5 historical figures compared to ERA Interim is expected due to the 17-model ensemble mean, the coarser resolution (2.5 degrees compared to 0.75 degrees in ERA-Interim), and the longer time period. The impact of the coarser resolution is evident over the Gulf of Finland (the easternmost part of the Baltic Sea situated between Finland to the north and Estonia to the south) and Lake Ladoga (61°N, 31.3°E). In ERA-Interim both of these water areas are resolved and consequently the frequency with which the temperature thresholds are exceeded is lower in these areas than in neighboring grid points. In contrast, in the CMIP5 ensemble the Gulf of Finland and Lake Ladoga are largely unresolved at the 2.5°x2.5° resolution.

The percentage of summertime days which exceed the three temperature thresholds in the CMIP5 historical ensemble calculated from the direct model output (Figure 3a,b) is largely in agreement with ERA-Interim (Figure 1), especially over Finland. However, Table 2 shows that some small quantitative differences do exist. For example, in the CMIP5 historical simulations 24 days per summer exceed the 20°C threshold in southern Finland and 6 days exceed the 24°C threshold whereas the corresponding values in

ERA-Interim are 22 and 3 days per summer. The CMIP5 historical simulations, with no bias corrections applied, have more hot days in southern Finland and fewer hot days in northern Finland than in ERA-Interim.

Applying the bias correction to the historical CMIP5 simulations does not dramatically alter the spatial pattern of the frequency of hot days, but it reduces the frequency with which both the 20°C and 24°C temperature thresholds are exceeded (compare Figs. 3c,d with Figs. 3a,b). Table 2 confirms that the bias correction leads, in general, to better quantitative agreement between ERA-Interim and the CMIP5 historical simulations with the only exception being the 20°C threshold for northern Finland. The decrease in the frequency of hot days in the bias-corrected ensemble is not uniform across the models, but is rather due to large decreases in some of the warmest models that greatly overestimate the hot day frequency before the correction (not shown). The differences that remain between the bias-corrected ensemble and ERA-Interim suggest that there are biases in the shape of the simulated temperature distribution in the models. Accounting for these would require a more sophisticated bias correction method.

The CMIP5 ensemble mean composites of MSLP anomalies associated with hot days (Figure 4) are largely similar to those created from ERA-Interim data (Figure 2), especially when only the statistically significant MSLP anomalies are considered. The significant positive pressure anomalies over and to the east of Finland as well as the significant negative pressure anomalies over Russia between 90°E and 120°E which were present in the ERA-Interim composites can also be seen in the CMIP5 composites for the 20°C temperature threshold. The position and magnitude of the significant positive pressure anomaly east of Finland is consistent between ERA-Interim and the CMIP5 historic ensemble mean although the anomaly over Sweden and Norway is weaker in the CMIP5 than in the ERA-Interim composites. Likewise, the positive MSLP anomaly over

the Atlantic is also reproduced in the historical CMIP5 ensemble but again with a smaller magnitude than in the ERA-Interim composites. In the composite for the 20°C threshold for southern Finland (Figure 4a), the Atlantic positive MSLP anomaly is statistically significant although the magnitude of this anomaly is less than 1 hPa and thus is not shown in colour.

Comparison of the MSLP composites for the 24°C temperature threshold between the CMIP5 historical ensemble (Figures 4b,d) and ERA-Interim data (Figure 2b,d) reveals some features which are absent in the CMIP5 historical composites. In the ERA-Interim composites (Figures 2b,d), there are statistically significant negative and positive pressure anomalies over North America for the southern and northern Finland composites respectively. These features are not present in the CMIP5 historical ensemble analysis (Figures 4b,d). As stated above, the small sample sizes for the ERA Interim 24°C thresholds, 3.0% for southern Finland and 0.4% for northern Finland of summer days, can explain the noisier composites.

4 Future Climate: results from CMIP5 RCP4.5

The ensemble mean temperature changes between the CMIP5 historical and RCP4.5 simulations in southern and northern Finland are 2.3°C and 2.1°C respectively (Figure 5). The mean temperature of southern Finland changes from 15.0°C to 17.3°C between the bias-corrected historical and RCP4.5 simulations. For northern Finland, the change is 12.2°C to 14.3°C. The warming in the individual models varies from approximately 1°C to 3.5°C in both southern and northern Finland.

Consistent with this increase in mean temperature, the frequency of hot days increases (Figure 6 and Table 2). This is the case for both the original and bias-corrected model

output. Here we focus on the bias-corrected values (Figures 6c,d and values in parentheses in Table 2) because they are expected to be more relevant for the real world, but Figures 6a,b and Table 2 also include the original values for reference.

The bias-corrected model output shows an increase in the frequency of occurrence of hot days for both the 20 and 24°C thresholds (compare Figs. 6c,d with Figs. 3c,d). In the RCP4.5 future projections, the daily mean temperature exceeds 20°C (Figure 6c) during at least 18% of summertime days in nearly all of southern Finland (south of 62.5°N) but only during about 6% of days in the coolest parts of northern Finland. In comparison with the equivalent values from the the CMIP5 historical ensemble (Figure 3c), an absolute increase of 6% or more (3% or more) is evident throughout southern (northern) Finland. For the number of days in which the 20°C threshold is exceeded somewhere in southern and northern Finland, the absolute increases between the bias-corrected historical and RCP4.5 ensemble means are 25.7% and 9.5% (or ca. 24 and 9 days per summer) respectively (Table 2). Although the absolute change is larger in the south, the relative change is larger in the north (Table 2).

In the CMIP5 RCP4.5 ensemble mean based on the bias-corrected model output, the 24°C threshold (Figure 6d) is exceeded in 1–5% of summertime days in nearly all of Finland with the exception of the areas north of the Arctic circle (66.6°N) and over the most westerly parts of Finland where lower values occur. In comparison, the highest frequency with which the 24°C threshold is exceeded in the CMIP5 historical ensemble is 0.5% (Figure 3d) and this only occurs in the warmest, southernmost parts of Finland. The absolute difference from the bias-corrected historical to the bias-corrected RCP4.5 ensemble in the frequency of days in which 24°C is exceeded somewhere in southern and northern Finland is 8.5% and 1.5% (or ca. 8 and 1 days per summer) respectively (Table 2). The relative increase in the number of threshold exceeding days is larger in northern

Finland which, historically, very seldom experienced daily mean temperatures exceeding this threshold. Considering this contrast between the absolute and relative changes, it is not clear whether it will be more difficult for the population in southern or northern Finland to acclimate to the increased frequency of very high temperatures in the projected warmer summer climate.

The structure of the significant MSLP anomaly pattern in the CMIP5 RCP4.5 composites (Figure 7) is very similar to the CMIP5 historical composites (Figure 4). As was the case for the historical composites, there are more significant grid cells in the 20°C threshold (Figures 7a,c) than in the 24°C threshold composites (Figures 7b,c) for both the south and north.

In comparison to the CMIP5 historical ensemble, the magnitude of the MSLP anomalies associated with hot days is projected to decrease in the CMIP5 RCP4.5 ensemble. The centers of both low and high pressure anomalies weaken by 1-2 hPa. The increase in mean temperature (Figure 5) means that it is easier for the temperature thresholds to be reached in the future and thus explains why the MSLP anomalies associated with both the 20° and 24°C threshold in the RCP4.5 simulations (Figure 7) are weaker than those in the historical simulations (Figure 4). Hence, in the future, hot days will result from weaker circulation anomalies than in the current climate.

5 Projected future changes to heat waves

The long-term temporal evolution of the number of heat waves (defined as 3+ consecutive days exceeding temperature thresholds) that occur each year in CMIP5 historical and RCP4.5 simulations after bias correction from 1900-2100 was examined (Figure 8). From 1900 – 1950, the number of heat waves per year is relatively constant. However,

from around 1950 until approximately 2050 there is an increasing trend in the number of heat waves in both northern and southern Finland. The number of heat waves begins to level off at 2050 in the RCP4.5 simulations and there are no further increases in the number of heat waves affecting Finland between 2050 and 2100. The increasing trend from 1950 is consistent with global mean temperature data. The leveling off in the mid 21st century reflects the projected CMIP5 RCP4.5 global mean temperature increase, which slows down in the second half of the century.

The increase in the number of heat waves between the bias-corrected historical simulations and the RCP4.5 simulations is summarized in Table 3. There are increases in the number of heat waves for all temperature thresholds for both southern and northern Finland, but the largest relative increases occur in northern Finland. The relative change for southern Finland for the 20°C threshold from historical to RCP4.5 simulation is 60% compared to 172% for northern Finland. For the 24°C threshold, the relative changes for southern and northern Finland are even larger at 357% and 525% respectively. These results are in line with the changes in frequency of threshold exceeding days for the three temperature thresholds (Figures 3 and 6) which also indicate larger relative changes in northern Finland than southern Finland.

Not only is the number of heat waves projected to increase but the length of heat waves is also predicted to increase in the future. The mean length of heat wave events for each temperature threshold in northern and southern Finland was determined from the bias-corrected CMIP5 historical and RCP4.5 simulations (Table 3). The heat waves in every category for both southern and northern Finland increase in length. The largest increase in length occurs for the 20°C threshold with the mean heat wave length increasing by 3.3 days and 1.2 days for southern and northern Finland respectively. Figure 9 shows the number of heat waves per summer in the bias-corrected data as a function of heat

484 wave length. The mean number of heat waves per summer which are very long is very
485 small. For example, a heat wave in which the daily mean temperature exceeded 20°C for
486 20 consecutive days is only predicted to occur 0.33 and 0.04 times per year in southern
487 and northern Finland respectively in the RCP4.5 simulations. However, Figure 9 does
488 show that the number of long heat waves is projected to increase in the future for all
489 temperature thresholds.

490
491 Studies have suggested that heat waves which occur earlier in the summer are more likely
492 to result in health impacts than those occurring later in the summer (e.g. Anderson and
493 Bell, 2011). Thus, we calculated the percentage of each calendar day temperatures in
494 the bias-corrected, multi-year CMIP5 historical and RCP4.5 simulations which exceeded
495 the 20°C and 24°C thresholds in southern and northern Finland (Figure 10). In the
496 historical simulations, the temperature thresholds are most often exceeded in the middle
497 of July. In the RCP4.5 simulations, the peak does not move and remains in mid-July for
498 northern Finland. For southern Finland, the peak shifts towards the end of July. For
499 southern Finland, relative changes occurring in June are less pronounced when compared
500 to the changes occurring in August. In northern Finland as well, the 20°C threshold has
501 the largest relative increase in August but for the 24°C threshold the relative increase is
502 largest in June. This suggests that summer time changes of warm weather days will be
503 different for southern and northern Finland. Southern Finland will experience the largest
504 warm weather shifts late in summer. Northern Finland will experience the largest shift
505 early in summer for 24°C days and late in summer for 20°C days.

506 6 Conclusions

507 The frequency and intensity of hot days and heat waves in southern and northern Fin-
508 land, as well as the circulation patterns associated with extreme summertime daily mean

temperatures in these two regions, have been analyzed in the current and future climate using ERA-Interim reanalysis data and both the direct model output and bias-corrected CMIP5 simulations. Hot days were defined using the operational warning criteria employed by the Finnish Meteorological Institute and heat waves were defined to be 3 or more consecutive hot days. The frequency of summertime days exceeding the 20°C daily mean temperature threshold in the ERA-Interim data set is 23.9% and 9.5% in southern and northern Finland respectively. The 24°C threshold is exceeded during 3.0% and 0.36% of summertime days in southern and northern Finland respectively. The 28°C threshold is never exceeded in Finland in ERA-Interim.

An examination of the circulation patterns from ERA-Interim during extreme summertime daily mean temperature in both southern and northern Finland shows a statistically significant high pressure anomaly over and to the east of Finland and a significant low pressure anomaly over Russia between 90°E and 120°E. When extreme summertime daily mean temperatures occur in northern Finland, the high pressure anomaly is shifted northeastward compared to when southern Finland experiences extreme warmth. The strength of these surface pressure anomalies increases as the daily mean temperature threshold increases from 20°C to 24°C. This study confirms forecasters experience that hot days take place in context of a high pressure area with the center over or east of Finland. This information can be applied in operational forecasting while assessing probability of hot days and issuing heat warnings. The CMIP5 historical ensemble is able to recreate these features in terms of both circulation pattern and magnitude of the MSLP anomaly. The frequency of summer days exceeding the three daily mean temperature thresholds throughout Finland in the CMIP5 historical ensemble is also largely in agreement with results from ERA-Interim.

Projections under RCP4.5 show a decrease in the magnitude of the pressure anomalies

associated with hot days. Thus, in the future, extreme temperatures will occur with less pronounced circulation anomalies. Furthermore, RCP4.5 projections suggest an increase in the frequency, intensity, and duration of heat waves. The relative changes in northern Finland are more severe than in southern Finland while the absolute changes are larger in southern Finland than in northern Finland. It is unclear whether a higher absolute or higher relative change is more difficult to acclimatize to and which increases the risk of human health impacts more.

Increasing number of hot (greater than 20°C) and very hot (greater than 24°C) days and lengthening of heat waves will increase the risk of heat related mortality and morbidity in the future. However, the health risks also depend on the capability of the Finnish population to adapt to these changes. Acclimatization, or decreasing sensitivity of the population to heat waves, may take place over a long period of time (decades) parallel to the gradual increase in the mean temperature. Evidence for this process has been presented by Nyh (2005) who showed that heat related mortality has decreased over the years and by Oudin strm *et al.* (2016) who concluded that autonomous adaptation has occurred in Swedish population — in somewhat similar climatic conditions as in Finland — over the course of the 20th century.

According to our study more than 45% of summer days will be hot days (warmer than 20°C) in southern Finland in the future. It may be that acclimatization to these relatively common future thermal conditions will be remarkable, and the health impacts will not be as severe as could be expected based only on climate change projections. On the other hand, the newly emerging extreme heat stress levels will pose higher health risks for the Finnish population. Our study suggests that by the middle of the 21st century, on the average one day per summer (1.2% of days) will be extremely hot in southern Finland with daily mean temperature exceeding 28°C.

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Table 1: Description of CMIP5 models used in this study.

Model	Institution and Country	Resolution (Lat x Lon)
ACCESS1-0	CSIRO and the Bureau of Meteorology, Australia	1.25° x 1.875°
BCC-CSM1-1	Beijing Climate Center, China	2.7906° x 2.8125°
CanESM2	Canadian Centre for Climate Modelling and Analysis, Canada	2.7906° x 2.8125°
CCSM4	NCAR, USA	0.9424° x 1.25°
CMCC-CMS	Centro Euro-Mediterraneo per I Cambiamenti Climatici, Italy	3.7111° x 3.75°
CNRM-CM5	Centre National de Recherches Météorologiques, France	1.4008° x 1.40625°
CSIRO-Mk3-6-0	CSIRO, Australia	1.8653° x 1.875°
FGOALS-s2	Institute of Atmospheric Physics, Tsinghua University, China	1.6590 x 2.8125
GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory, USA	2.0225° x 2.5°
GISS-E2-R	NASA Goddard Institute for Space Studies, USA	2° x 2.5°
INM-CM4	Russian Institute for Numerical Mathematics, Russia	1.5° x 2°
IPSL-CM5A-MR	Institut Pierre-Simon Laplace, France	1.2676° x 2.5°
MIROC-ESM-CHEM	JAMSTEC, The University of Tokyo and NIES, Japan	2.7906° x 2.8125°
MIROC5	JAMSTEC, The University of Tokyo and NIES, Japan	1.4008° x 1.40625°
MPI-ESM-MR	Max-Planck-Institut fr Meteorologie, Germany	1.8653° x 1.875°
MRI-CGCM3	Meteorological Research Institute, Japan	1.12148° x 1.125°
NorESM1-M	Norwegian Climate Centre, Norway	1.8947° x 2.5°

Table 2: The percentage of summertime days which exceed the daily mean temperature thresholds for south and north Finland and for ERA Interim, CMIP5 historical ensemble, and CMIP5 RCP4.5 ensemble. Relative change percentages from CMIP5 Historical to CMIP5 RCP4.5 are included. Percentages in parentheses are for bias-corrected data.

Categories	ERA Interim	CMIP5 Historical	CMIP5 RCP4.5	Relative Change
Days in Data Set	3312	9752	8740	N/A
South 20°C	23.9 %	25.9 % (20.8 %)	43.3 % (46.5 %)	67 % (124 %)
South 24°C	3.0 %	6.8 % (2.5 %)	16.1 % (11.0 %)	138 % (340 %)
South 28°C	0 %	1.2 % (0.1 %)	4.2 % (1.2 %)	268 % (1100 %)
North 20°C	9.5 %	7.8 % (4.8 %)	18.2 % (14.3 %)	132 % (198 %)
North 24°C	0.4 %	1.0 % (0.3 %)	4.3 % (1.8 %)	313 % (500 %)
North 28°C	0 %	0.07 % (0 %)	0.6 % (0.1 %)	729 % (N/A)

Table 3: Mean number of heat waves per summer and mean heat wave length for ERA Interim, bias-corrected CMIP5 Historical and RCP4.5 Ensembles. Relative change percentages from CMIP5 Historical to CMIP5 RCP4.5 are included.

Categories	ERA Interim		Historical		RCP4.5		Relative change	
	number	length	number	length	number	length	number	length
South 20°	2.8	7.2	2.7	6.1	4.3	9.4	60%	55%
South 24°	0.4	3.9	0.3	4.4	1.4	5.8	357%	34%
South 28°	0	N/A	0.0	3.4	0.1	4.6	1519%	25%
North 20°	1.4	4.8	0.7	5.0	1.8	6.3	172%	24%
North 24°	0	N/A	0.0	4.0	0.2	4.9	525%	25%
North 28°	0	N/A	0.0	N/A	0.0	3.9	N/A	N/A

Figure 1: The frequency of summer days surpassing the 20°C (a) and 24°C (b) threshold for ERA Interim 1979-2014. Note the different color scale in panels (a) and (b).

Figure 2: Composites of the mean sea level pressure anomaly for the 20°C and 24°C daily mean temperature threshold in south and north Finland for ERA Interim 1979-2014. Pink and gray dots on grids represent positive and negative anomaly significance respectively. (a) South 20°C, (b) South 24°C, (c) North 20°C, (d) North 24°C.

Figure 3: The frequency of summer days surpassing the 20°C (a, c) and 24°C (b, d) threshold for the CMIP5 historical ensemble in 1900-2005. Panels a and b show the uncorrected data and panels c and d show the bias-corrected data.

Figure 4: Composites of the mean sea level pressure anomaly for the 20°C and 24°C daily mean temperature thresholds in south and north Finland for the CMIP5 historical ensemble 1900-2005. Pink and gray dots on grids represent positive and negative anomaly significance respectively. (a) South 20°C, (b) South 24°C, (c) North 20°C, (d) North 24°C.

Figure 5: Change in mean temperature for southern (a) and northern (b) Finland between CMIP5 Historical and RCP4.5 simulations. The ensemble mean temperature increase (shown in gray) is 2.3°C and 2.1°C for south and north Finland respectively.

Figure 6: The frequency of summer days surpassing the 20°C (a, c) and 24°C (b, d) threshold for the CMIP5 RCP4.5 ensemble in 2006-2100. Panels a and b show the uncorrected data and panels c and d show the bias-corrected data.

Figure 7: Composites of surface pressure for the 20°C and 24°C daily mean temperature threshold in south and north Finland for CMIP5 RCP4.5 ensemble 2006-2100. Pink and gray dots on grids represent positive and negative anomaly significance respectively. (a) South 20°C, (b) South 24°C, (c) North 20°C, (d) North 24°C.

Figure 8: Five-year running mean number of heat waves per year for the CMIP5 historical and RCP4.5 ensemble means. Southern and northern Finland are differentiated by solid and dotted lines. A solid vertical line splits the Historical from RCP4.5 data sets. Only bias-corrected data is shown.

Figure 9: The number of heat waves that occur per year in southern (a) and northern (b) Finland in the CMIP5 Historical and RCP4.5 ensemble for varying lengths in days. Only bias-corrected data is shown

Figure 10: Frequency in percent that each day exceeds the 20°C and 24°C threshold for north and south Finland for both CMIP5 historical and RCP4.5 ensembles. Average frequencies for each month for both ensembles are listed under each month's x-label. The darker and lighter colors represent the historical and RCP4.5 ensembles. (a) South 20°C, (b) South 24°C, (c) North 20°C, (d) North 24°C. Note the different scales on the y-axes. Only bias-corrected data is shown.