Impact of 3D groundwater dynamics on heat events in historical regional climate simulations over Europe

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Abstract. The representation of groundwater processes is simplified in most regional climate models (RCMs), potentially leading to biases in simulated heat waves. ~~Here, we introduce~~ This paper introduces a unique dataset from the regional Terrestrial Systems Modelling Platform (TSMP) forced by Max Planck Institute Earth System Model at Low Resolution (MPI-ESM-LR) boundary conditions for a historical time span in the context of dynamical downscaling of global climate models (GCMs) for climate change studies. TSMP explicitly represents 3D subsurface and groundwater ~~hydrodynamics~~ dynamics together with overland flow, closing the water and energy cycle from the bedrock to the top of the atmosphere. ~~We perform an analysis of~~ By comparing summer heat events statistics (i.e. a series of consecutive days with a near-surface temperature exceeding the 90th percentile ~~) for the historical time period 1976-2005 relative to~~ of the reference period~~1961-1990 in a TSMP climate change scenario control run. For comparison, the analysis is repeated for an ensemble of~~) from TSMP and those from GCM-RCM simulations with simplified groundwater dynamics from the Coordinated Regional Climate Downscaling Experiment ~~initiative~~ (CORDEX) for the European domain~~(EURO-CORDEX)~~, we aim to improve the understanding of how 3D groundwater dynamics affect regional heat events over Europe.

The analysis is carried out for 1976-2005 relative to the 1961-1990 period. While our results show that TSMP simulates heat events consistently with the CORDEX ensemble, there are some systematic differences that we attribute to the representation of groundwater in TSMP. Compared to the CORDEX ensemble, TSMP simulates lower means and lower interannual variability in the number of hot days (i.e., days with a near-surface temperature exceeding the 90th percentile of the reference period) on average over Europe. The decadal change in the number of hot days is also lower in TSMP than on average in the CORDEX ensemble. TSMP systematically simulates fewer heat waves (i.e., heat events lasting 6 days or more) compared to the CORDEX ensemble, moreover, they are less intense. Southern Europe is particularly sensitive to groundwater coupling, while Scandinavia is the least sensitive. Therefore, an explicit representation of groundwater dynamics in RCMs may be a key in ~~bias reduction~~ reducing the bias in simulated duration and intensity of heat waves, especially in Southern Europe. The results emphasise the importance of groundwater coupling in long-term regional climate simulations and potential implications for climate change projections.

1 Introduction

Over the past decades, the number of heat waves has increased (e.g., Frich et al., 2002; Alexander et al., 2006; Christidis et al., 2015; Zhang et al., 2020). The years 2003, 2010, 2018, and 2022 were exceptionally hot in Europe, characterised by record-breaking near-surface air temperatures (e.g., Stott et al., 2004; Barriopedro et al., 2011; Liu et al., 2020; Dirmeyer et al., 2021; Yule et al., 2023). With projected climate change, the occurrence of heat waves will continue to increase (e.g., Russo et al., 2015; Myhre et al., 2019; Hari et al., 2020; Molina et al., 2020; Masson-Delmotte et al., 2021), leading to multiple negative socio-economic impacts (e.g., Bosello et al., 2007; Ciscar et al., 2011; Amengual et al., 2014; Yin et al., 2022).

The underlying hydrometeorological mechanisms of heat waves have been extensively studied (e.g., Lhotka and Kyselý, 2015; Horton et al., 2016; Liu et al., 2020). Heat waves are triggered by strong, persistent quasi-stationary large-scale high pressure systems associated with atmospheric blocking events, resulting in subsiding, adiabatically warming air masses, and clear skies allowing for high insolation (Tomczyk and Bednorz, 2016; Horton et al., 2016; Kautz et al., 2022). Atmospheric blocking events also impact winter and early spring precipitation in most parts of Europe and, in turn, affect soil moisture (e.g., Vautard et al., 2007; Ionita et al., 2020). The evolution of heat waves depends primarily on the synoptic weather patterns in combination with ambient soil moisture conditions, further altered by multiple land-atmosphere feedback processes (e.g., Fischer et al., 2007; Horton et al., 2016).

Many European summer heat waves were preceded by a deficiency of spring precipitation (Dirmeyer et al., 2021; Stegehuis et al., 2021; Hartick et al., 2021). Due to the soil moisture memory effect, the lack of precipitation in early spring causes negative soil moisture anomalies in early summer and leads to strong land-atmosphere coupling (a measure of the response of the atmosphere to anomalies in the land surface state) with a lower evaporation fraction. This reduces latent cooling and amplifies summer temperatures (e.g., Fischer et al., 2007; Miralles et al., 2012; Knist et al., 2017; Dirmeyer et al., 2021). Note that soil moisture memory is a phenomenon of persistence of wet or dry anomalies over a long period of time, from weeks to months, after the atmospheric conditions that caused them have passed; this allows to preserve the hydroclimatic conditions of the preceding months (e.g., Manabe and Delworth, 1990; Song et al., 2019). Thus, depending on soil moisture conditions, the soil moisture memory effect can contribute to either buffering negative droughts impacts and weakening a heat wave, or, conversely, delaying drought recovery and exacerbating the occurrence of a heat wave (e.g., Erdenebat and Tomonori, 2018; Martínez-de la Torre and Miguez-Macho, 2019). In addition to precipitation, soil moisture is strongly influenced by groundwater dynamics via vertical fluxes across the water table (capillary rise) and via horizontal fluxes through gravity-driven lateral transport within the saturated zone. Here, the water table depth dictates the intensity of shallow groundwater–soil moisture and evapotranspiration coupling (Kollet and Maxwell, 2008).

In the context of climate impact assessments, dynamical downscaling of GCMs with RCMS global climate models (GCMs) with regional climate models (RCMs) is widely used to generate regional climate change scenario information (Vautard et al., 2013b; Mearns et al., 2015; Jacob et al., 2020). RCMs have been shown to provide added value to driving GCMs by better capturing small-scale processes (Giorgi and Gutowski, 2015; Torma et al., 2015; Prein et al., 2016; Iles et al., 2020; Rummukainen, 2016), but model biases (offset during the historical period against observations) and uncertainties in climate projections still remain (Hawkins and Sutton, 2009; Lhotka et al., 2018; Sørland et al., 2018; Fernandez-Granja et al., 2021). In fact, many RCMs tend to overestimate the frequency, duration, and intensity of heat waves (Vautard et al., 2013a; Plavcová and Kyselý, 2016; Lhotka et al., 2018; Furusho-Percot et al., 2022).

The role of soil moisture in modelling heat waves is crucial (e.g., Seneviratne et al., 2006, 2010; Fischer et al., 2007), but due to the complexity of the feedbacks involved and related high computational cost, the explicit representation of hydrological processes is oversimplified or neglected in most RCMs. Commonly applied hydrology schemes are based on 1D-parameterizations in the vertical direction with runoff generation at the land surface and a gravity driven free drainage approach as the lower boundary condition; in such a parametrisation there is no lateral subsurface flow and only the 1D-Richards' equation is solved (e.g., Niu et al., 2007; Campoy et al., 2013). RCMs with a simplified representation of hydrological processes have difficulties in reliably reproducing the land surface energy flux partitioning and, consequently, near-surface air temperatures, leading to warm biases (Vautard et al., 2013a; Barlage et al., 2021; Furusho-Percot et al., 2022). Hydrological parameters tuning (e.g., Teuling et al., 2009; Bellprat et al., 2016) or developing new parameterizations of groundwater dynamics (e.g., Liang et al., 2003; Yeh and Eltahir, 2005; Schlemmer et al., 2018) have been shown to improve model results. A physically consistent description of hydrological processes in RCMs can be achieved by an explicit representation of 3D subsurface and groundwater hydrodynamics together with overland flow. Thereby accounting for the feedback loops over the terrestrial system ~~(e.g., Maxwell et al., 2007)~~(Maxwell et al., 2007), i.e., the closure of water and energy cycles from groundwater across the land surface to the top of the atmosphere, as for instance in the Terrestrial Systems Modelling Platform (TSMP) ~~(Shrestha et al., 2014; Gasper et al., 2014)~~(e.g., Shrestha et al., 2014; Gasper et al., 2014), a regional climate system model.

Keune et al. (2016) demonstrated the link between groundwater dynamics and near-surface air temperature in an analysis of the August 2003 European heat wave from TSMP simulations nested within ERA-Interim reanalysis (Dee et al., 2011). The model ~~set up is over the CORDEX European domain~~ was set up over the European domain of the Coordinated Regional Climate Downscaling Experiment (CORDEX) (Gutowski et al., 2016; Jacob et al., 2020) with two different groundwater configurations: (i) simplified 1D free drainage approach and (ii) 3D physics-based variably saturated groundwater dynamics. The study clearly showed the impact of groundwater dynamics on the land surface water and energy balance: latent heat fluxes were higher and maximum temperatures were lower, especially in areas with shallow water table depth, in the 3D configuration compared to the simplified 1D free drainage approach. Keune et al. (2016) suggest that the 3D groundwater dynamics in TSMP alleviate the evolution of a single heat wave due to weaker land-atmosphere feedbacks compared to the simplified 1D free drainage approach, at least during the investigated European heat wave of summer 2003.

Therefore, compared to the 1D approach, the 3D groundwater dynamics in TSMP ~~lead~~ leads to regionally shallow groundwater levels, causing wetter soils, and a reduction in the Bowen ratio (i.e., ratio between sensible heat flux to latent heat flux) due to an increase in surface latent heat flux and a decrease in surface sensible heat flux, that leads to increased evapotranspiration (Maxwell and Condon, 2016). Such an increase in a latent heat flux also causes moistening of the lower atmosphere and increases downward longwave radiation due to the greenhouse effect of water vapor, on the other hand, it cools the surface and reduces outgoing surface longwave radiation. ~~(Pal and Eltahir, 2001).~~ In addition, increased evapotranspiration may cause moist convection or rainfall, which further affects soil moisture ~~(Eltahir, 1998; Yang et al., 2018)~~

(Eltahir, 1998; Pal and Eltahir, 2001; Yang et al., 2018). In its turn, the simplified representation of groundwater dynamics with the 1D free drainage approach leads to the opposite effect, namely an overestimation of the land surface-atmosphere coupling, i.e., deeper groundwater levels cause drier soils, an increase in the Bowen ratio, a decrease in cloud cover and enhancement of net solar radiation and a reduction in downward longwave radiation (Hartick et al., 2022), and, as a result, higher near-surface temperatures, which in turn further reduces soil moisture (Vogel et al., 2018). (e.g., Vogel et al., 2018; Hartick et al., 2022). The ability of groundwater to decrease warm summer biases and moderate maximum air temperatures during a single seasonal heat wave in RCM simulations was also discussed in Barlage et al. (2015, 2021) and Mu et al. (2022).

Further studies were carried out to understand whether the observed differences in simulated near-surface temperature due to differences in groundwater configuration persist over a long time period, and how this manifests itself for heat waves in the EURO-CORDEX realm CORDEX realm for the European domain. Furusho-Percot et al. (2019) showed that TSMP evaluation run (1996–2018) forced by the ERA-Interim reanalysis is able to capture climate system dynamics and the succession of warm and cold seasons on the regional scale for the PRUDENCE regions of Europe PRUDENCE regions (Christensen and Christensen, 2007) consistently with E-OBS observations (Cornes et al., 2018). Furusho-Percot et al. (2022) demonstrated that TSMP multiannual simulations exhibit lower deviations of summer heat wave indices from the E-OBS observational dataset, compared to ERA-Interim driven RCM evaluation simulations of the EURO-CORDEX CORDEX experiment, which tend to simulate too persistent heat waves. This particular behaviour of TSMP is attributed to its improved hydrology. The improved capacity to sustain soil moisture translates into more reliable latent heat flux and evapotranspiration, that, in turn , which in turn leads to a decrease in the heat wave intensity, its spatial extent, and the number of days with anomalously high near-surface temperatures. An important question still remains: how will these findings be reflected in long-term regional climate simulations?

In this paper, we present a unique dataset from the regional climate system model TSMP forced by the Max Planck Institute Earth System Model at Low Resolution, MPI-ESM-LR (Giorgetta et al., 2013) , historical boundary conditions in the context of EURO-CORDEX GCM-RCM downscaling and long-term climate modellingregional long-term climate simulations and dynamical GCM-RCM downscaling for climate change studies. We interrogate the statistics of heat events (i.e., a series of consecutive days with a near-surface temperature exceeding the 90th percentile) the characteristics (frequency, duration, intensity) for the summers of heat events for the summer seasons of 1976-2005 with respect to the reference period 1961-1990 by comparing TSMP results with the EURO-CORDEX CORDEX multi-model RCM ensemble driven by GCM control simulations of phase five of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012), to understand the influence of 3D groundwater dynamics on simulated heat events for historical regional climate simulations and potential consequences for ensuing climate change projections. While the 1996-2018 TSMP evaluation runs nested within ERA-Interim reanalysis were examined for heat wave statistics (Furusho-Percot et al., 2022)by Furusho-Percot et al. (2022), long-term historical climate simulations of TSMP forced by GCM over CORDEX European domain have not been previously presented. Thus, this is the first downscaled regional historical climate simulation over Europe from groundwater across the land surface to the top of the atmosphereplaced in the context of the climate scenario runs of the EURO-CORDEX RCM ensemble and , analysed for summer heat events.

In Sec. 2, we describe TSMP setup and configurationthe TSMP modelling platform and its setup, the ensemble of the EURO-CORDEX CORDEX GCM-RCM climate change scenario GCM-RCM control runs , control runs and the methodology of heat events analysis are also presented here. In Sect. 3, we examine the new GCM-RCMTSMP TSMP-MPI dataset for consistency with the CORDEX ensemble , and we present the and present results on the impact of 3D groundwater dynamics on simulated heat events for in regional historical climate simulations. Section 4 provides a summary and overall conclusions.

2 Methods

2.1 TSMP

TSMP is a scale-consistent, highly modular, fully integrated soil-vegetation-atmosphere modelling system (e.g., Shrestha et al., 2014; Gasper et al., 2014). TSMP consists of three component models: the atmospheric COnsortium for Small Scale Modelling (COSMO) model version 5.01(e.g., Baldauf et al., 2011), the Community Land Model (CLM) version 3.5(e.g., Oleson et al., 2004, 2008), and the hydrological model ParFlow version 3.2(e.g., Maxwell and Miller, 2005; Kollet and Maxwell, 2006; Kuffour et al., 2020). The component models are externally coupled via the Ocean Atmosphere Sea Ice Soil (OASIS) version 3.0 Model Coupling Toolkit (MCT) coupler (e.g., Valcke, 2013), which enables closure of the terrestrial water and energy cycles from the bedrock to the top of the atmosphere.For details on TSMP, see Shrestha et al. (2014); Gasper et al. (2014).

COSMO is a non-hydrostatic limited-area atmospheric model (e.g., Baldauf et al., 2011). It is based on the primitive thermo-hydrodynamical Euler equations formulated in rotated geographical coordinates and generalized terrain-following height coordinates, describing compressible flow in a moist atmosphere. COSMO parameterization schemes cover various physical processes, such as radiation, cloud microphysics, deep convection, etc. The boundary conditions used for COSMO are typically are provided by a coarse grid model. In the coupled setup of TSMP, , whereas the lower boundary conditions for COSMO (e.g., surface albedo, energy fluxes, surface temperature, surface humidity) are provided by CLM.

CLM is a biogeophysical model of the land surface (e.g., Oleson et al., 2004, 2008). It simulates land-atmosphere exchanges in response to atmospheric forcings. CLM consist of four components that describe biogeophysics, hydrologic cycle, biogeochemistry, and dynamic vegetation. In TSMP, CLM receives short-wave radiation, wind speeds, barometric pressure, precipitation, near-surface temperature, and specific humidity from COSMO. In turn, CLM sends to ParFlow infiltration and evapotranspiration fluxes for each soil layer of ParFlow.

ParFlow is a hydrological model that simulates variably saturated three-dimensional subsurface hydrodynamics using Richards equation integrated with shallow overland flow based on a kinematic wave approximation (e.g., Maxwell and Miller, 2005; Kollet and Max. ParFlow allows 3D-redistribution of subsurface water in a continuum approach. In TSMP, ParFlow replaces the hydrologic functionality of CLM.

2.2 Model setup

TSMP simulations ~~in this study~~ are conducted for the historical time period from December 1949 to the end of 2005 over the European ~~continent~~ domain according to the ~~EURO-CORDEX~~ CORDEX simulation protocol (e.g., Gutowski et al., 2016) using rotated latitude-longitude model grid with a horizontal resolution of 0.11° (EUR-11) or about 12.5 km. Note ~~, the simulations represent the first EURO-CORDEX~~ that these model runs are the first CORDEX climate change control simulations over Europe with explicit representation of 3D groundwater. ~~COSMO extends vertically to 22 km subdivided into 50 levels.~~ The COSMO configuration used in ~~the~~ this TSMP setup resembles that of the COSMO model in CLimate Mode (CCLM) (e.g., Rockel et al., 2008). COSMO extends vertically up to 22 km, divided into 50 levels. CLM has 10 soil layers with a total depth of 3 m. These layers coincide with the 10 top layers of ParFlow, which has 5 additional layers that increase in thickness to a total depth of 57 m. The time step for ParFlow and CLM is 900 sec, for COSMO it is 75 sec. The coupling time step between TSMP component models is 900 sec.

For CLM, plant functional types (PFT) are taken from the Moderate Resolution Imaging Spectroradiometer (MODIS) dataset (Friedl et al., 2002). Leaf area index, stem area index, and the monthly bottom and top heights of each PFT are calculated based on the global CLM surface dataset (Oleson et al., 2008). Compared to the previous studies of Furusho-Percot et al. (2019, 2022); Hartick et al. (2021), where soil parameters were assumed to be vertically homogenous in ParFlow, in this work we have improved the subsurface hydrogeology, which is described below. Static input fields (i.e., soil color, percentage clay, percentage sand, dominant land use type, dominant soil types in the top layers, dominant soil types in the bottom layers and subsurface aquifer and bedrock bottom layers) are derived from MODIS, Food and Agriculture Organization soil database (FAO, 1988), pan-European River and Catchment Database (Vogt et al., 2007), International Hydrogeological map of Europe (IHME) (Duscher et al., 2015) and the GLobal HYdrogeology MaPS (GLHYMPS) (Gleeson et al., 2014). ~~In particular, the bedrock geology is constructed using the IHME dataset and the lower resolution GLHYMPS.~~ The pan-European River and Catchment Database serves in ParFlow as a proxy for the alluvial aquifer system, with the assumption that alluvial aquifers lie underneath or in proximity of existing rivers.

Forcing data for the TSMP atmospheric component model, i.e., for COSMO, are provided by the Max-Planck Institute's MPI-ESM-LR r1i1p1 CMIP5 GCM ~~experiment,~~ with a resolution of T63L47 (Giorgetta et al., 2013). CLM and ParFlow are initialised (i.e., land surface, subsurface hydrology, and energy states) with the moisture conditions of the 1st of December 2011 from the previous evaluation run driven by ERA-Interim reanalysis (Furusho-Percot et al., 2019). In the analysis, we discard the first 10 years of TSMP simulations due to hydrodynamic spin-up.

2.3 ~~EURO-CORDEX~~ CORDEX ensemble

The selected ~~EURO-CORDEX~~ CORDEX ensemble members of the multi-physics ~~RCM climate change scenario control runs~~ RCMs with EUR-11 horizontal resolution driven by different CMIP5 GCMs (r1i1p1 ensemble members) ~~on 0.11° grid (EUR-11)~~ is used in conjunction with the coupled TSMP modelling platform to study the characteristics of summer heat events. Note that CMIP5 GCM historical control simulations are performed under observed natural and anthropogenic forcing

(Taylor et al., 2012). Based Suggestions and limitations of multi-model GCM-RCM ensembles were previously discussed in, for example, Déqué et al. (2007); Kendon et al. (2010); Fernández et al. (2019); Vautard et al. (2021). In this study, based on availability, the following EURO-CORDEX simulations models are considered, identified by their institution, and the RCM and GCM IDs (Table 1): CCLM4-8-17 institutions: CLMcom (CCLM4-8-17 forced by MPI-ESM-LR and CNRM-CM5), CLMcom-ETH (COSMO-crCLIM forced by MPI-ESM-LR, CNRM-CM5, and NCC-NorESM1-M), MPI-CSC (REMO2009 driven by MPI-ESM-LR), GERICS (REMO2015 forced by NCC-NorESM1-M, NOAA-GFDL-ESM2G, and IPSL-CM5A-LR); see Table 1. The considered CORDEX multi-model ensemble includes two main groups of RCMs, namely COSMO (v5.01 in TSMP, v4.8, and an accelerated version of COSMO in COSMO-crCLIM) and REMO(v2009 and v2015)REMO, driven by 5 different GCMs, for a total of 10 different GCM-RCM pairs. For a reliable analysis, Giorgi and Coppola (2010) points out that a subset of at least 4-6 models is needed, and Déqué et al. (2007) shows that the number of GCMs involved should at least be the same as the number of RCMs. The CORDEX RCM most compatible with TSMP is CCLM4-8-17, where the largest differences arise from the lower boundary condition in COSMO. In : in TSMP, the lower boundary condition for COSMO accounts for groundwater feedbacks due to the coupling between with the land surface model CLM and the hydrologic model ParFlow, unlike in the CCLM where the CCLM4-8-17, where soil processes are modelled with the TERRA-ML soil-vegetation land surface model (Grasselt et al., 2008; Doms et al., 2013). All members of the ensemble, except for TSMP, include simplified representations of subsurface hydrodynamics.

Note that the ensemble of EURO-CORDEX CORDEX climate change scenario RCM control runs is not intended for direct comparison between individual models, as it includes different RCMs in combination with different driving GCMs. Therefore, due to connections of various factors (e.g., model setupssetup, conceptual and structural model uncertainties, different physical parameterizations, internal variability, representation of subsurface-land-atmosphere interactions, lower and lateral atmospheric GCM boundary conditions, etc.) in addition to the groundwater coupling, it is challenging in the multi-model CORDEX ensemble to reveal the exact cause and effect relationships of cause-and-effect relationships between the explicit groundwater representation for and simulated hot daysand , as well as the associated characteristics of heat eventsin RCMs, in the multi-model CORDEX ensemble. However, the consideration of an extended period, e.g., 30 years, allows to draw statistical conclusions. In this study , the aim of the analysis of the TSMP historic simulations in the context of the CORDEX RCM ensemble is to interrogate This study aims to investigate whether the new dataset from TSMP driven by MPI-ESM-LR GCM-RCM dataset is consistent with the CORDEX ensemble and, in particular, to gain insight into the role of groundwater for long-term climate simulations from the statistical analysis of heat events over Europe.

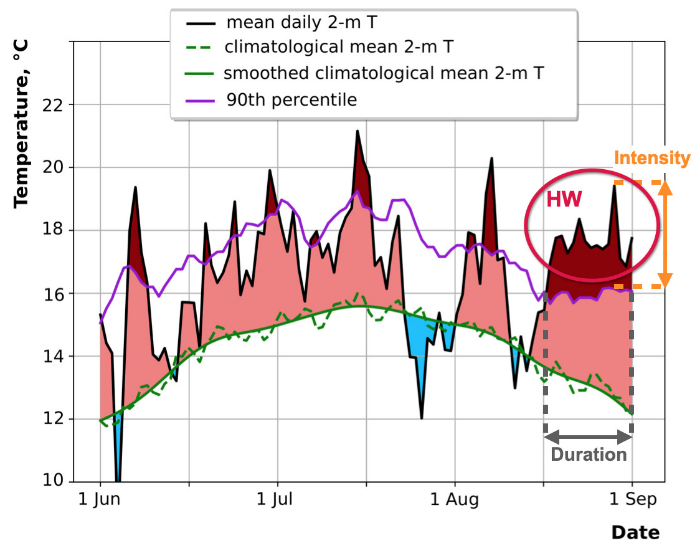
2.4 Analysis of heat events

There is no universally accepted method for defining heat events, but the most commonly used approach is built on a percentile temperature threshold (e.g., Zhang et al., 2005, 2011; Sulikowska and Wypych, 2020). Note that although the focus is on temperature-based diagnostics, it is often ambiguous or inconsistent, describing heat events only partially (Perkins and Alexander, 2013).

Table 1. The multi-model ensemble of ~~EURO-CORDEX~~ GCM-RCM climate change scenario control runs.

GCM-RCM	MPI-ESM-LR ~~(Mauritsen et al., 2019)~~*(Giorgetta et al., 2013)*	CNRM-CM5 *(Voldoire et al., 2013)*	NCC-NORESM1-M *(Bentsen et al., 2013)*	NOAA-GFDL-ESM2G *(Dunne et al., 2012)*	IPSL-CM5A- *(Dufresne et al.,*
TSMP *(Shrestha et al., 2014)*	X				
CCLM4-8-17 *(Rockel et al., 2008)*	X	X			
COSMO-crCLIM *(Pothapakula et al., 2020)*	X	X	X		
REMO2009 *(Jacob and Podzun, 1997)*	X				
REMO2015			X	X	X

In this study, we define a hot day as a day with a daily mean temperature above the local 90th percentile ~~from the reference 1961-1990~~ of the reference period. We calculate the 90th percentile for every summer day and for each EUR-11 grid point of the ~~EURO-CORDEX domain for every summer day~~ CORDEX European domain from a consecutive 5-day moving window



Heat event #	Start date	End date	Duration, days	Intensity, °C
1.	1.06	1.06	1	0,26
2.	6.06	9.06	4	2,71
3.	19.06	19.06	1	1,30
4.	24.06	24.06	1	1,07
5.	30.06	1.07	2	1,40
6.	7.07	7.08	2	0,41
7.	15.07	17.07	3	1,90
8.	3.08	4.08	2	0,63
9.	6.08	7.08	2	3,08
10.	17.08	31.08	15	3,28

Figure 1. Schematic of detection of a summer heat wave (HW)~~detection~~. An example is given for June-July-August of 1972 for one grid point ~~250, 300~~[250, 300] of the ~~EURO-CORDEX~~ CORDEX European domain. Data taken from the TSMP simulations. The solid black line is the mean daily 2 m air temperature ~~.~~ for the summer season of 1972. The dashed green line ~~represents~~ shows the climatological ~~(1961-1990)~~ mean daily 2 m air temperature calculated from the reference period 1961-1990, and the solid green line ~~represents the same dependence~~ is its smoothing with a Butterworth filter. The solid violet line ~~is~~ represents the 90th percentile of the mean daily 2 m air temperature ~~in summer~~ calculated from a 5-day window centered on each calendar day ~~for~~ of the 1961-1990 reference period. The shaded light red colour indicates days with temperatures above the climatological mean, and the shaded dark red colour emphasizes days with temperatures above the 90th percentile, ~~i.e.~~ classified within the scope of this paper as “hot days”, “heat events”, or “heat waves”.

centered on that calendar day from the 30-year reference period between 1961 and 1990. The first occurrence of a hot day determines the start of a heat event. A series of hot days constitutes a heat event, highlighted in dark red in Fig. 1. A heat event is interrupted if the mean daily temperature drops below the 90th percentile-based threshold. ~~The total number of hot days during the investigated period corresponds to the TG90p heat index from the joint CCl/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI) (e.g., Karl et al., 1999). TG90p describes the number of days with $TG_{ij} > TG_{in}90$, where TG_{ij} is the mean daily temperature on day i of period j and $TG_{in}90$ is the i-day 90th percentile calculated from a 30-year reference period n.~~

A heat event can be characterised by its duration, intensity, and frequency (e.g., Horton et al., 2016). A heat event duration is the number of consecutive days over which the heat event lasts. If a heat event lasts long enough, it can be classified as a heat wave. Similar to Fischer and Schär (2010), we consider a heat wave as a spell of at least six consecutive days with mean daily 2 m air temperatures above the local 90th percentile of the reference 1961-1990 period. See Fig. 1 for ~~an explanation of the~~ the explanation of a heat wave detection. Therefore, we consistently use the terminology "hot day", "heat event", and "heat wave" throughout this analysis.

Note that the total number of hot days during the investigated period corresponds to the TG90p heat index from the joint CCl/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI) (e.g., Zhang et al., 2011). TG90p describes the number of days with $TG_{ij} > TG_{in}90$, where TG_{ij} is the mean daily temperature on day i of the investigated period j and $TG_{in}90$ is the 90th percentile calculated for day i from a 30-year reference period n.

A heat event intensity is the maximum of the difference between the mean daily temperature and the 90th percentile of the reference 1961-1990 period within a single heat event (e.g., Vautard et al., 2013a). Intensity represents the severity of a heat event (see Fig. 1). Adopting the definition from the heat wave duration index ~~(e.g., Frich et al., 2002; Espírito Santo et al., 2014),~~ (Frich et al., 2002), we classify a heat wave as intense if it exceeds 5 K. Some studies ~~also classify~~ group heat waves according to their intensity as low, severe, or extreme (e.g., Nairn and Fawcett, 2014).

A frequency of heat events of a certain type (e.g., ~~specific~~ of a certain duration or intensity) ~~during~~ over the investigated period is the number of ~~specific~~ these heat events divided by the total number of all heat events that occurred during ~~this investigated period~~ the period under study (e.g., Vautard et al., 2013a). For example, in Fig. 1, the frequency of heat events with 2 days duration is equal to the number of those heat events, ~~(~~i.e. ~~,~~ 4~~)~~ divided by the total number of all heat events~~(~~, i.e. ~~, 10).~~ 10. The resulting frequency is 0.4 and indicates that 40% of all heat events have a duration of 2 days.

~~We~~ In this study, we examine heat events in Europe by assessing their characteristics ~~explained above~~ as explained above, based on mean daily 2 m air temperatures on the native EUR-11 grid ~~in the ensemble of EURO-CORDEX~~ for TSMP simulations and the CORDEX ensemble of GCM-RCM climate change scenario ~~RCM control runs driven by different GCMs, as listed in~~ control runs (see Table 1). The analysis is ~~performed for the summer season of the 30-year period, from 1976 to 2005 with regard to the reference period from 1961 to 1990 in each RCM. The analysis is conducted over~~ conducted in the focus domain covering the European continent [10°W-30°E, 36°N-70°N], as shown in Fig. 2, for the summer season of the 30-year period, from 1976 to 2005, with regard to the reference period 1961-1990 in each RCM. Note that we analyse only ~~land grid elements .~~ grid elements that belong to land.

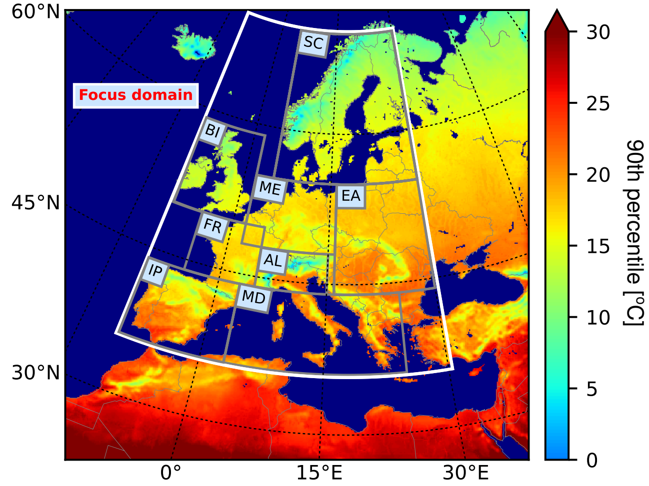


Figure 2. Mean of the Summer mean 90th percentile of 2 m air temperatures in summer simulated with TSMP simulations. The 90th percentile is calculated from a consecutive 5-day moving window centered on each calendar day of the summer season from over the 30-year reference period from 1961 to 1990. 1961-1990. The white box indicates the focus domain for the analysis in our study [10°W-30°E, 36°N-70°N]. PRUDENCE analysis regions are shown as with grey boxes: British Isles (BI), Iberian Peninsula (IP), France (FR), Mid-Europe (ME), Scandinavia (SC), Alps (AL), Mediterranean (MD) and Eastern Europe (EA).

3 Results

3.1 Hot days number

In order to evaluate To assess the impact of groundwater coupling dynamics on the interannual variability of the number of hot days during the summer seasonin RCMs, we examine the occurrence of hot days in the focus domain in the ensemble of the EURO-CORDEX climate change scenario GCM-RCM historical control runs TSMP simulations and the CORDEX ensemble from 1976 to 2005 with regard to the reference period 1961-1990. A comparison of the mean hot days number (number of hot days averaged over the total number of land grid points in the focus domain, i.e., the mean seasonal TG90p index) per summer over the focus domain from TSMP and the CORDEX ensemble , suggests that the impact of groundwater coupling varies from year to year (Fig. 3). Here, the long-term soil moisture memory effects can play an important role, for example by increasing the probability of a water subsurface water storage deficit in regions that had a have had a subsurface water deficit in the previous year (e.g., Hartick et al., 2021), and consequently influencing the hot days occurrencethereby influencing the occurrence of hot days (see description of the respective processes in Sec. 1). A positive linear trend in the mean TG90p index in the focus domain is observed in all considered RCMs on average in the focus domain (see Fig. 3). The decadal change in the of the mean TG90p index in TSMP the TSMP simulations is 1.53 days. In contrast, the decadal change in the TG90p index , whereas its value averaged over the multi-model RCM CORDEX ensemble (excluding TSMP) is higher, CORDEX ensemble reaches up to 2 days.

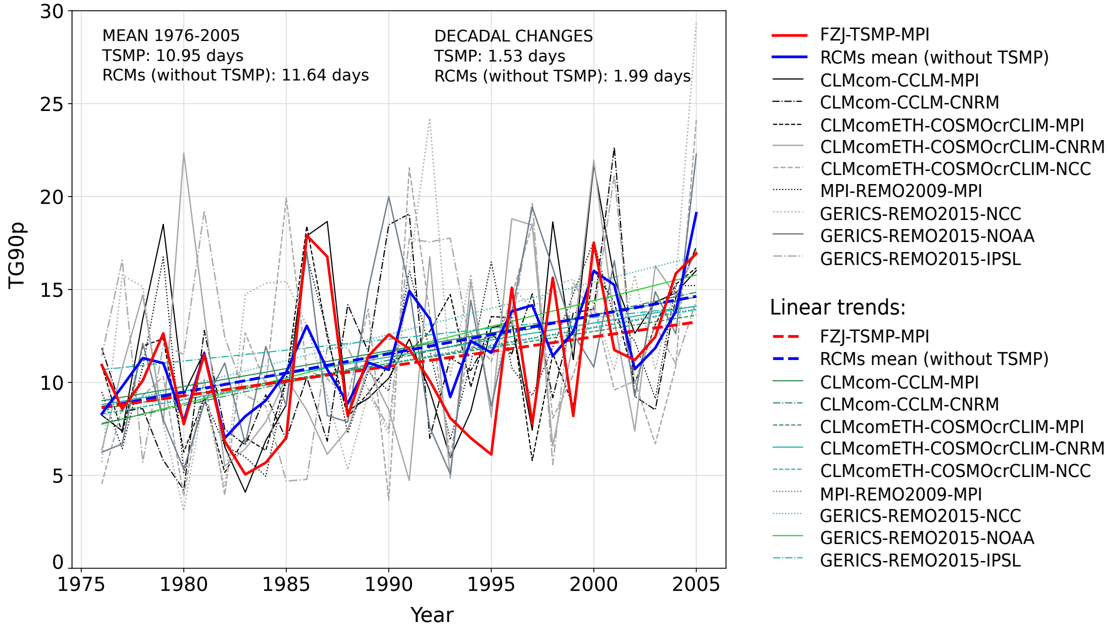


Figure 3. Time series of the mean ~~hot days number (~~TG90p index ~~)~~ and its linear trends during the summer season ~~over~~ in the focus domain ~~and its linear trends~~ during 1976-2005 with respect to the reference period 1961-1990, in the TSMP simulations and the CORDEX ensemble~~of EURO-CORDEX climate change scenario RCM control runs~~. Averaging of TG90p is performed over the total number of land grid points in the focus domain every sumer. The solid and dashed red lines show the ~~TG90p~~ mean TG90p and its linear trend from the TSMP simulations~~, as well as its linear trend~~. The black and grey lines represent the ~~TG90p~~ mean TG90p index from the CORDEX ensemble and the ~~different~~ green lines are their linear trends respectively. The TG90p index averaged over the multi-model ~~RCM~~ CORDEX ensemble ~~(excluding TSMP)~~ is shown with the solid blue line, and its linear trend is shown with the dashed blue line.

A spatial distribution of the ~~TG90p mean and~~ mean TG90p ~~variability,~~ index and its variability as well as the decadal change~~of TG90p is~~ , for 1976-2005 with respect to the reference period 1961-1990, are shown in Fig. 4-6. ~~Uncertainty~~ Note that the uncertainty in simulated near-surface temperature in summer is strongly controlled by the large-scale atmospheric circulation imposed by the ~~boundary conditions (e.g., Déqué et al., 2007; Fernández et al., 2019), with larger impact in the South-West (IP, FR) than the North-East (SC, ME, EA) PRUDENCE regions (Déqué et al., 2012). Hence~~ GCM boundary conditions, with the largest impacts occurring in the southwestern PRUDENCE regions (e.g., Déqué et al., 2012; Evin et al., 2021) . For this reason, the spatial pattern of the TG90p index ~~significantly differs between different GCM-RCMs and the results from~~ in RCMs driven by the same GCMs show a rather similar behaviour. TSMP produces the smoothest spatial distribution of the ~~TG90p mean and~~ mean TG90p index and its variability compared to the CORDEX ensemble (see ~~the standard deviation~~ standard deviations indicated in Fig. 4, 5)~~. Thus, in TSMP, the regional difference in the distribution of the hot days number is smaller, and the climate is more steady~~ , suggesting that an explicit representation of groundwater dynamics in RCMs may lead to more steady climate with respect to the interannual changes in the simulated number of hot days in summer. ~~In the considered ensemble,~~ Details on the TG90p mean, variability, and ~~TG90p variability averaged over the focus domain are lowest in TSMP~~

driven by MPI-ESM-LR, 10.95 days and 6.80 days, respectively, and highest in REMO2015 driven by NCC-NorESM1-M, 12.72 days and 9.42 days, see Fig. ??-?? in Appendix A for details. The decadal change in the TG90p index decadal change averaged over the focus domain ranges from the lowest value of 1.13 days in REMO2015 driven by IPSL-CM5A-LR and the highest of 2.68 days in REMO2015 driven by NOAA GCM (Fig. ?? PRUDENCE regions and the focus domain, from the TSMP simulations and the CORDEX ensemble, are given in Appendix A)).

In particular, the The TSMP-simulated TG90p index simulated by TMSP is consistent with the CORDEX RCMs driven by the same MPI-ESM-LR GCMthat of MPI-ESM-LR driven RCMs from the CORDEX ensemble, although there are some regional differences (see Fig. 4a-d, Fig. 5a-d). The largest differences are found in the Iberian Peninsula, where TSMP produces the TG90p meanof 10.36 days and , Fig. 6a-d). On average over the focus domain, TSMP yields the lowest mean, variability, and decadal change of the TG90p mean simulated by the CORDEX index, among the MPI-ESM-LR driven RCMs is 12.54-12.75(see Tables days (see Fig. ?? A1, A2, A3 in Appendix A). At the same time, the interannual A comparison of TSMP simulations and MPI-ESM-LR driven RCMs from the CORDEX ensemble shows that the largest differences in the TG90p variability mean and variability occur in the Iberian Peninsula, with TSMP giving the lowest values. In this region, the mean TG90p index is equal to 10.36 days in TSMP and 12.54-12.75 days in the CORDEX RCMs driven by MPI-ESM-LR, at the same time the TG90p variability reaches 6.17 days in TSMP and 8.01-9.59 days in the CORDEX MPI-ESM-LR driven RCMs (see Fig. ?? RCMs driven by MPI-ESM-LR (see Tables A1, A2 in Appendix A). All considered RCMs driven by MPI-ESM-LR simulate a negative decadal change in As for the decadal change of the TG90p indexin Scandinavia, , TSMP as well as MPI-ESM-LR driven RCMs from the CORDEX ensemble simulate a negative trend in Scandinavia and a positive decadal change is observed trend in Southern and Central Europe(Fig. 6a-d). TSMP simulates, on average, a lower decadal change in the TG90p index in the focus domain than the CORDEX RCMs driven by MPI-ESM-LR (see Fig. ?? in Appendix A). The largest differences in the decadal change of the TG90p appear over index appear again in the Iberian Peninsula, where TSMP produces 2.26 and CORDEX RCMs driven by MPI-ESM-LR simulate with an increase of 3.66-4.252.26 hot days per decade .

From a comparison of TSMP and its most compatible CORDEX RCM, i.e., CCLM driven by in TSMP and 3.66-4.25 days per decade in the MPI-ESM-LR , with the largest differences in the lower boundary condition for COSMO accounting for groundwater feedbacks in TSMP , TSMP simulates overall lower TG90p mean and TG90p variability in all PRUDENCE regions, with the largest discrepancies over the Iberian Peninsula and the Mediterranean and the smallest differences in Scandinavia. The decadal change in the TG90p is also lower in all PRUDENCE regions except the Alps and Eastern Europe. driven RCMs from the CORDEX ensemble (see A3 in Appendix A). Different responses to groundwater coupling in different PRUDENCE regions may can be explained by the soil moisture-temperature feedback associated with different evaporative regimes, energy-limited in Scandinavia and Northern Europe versus moisture-limited in Southern Europe (e.g., Koster et al., 2009; Seneviratne et al., 2010; Jach et al., 2022).

3.2 Heat events of different durations

The ~~average summer seasonal~~ number of heat events (i.e., ~~a~~ series of consecutive hot days) of different ~~duration that occur in~~ durations that occur on average over the focus domain in the summer seasons between 1976 and 2005 is presented in Fig. 7a. The total number of heat events (of any duration) per summer per land grid element of the focus domain ~~varies between~~ ranges from the lowest value of 4.18 in COSMO-crCLIM driven by CNRM-CM5 ~~and~~ to the highest of 4.86 in REMO2015 driven by NCC-NorESM1-M. The ratio of the number of heat events between ~~CORDEX RCMs~~ RCMs from the CORDEX ensemble and TSMP (blue lines in Fig. 7a) increases towards heat events of long durations (≥6 days), i.e., heat waves~~, and~~ . It indicates that TSMP systematically simulates the least number of heat waves compared to the CORDEX ensemble. ~~REMO RCMs tend~~ A comparison of RCMs within the CORDEX ensemble suggests that REMO tends to simulate more heat waves ~~with~~ of long durations than COSMO~~RCMs~~.

~~(a) Average number of heat events (HEN, y-axis) of duration equal or larger than a given number of days (x-axis) as a function of this number of days; the averaging is performed over the total number of land grid elements of the focus domain and 30 years, from 1976 to 2005. (b) Frequency of heat waves (HWF, y-axis) with an intensity higher or equal than a given value in abscissa occurring in the focus domain from 1976 to 2005 as a function of this intensity. The panels also show the ratio of HEN and HWF from RCMs and TSMP. Data are taken from the summer seasons between 1976 and 2005 with respect to the reference period 1961-1990 in each RCM of the CORDEX ensemble. The representation of the dependencies is adopted from the work of Vautard et al. (2013a).~~

~~Different GCM-RCMs~~ Different RCMs simulate different spatial distributions of heat waves for the period 1976-2005, shown in Fig. 8, whereas TSMP ~~produces again~~ generates the smoothest distribution ~~of the decadal number of heat waves~~ compared to the CORDEX ensemble, resulting in the ~~least~~ smallest regional differences (see indicated standard deviations in Fig. 8). ~~The~~ Averaged over the focus domain, the decadal number of heat waves ~~over a decade in the focus domain ranges from~~ in the considered RCMs lies between the lowest value ~~of 3.25 in TSMP driven by MPI-ESM-LR, to the highest of 5.09~~ in TSMP (3.25) and the highest in REMO2015 driven by IPSL-CM5A-LR (~~Fig. ??~~ 5.09), see Table B1 in Appendix B~~)~~. Comparing TSMP ~~with CORDEX MPI-driven RCMs , CORDEX RCMs driven by~~ and MPI-ESM-LR driven RCMs from the CORDEX ensemble, TSMP simulates the most heat waves towards Central Europe, while the CORDEX RCMs simulate the highest number of heat waves ~~toward Southern Europe, while in TSMP the most heat waves are located in Central Europe (see Fig. 8a-d). Strong differences between TSMP and the CORDEX MPI-driven RCMs appear over~~ towards Southern Europe; strong differences are observed on the Iberian Peninsula and in the Mediterranean, and the smallest differences are in Scandinavia (see Fig. ~~??~~ 8a-d and Table B1 in Appendix B). When comparing TSMP with the most compatible RCM from the CORDEX ensemble, i.e., CCLM4-8-17 forced by MPI-ESM-LR, TSMP simulates fewer heat waves in all PRUDENCE regions except Mid-Europe~~, compared to the most compatible available CORDEX RCM, CCLM forced by MPI-ESM-LR~~.

~~Spatial distribution of the heat waves number (HWN) over a decade based on data from 1976 to 2005 with respect to the reference period 1961-1990, in the ensemble of EURO-CORDEX climate change scenario RCM control runs (see Table 1). The standard deviation is also indicated above each figure.~~

The contribution of heat waves to the total number of hot days during the summer ~~season varies among GCM-RCMs (~~seasons of 1976-2005 is presented in Fig. 9~~). Heat waves account from~~ , with TSMP giving the lowest value (22.38 %~~of hot days in TSMP driven by MPI-ESM-LR to 34.40 % in REMO2015 driven by IPSL-CM5A-LR,~~) on average in the focus domain (~~Fig. ??~~ Table B2 in Appendix B). The highest value is registered in REMO2015 driven by IPSL-CM5A-LR, where heat waves account for 34.40 %. Therefore, the proportion of heat events that do not belong to heat waves~~is higher in TSMP compared to the CORDEX ensemble, indicating that TSMP generates more heat events~~ , i.e., with a duration of ~~fewer~~ less than 6 days~~.~~ , is higher in TSMP compared to the CORDEX ensemble. On average, in the considered RCMs, Scandinavia is the region with the largest contribution of heat waves to the total number of hot days, ~~on average in the considered RCM ensemble,~~ which is expected to coincide with the region ~~with~~ of the highest number of heat waves~~(see Fig. 8)~~. Eastern Europe is the region with the least number of heat waves and the ~~smallest~~ lowest contribution of heat waves to the total number of hot days. The largest discrepancy between TSMP and the ~~CORDEX RCMs driven by the MPI-ESM-LR~~ MPI-ESM-LR driven RCMs from the CORDEX ensemble appear in the Iberian Peninsula and the Mediterranean.

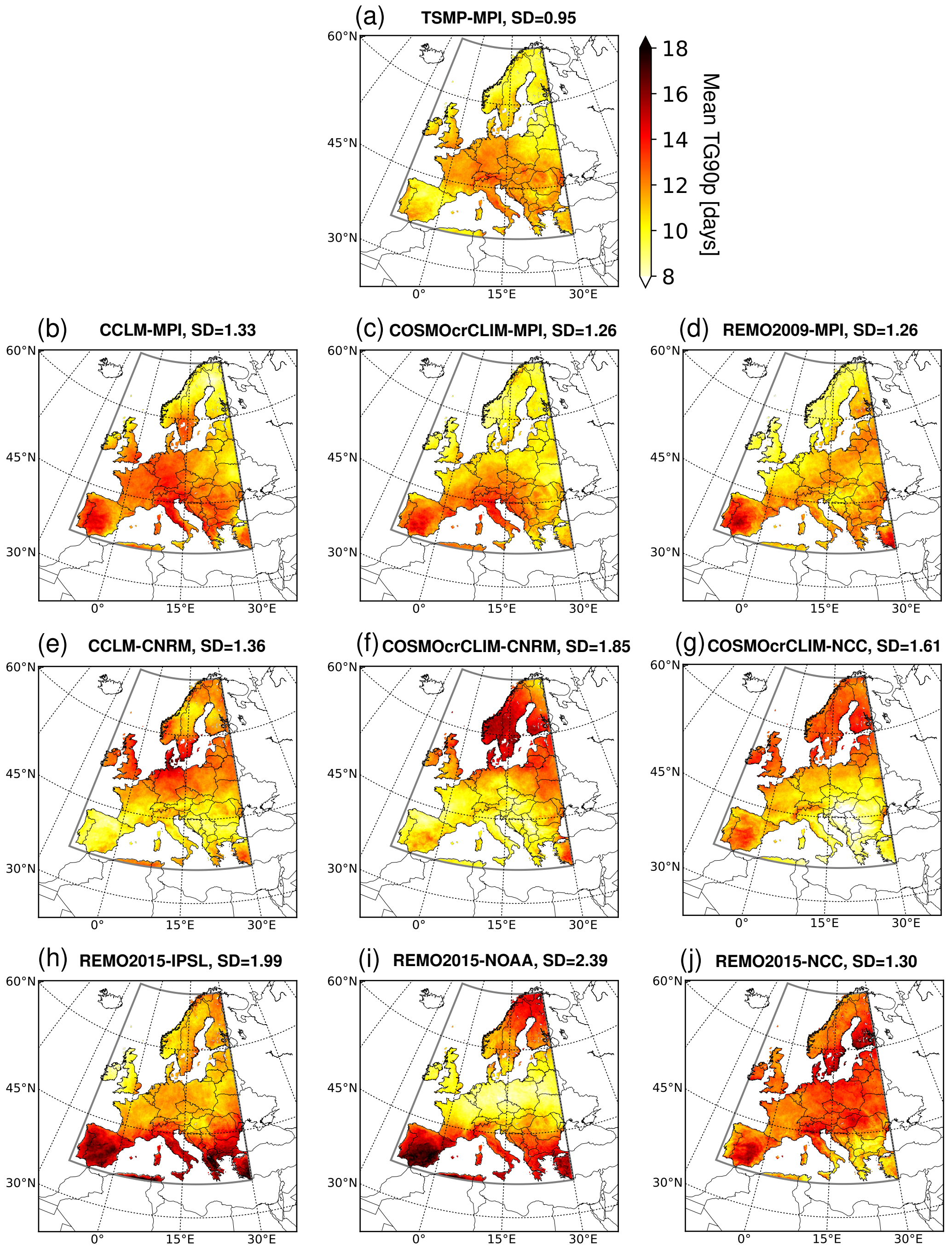


Figure 4. Spatial distribution of the ~~number of hot days (~~mean TG90p index ~~)~~ for the summer season averaged between 1976 and 2005 with respect to the reference period 1961-1990~~for the summer season~~, in TSMP and the CORDEX ensemble~~of EURO-CORDEX climate change scenario RCM control runs~~. The standard deviation (SD) ~~of the spatial distribution~~ is ~~also~~ indicated ~~on each~~ in every figure.

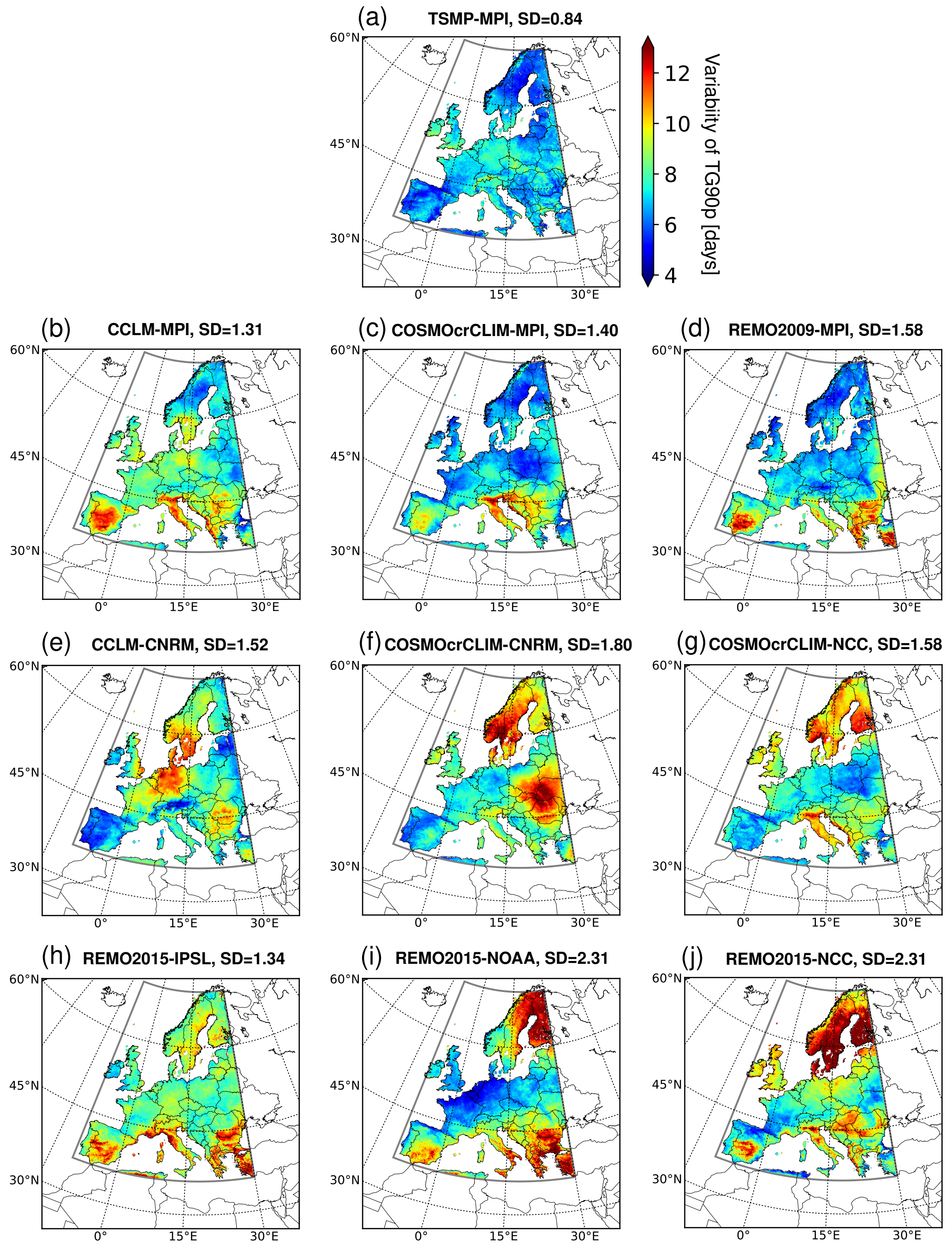


Figure 5. Variability of the ~~hot days number (~~TG90p index~~) for the summer season~~, calculated ~~for each land grid element~~ from the summer seasonal TG90p during 1976-2005 as the standard deviation ~~of TG90p between 1976 and 2005~~at each land grid element, ~~in~~ for TSMP and the CORDEX ensemble~~of EURO-CORDEX climate change scenario RCM control runs~~. The standard deviation (SD) of the spatial distribution of the TG90p variability is ~~also~~ indicated ~~on each~~ in every figure.

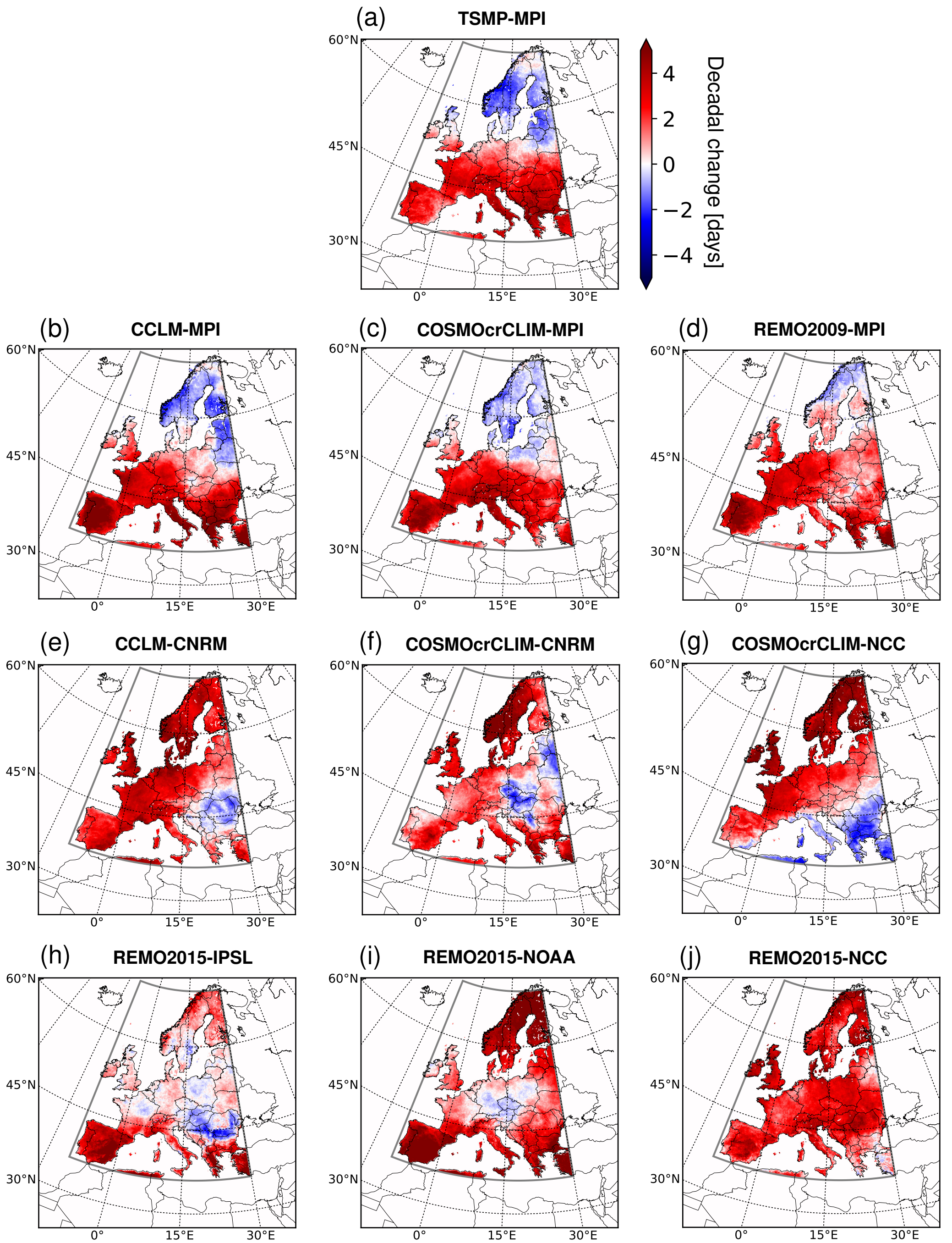
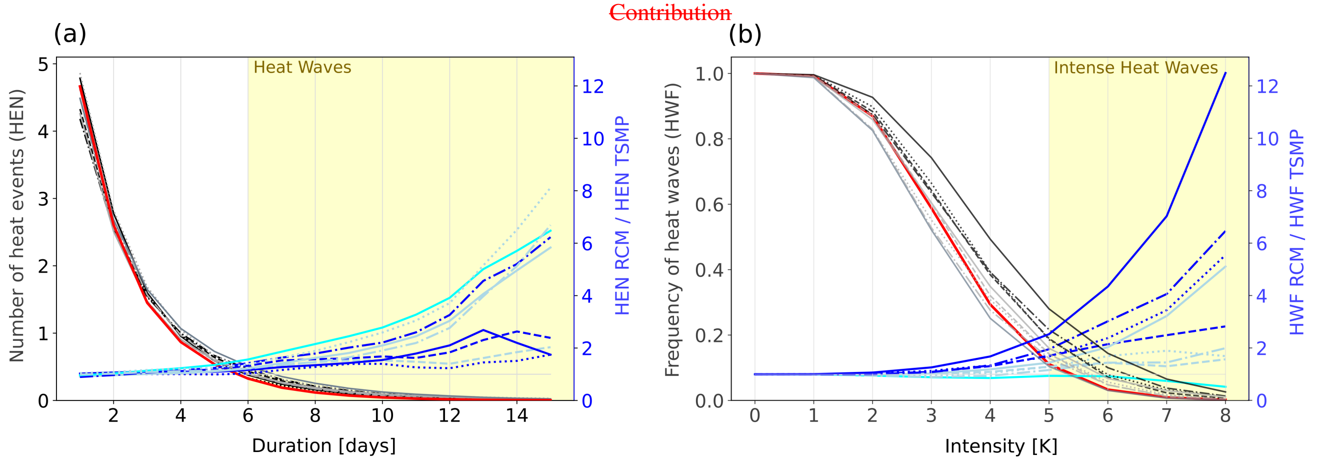


Figure 6. Spatial distribution of the decadal change in the ~~number of hot summer days (~~TG90p index~~)~~, ~~based on data~~ calculated from the summer seasonal TG90p from 1976 to 2005 ~~with respect to the reference period 1961-1990, in the ensemble of EURO-CORDEX climate change scenario RCM control runs. Decadal change is calculated~~ as a linear trend for ~~every~~ each land grid element, for TSMP and the CORDEX ensemble.

~~Contribution~~



RCM-GCM	Total HEN per land pixel
TSMP-MPI	4.66
CCLM-MPI	4.79
CCLM-CNRM	4.33
COSMO-crCLIM-MPI	4.62
COSMO-crCLIM-CNRM	4.18
COSMO-crCLIM-NCC	4.26
REMO2009-MPI	4.49
REMO2015-NCC	4.86
REMO2015-NOAA	4.63
REMO2015-IPSL	4.49

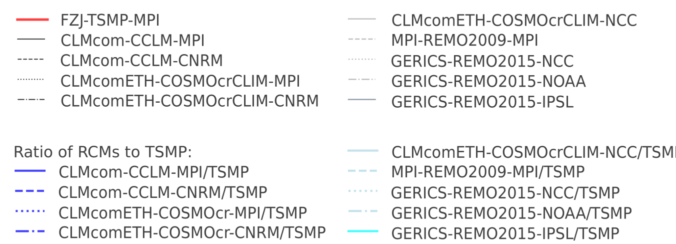


Figure 7. (a) Average number of summer heat ~~waves~~ events (HEN, y-axis) of duration equal to ~~the~~ or greater than a given number of ~~hot~~ days ~~%, calculated from the~~ (x-axis) as a function of this number of ~~hot~~ days; the averaging is performed over the total number of land grid elements of the focus domain and 30 years, from 1976 to 2005. (b) Frequency of heat waves ~~accumulated~~ (HWF, y-axis) with intensities equal to or higher than a value indicated on the abscissa, that occur in the focus domain from 1976 to 2005 as a function of this intensity. The panels also show the ratio of HEN and HWN values between RCMs from the CORDEX ensemble and TSMP. Data are taken from the summer seasons between 1976 and 2005 ~~,~~ with respect to the reference period 1961-1990 in each RCM. The representation of the ~~ensemble~~ dependencies is adopted from the work of ~~EURO-CORDEX climate change scenario RCM control runs~~Vautard et al. (2013a).

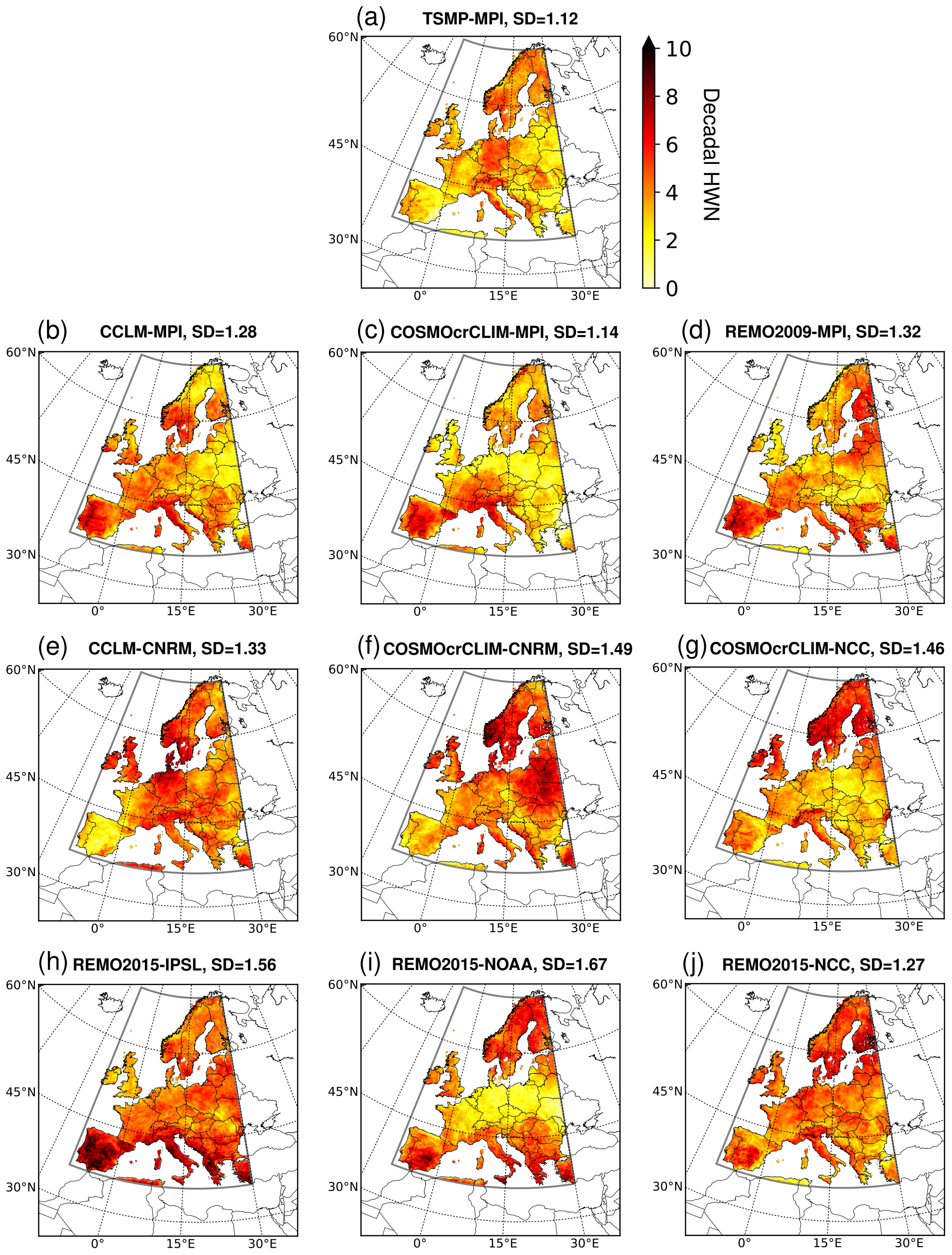


Figure 8. Spatial distribution of the decadal number of heat waves (HWN) based on data from 1976 to 2005 with respect to the reference period 1961-1990, in TSMP and the CORDEX ensemble. The standard deviation (SD) is indicated in every figure.

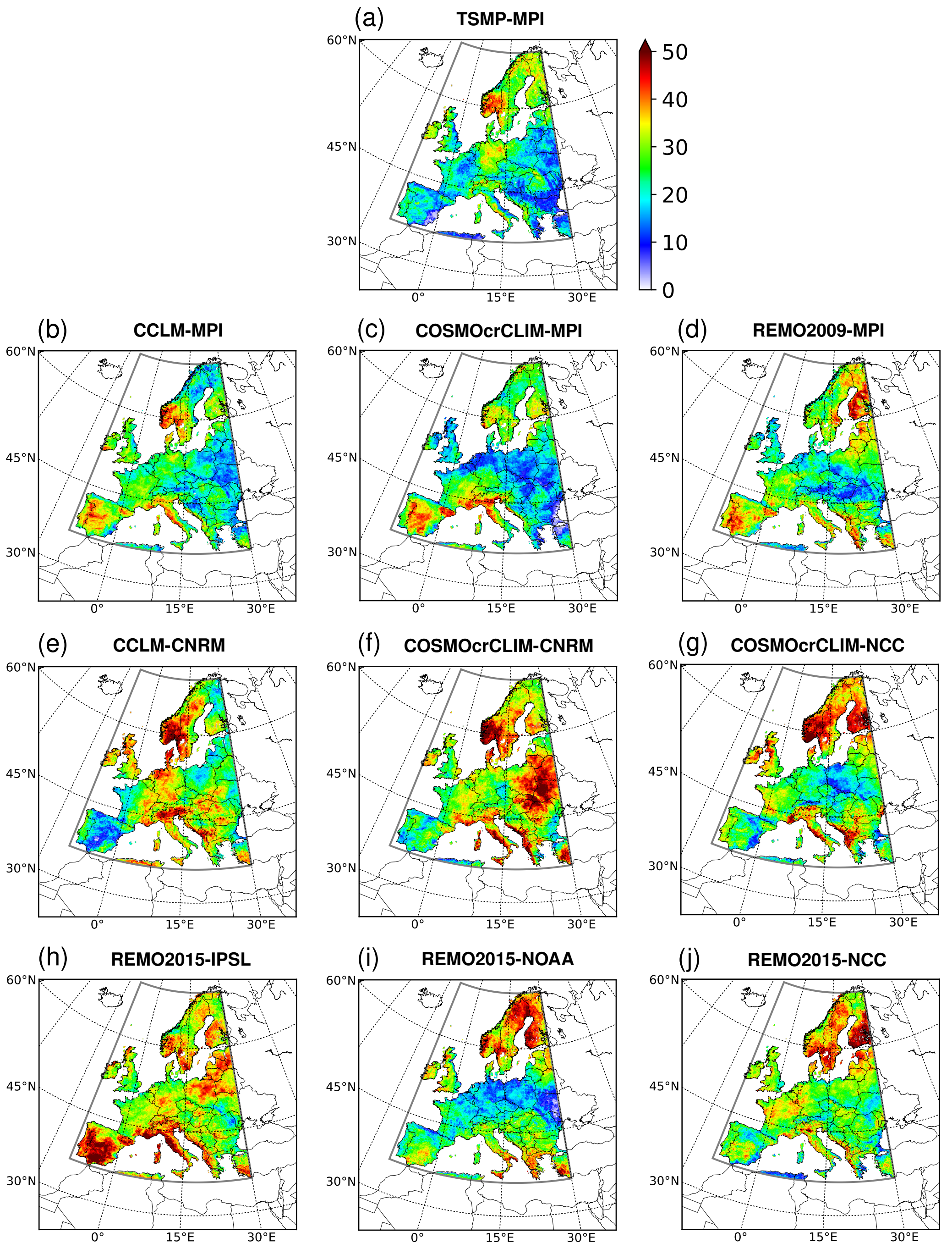


Figure 9. Contribution of heat waves to the number of hot days [%], calculated from the total number of heat waves and hot days accumulated between 1976 and 2005, for TSMP and the CORDEX ensemble.

3.3 Heat waves of different intensities

The dependence of the frequency of heat waves ~~, which~~ that occurred between 1976 and 2005 in the focus domain ~~, on the intensity~~ on their intensities is shown in Fig. 7b. The maximum frequency of heat waves is equal to 1 for an intensity greater than 0~~because~~, since all heat waves are taken into account for each RCM. The ratio of the frequency of heat waves between ~~CORDEX RCMs~~ RCMs from the CORDEX ensemble and TSMP (blue lines in Fig. 7b) increases toward intense heat waves ($\geq$5 K). It shows a systematic behavior of TSMP to simulate less intense heat waves on average in the focus domain compared to the CORDEX ensemble. The largest discrepancy is found between TSMP and ~~CCLM driven~~ CCLM4-8-17 forced by MPI-ESM-LR (blue solid line in Fig. 7b), up to a factor of 12 or even more, depending on the intensity considered. ~~The REMO RCM, driven by different GCMs, shows the smallest differences to TSMP, while~~ Overall, when comparing RCMs within the CORDEX ensemble, COSMO tend to simulate more intense heat waves than REMO. And REMO2015 driven by IPSL-CM5A-LR simulates even less intense heat waves than TSMP. ~~Overall, COSMO RCMs tend to simulate more intense heat waves than REMO RCMs.~~

~~Frequency of heat waves (HWF) with an intensity above 5 K occurring between 1976 and 2005 with respect to the reference period 1961-1990, in the ensemble of EURO-CORDEX climate change scenario RCM control runs.~~

The spatial distribution of the intense heat waves ~~differs between GCM-RCMs~~is presented in Fig. 10, with their highest frequency in France and ~~Scandinavia and the~~ lowest in the Alps, on average ~~in the CORDEX ensemble (Fig. 10, Fig. **??**~~ among the considered RCMs (Table B3 in Appendix B). Note that the frequency ~~is defined in relation~~ here is calculated relative to the total number of heat waves in each RCM, see Sec. 2.4 for definitions. The mean frequency of intense heat waves in the focus domain ranges from the lowest value ~~of 0.174~~ in REMO2015 driven by IPSL-CM5A-LR (0.174) to the highest ~~of 0.301 in CCLM~~ value in CCLM4-8-17 driven by MPI-ESM-LR ~~, i.e. ,~~ (0.301). It indicates that 17.4-30.1 % of all simulated heat waves exceed the intensity of 5 K. ~~Compared to CCLM driven~~ When comparing TSMP with the most compatible RCM from the CORDEX ensemble, i.e., CCLM4-8-17 forced by MPI-ESM-LR, TSMP simulates a lower frequency of intense heat waves in all PRUDENCE regions except Scandinavia. The largest discrepancies ~~and the highest number of intense heat waves are~~ between TSMP and CCLM4-8-17 forced by MPI-ESM-LR are observed in France, ~~with TSMP simulating~~ where TSMP simulates 24.6 % and CCLM4-8-17 46.8 % of all heat waves as intense~~and CCLM – 46.8 %,~~, the smallest differences are found in Scandinavia, ~~where TSMP simulates~~ with 19.3 % ~~of all heat waves as intense and CCLM –~~ intense heat waves in TSMP and 17.5 % in CCLM4-8-17. It is important to note that the regions ~~with~~ of the highest number of heat waves do not necessarily coincide with the regions ~~with~~ of the highest number of intense heat waves (see Fig. 8 and Fig. 10), in other words, intense heat waves do not necessarily occur where the majority of heat waves are detected. The origin of these differences should be further investigated and is beyond the scope of this analysis.

4 Summary and conclusions

~~In this study, we presented , in the context of dynamical downscaling of GCMs with RCMs experiment for climate change studies,~~ We presented a first-of-its-kind TSMP dataset forced by the CMIP5 MPI-ESM-LR GCM boundary conditions, ~~where~~

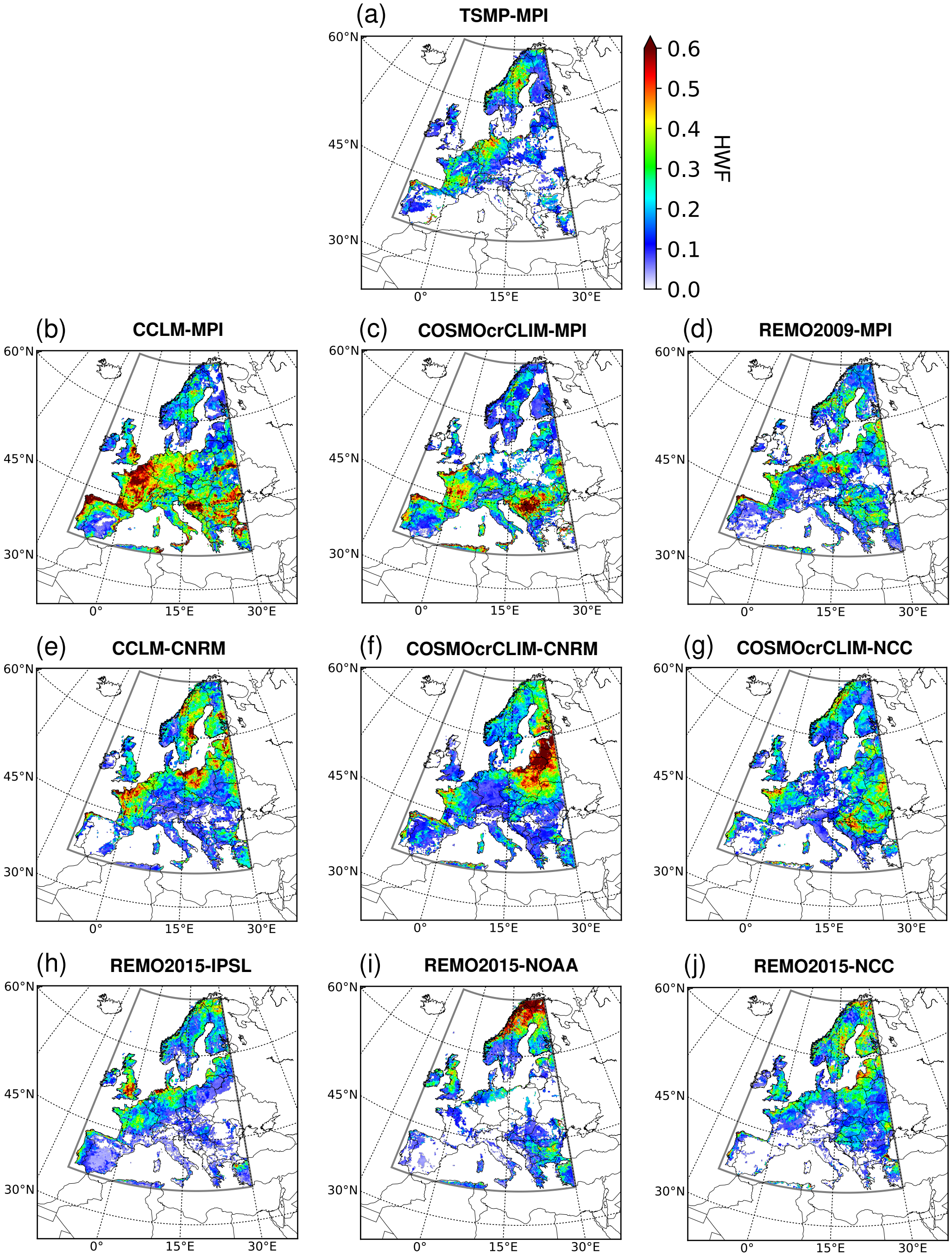


Figure 10. Frequency of heat waves (HWF) with intensities above 5 K occurring between 1976 and 2005 with respect to the reference period 1961-1990, in TSMP and the CORDEX ensemble.

with an explicit representation of 3D groundwater hydrodynamics~~were explicitly represented. We studied~~ , in the context of dynamical downscaling of GCMs for climate change studies. By comparing the TSMP simulation results with those of the RCMs with simplified groundwater dynamics from the CORDEX ensemble, we investigated the impact of groundwater ~~coupling~~ dynamics on the statistics of simulated heat events in ~~regional historical climate simulations~~historical regional climate simulations over Europe, with potential implications for climate change projections~~, by comparing TSMP results with the ensemble of EURO-CORDEX climate change scenario RCM control runs driven as well by CMIP5 GCMs~~. In particular, we ~~investigated the number of hot days and heat waves~~ examined the characteristics of heat events of different durations and intensities ~~in Europe~~ during the summer season between 1976 and 2005 ~~relative~~ with respect to the reference period 1961-1990 in each RCM.

Our ~~analysis shows that TSMP simulates heat events consistently with the EURO-CORDEX~~ results show that the characteristics of the TSMP-simulated heat events are consistent with the CORDEX ensemble, although there are ~~statistical differences and we relate these~~ systematic differences that we attribute to groundwater coupling. TSMP simulates lower ~~means~~ mean values as well as ~~a~~ lower interannual variability in the number of hot days on average in Europe, compared to the CORDEX ensemble. The decadal change in the number of hot days ~~over Europe in TSMP~~ is also lower in TSMP compared to the CORDEX ensemble ~~average. TSMP systematically~~ mean. TSMP simulates fewer heat waves and tends to simulate less intense heat waves compared to the CORDEX ensemble. The most sensitive regions to groundwater coupling ~~appear to be~~ are the Iberian Peninsula and the Mediterranean, while Scandinavia is the least sensitive.

~~From a comparison of TSMP and CCLM driven by MPI-ESM-LR, with the largest differences in the COSMO lower boundary condition accounting for groundwater feedbacks in TSMP, we found that TSMP in the considered focus domaincovering Europe simulates on average lower~~Comparing TSMP with the most compatible RCM from the CORDEX ensemble, i.e., CCLM4-8-17 forced by MPI-ESM-LR, we find that TSMP simulates lower values of hot days and heat waves characteristics, on average over the focus domain, based on the 1976-2005 data, namely:

- mean number of hot days~~(TSMP –~~: 10.95 days ~~, CCLM –~~in TSMP and 11.80 days ~~)~~in CCLM4-8-17;
- variability of the number of hot days~~(TSMP –~~: 6.80 days ~~, CCLM –~~TSMP and 8.33 days ~~)~~in CCLM4-8-17;
- decadal change in the number of hot days~~(TSMP –~~: 1.53 days ~~, CCLM –~~in TSMP and 1.86 days ~~)~~in CCLM4-8-17;
- decadal number of heat waves~~(TSMP –~~: 3.25 ~~, CCLM –~~in TSMP and 3.78 ~~)~~in CCLM4-8-17;
- contribution of heat waves to the number of hot days~~(TSMP –~~: 22.38 % ~~, CCLM –~~in TSMP and 24.96 % ~~)~~in CCLM4-8-17;
- frequency of intense heat waves~~(TSMP –~~: 0.193 ~~, CCLM –~~in TSMP and 0.301 ~~)~~in CCLM4-8-17.

This study clearly indicates that a coupled regional climate system with a closed terrestrial water cycle, such as TSMP, systematically simulates a different climatology of heat ~~event~~ events compared to uncoupled RCMs. The explicit representation of ~~subsurface hydrodynamics and groundwater~~ groundwater hydrodynamics in RCMs may be a key for the reduction of biases in the simulated duration and intensity of heat waves, particularly in Southern Europe. ~~In the future, this work will be extended~~

to investigate the evolution of heat events under different climate change scenarios in TSMP compared to uncoupled RCMs and their control simulations.

Appendix A: ~~Number~~ Average characteristics of hot days for different regions

RCMs \ Regions	BI	IP	FR	ME	SC	AL	MD	EA	FD
TSMP-MPI	10.95	10.36	11.50	11.76	10.00	12.20	11.40	11.13	10.95
CCLM-MPI	11.49	12.64	12.46	12.80	10.42	13.27	12.62	11.50	11.80
COSMO-crCLIM-MPI	9.94	12.54	11.28	11.18	9.93	12.91	12.03	10.82	11.10
REMO2009-MPI	9.45	12.75	10.82	10.90	10.24	11.56	11.59	11.28	11.14
CCLM4-CNRM	12.89	9.66	10.93	12.62	12.06	10.74	10.49	11.16	11.32
COSMO-crCLIM-CNRM	12.05	10.14	9.87	10.87	13.87	10.15	9.85	11.26	11.46
COSMO-crCLIM-NCC	12.78	11.66	11.21	10.96	12.84	10.76	9.02	9.91	11.10
REMO2015-NCC	12.61	12.89	12.06	12.86	13.31	13.27	11.27	12.95	12.72
REMO2015-IPSL	9.56	15.00	11.45	11.48	11.29	12.64	15.25	11.63	12.38
REMO2015-NOAA	9.96	15.33	10.54	8.98	12.21	11.56	13.87	10.05	11.77

Table A1. Mean number of hot days, i.e. ~~,~~ TG90p index ~~,~~ [days], for the summer season averaged between 1976 and 2005 with respect to the reference period 1961-1990, in TSMP and the CORDEX ensemble~~of EURO-CORDEX climate change scenario RCM control runs~~ , for the focus domain (FD) and the PRUDENCE regions: British Isles (BI), Iberian Peninsula (IP), France (FR), Mid-Europe (ME), Scandinavia (SC), Alps (AL), Mediterranean (MD), Eastern Europe (EA); see Fig. 4 for the spatial distribution.

RCMs \ Regions	BI	IP	FR	ME	SC	AL	MD	EA	FD
TSMP-MPI	7.68	6.17	6.92	7.43	6.26	7.50	6.93	6.93	6.80
CCLM-MPI	8.50	9.59	8.30	8.53	7.45	8.82	9.34	8.02	8.33
COSMO-crCLIM-MPI	6.75	8.01	6.56	6.90	6.56	8.56	9.00	7.42	7.38
REMO2009-MPI	6.73	8.94	7.36	6.81	6.48	7.39	9.37	7.62	7.62
CCLM4-CNRM	8.07	6.37	8.72	10.00	8.47	7.32	8.28	8.17	8.21
COSMO-crCLIM-CNRM	8.50	6.84	7.38	7.42	10.22	8.38	8.19	10.31	8.90
COSMO-crCLIM-NCC	9.24	6.89	7.91	7.41	10.06	8.73	8.79	7.59	8.37
REMO2015-NCC	9.94	8.05	7.21	8.57	12.21	8.48	8.86	8.77	9.42
REMO2015-IPSL	7.74	9.51	8.16	8.39	8.94	9.60	10.13	8.40	8.97
REMO2015-NOAA	6.88	8.71	6.18	5.87	10.24	8.05	10.49	8.11	8.69

Table A2. Variability of the hot days number, i.e. ~~,~~ TG90p index ~~,~~ [days]~~for~~ , calculated from the summer ~~season from 1976 to 2005 with respect to~~ seasonal TG90p during 1976-2005 as the ~~reference period 1961-1990 in~~ standard deviation at each land grid element, for TSMP and the CORDEX ensemble~~of EURO-CORDEX climate change scenario RCM control runs~~ , for the focus domain (FD) and the PRUDENCE regions: British Isles (BI), Iberian Peninsula (IP), France (FR), Mid-Europe (ME), Scandinavia (SC), Alps (AL), Mediterranean (MD), Eastern Europe (EA); see Fig. ~~4~~ 5 for the spatial distribution.

RCMs \ Regions	BI	IP	FR	ME	SC	AL	MD	EA	FD
TSMP-MPI	0.62	2.26	2.90	1.52	-0.98	3.33	3.74	1.84	1.53
CCLM-MPI	1.39	4.25	3.49	2.03	-0.89	3.29	4.40	1.21	1.86
COSMO-crCLIM-MPI	0.79	3.66	2.87	1.98	-0.62	4.02	2.86	1.47	1.68
REMO2009-MPI	1.80	3.69	3.29	2.67	0.15	2.50	2.65	1.29	1.88
CCLM4-CNRM	3.56	2.78	3.52	3.40	3.29	2.88	1.66	0.43	2.35
COSMO-crCLIM-CNRM	3.00	1.76	1.34	1.36	2.95	1.49	2.54	0.08	1.77
COSMO-crCLIM-NCC	4.50	1.58	3.56	2.43	4.09	1.32	-1.24	0.52	1.87
REMO2015-NCC	3.92	2.64	2.23	2.51	3.08	3.17	1.97	2.85	2.71
REMO2015-IPSL	0.55	3.89	0.57	0.23	0.87	1.27	2.22	-0.20	1.13
REMO2015-NOAA	1.11	5.18	1.44	0.13	4.27	1.27	3.49	1.16	2.68

Table A3. Decadal change in the number of hot days, i.e. ~~,~~ TG90p index ~~,~~ [days]~~in~~ , calculated from the summer ~~season, based on data~~ seasonal TG90p from 1976 to 2005 ~~with respect to the reference period 1961-1990~~as a linear trend for each land grid element, ~~in~~ for TSMP and the CORDEX ensemble~~of EURO-CORDEX climate change scenario RCM control runs~~ , for the focus domain (FD) and the PRUDENCE regions: British Isles (BI), Iberian Peninsula (IP), France (FR), Mid-Europe (ME), Scandinavia (SC), Alps (AL), Mediterranean (MD), Eastern Europe (EA); see Fig. 6 for the spatial distribution.

Appendix B: ~~Heat waves~~ Average characteristics of heat waves for different regions

RCMs \ Regions	BI	IP	FR	ME	SC	AL	MD	EA	FD
TSMP-MPI	3.33	2.51	3.15	4.01	3.83	4.13	3.04	2.74	3.25
CCLM-MPI	3.85	4.88	4.20	3.84	3.59	4.50	4.48	2.86	3.78
COSMO-crCLIM-MPI	2.54	4.99	3.73	2.78	3.46	5.27	3.59	2.34	3.35
REMO2009-MPI	2.70	5.25	4.17	3.30	4.17	3.50	4.40	3.24	3.89
CCLM4-CNRM	5.25	2.53	3.57	5.31	4.69	5.09	4.43	4.15	4.31
COSMO-crCLIM-CNRM	4.84	3.18	3.69	4.09	5.65	4.03	4.18	5.27	4.63
COSMO-crCLIM-NCC	5.24	3.66	3.86	3.15	5.61	4.10	3.43	2.92	3.97
REMO2015-NCC	4.42	4.23	4.15	4.64	5.52	4.69	3.92	4.01	4.49
REMO2015-IPSL	3.21	7.25	4.49	4.23	4.44	5.59	6.77	4.58	5.09
REMO2015-NOAA	3.91	4.93	3.10	2.02	5.03	3.57	5.42	2.62	3.95

Table B1. Decadal number of heat waves based on data from 1976 to 2005 with respect to the reference period 1961-1990, in TSMP and the CORDEX ensemble~~of EURO-CORDEX climate change scenario RCM control runs~~, for the focus domain (FD) and the PRUDENCE regions: British Isles (BI), Iberian Peninsula (IP), France (FR), Mid-Europe (ME), Scandinavia (SC), Alps (AL), Mediterranean (MD), Eastern Europe (EA); see Fig. 8 for the spatial distribution.

RCMs \ Regions	BI	IP	FR	ME	SC	AL	MD	EA	FD
TSMP-MPI	25.36	17.47	19.62	25.61	29.87	24.40	19.33	17.79	22.38
CCLM-MPI	27.90	31.19	26.29	24.34	26.50	27.79	26.67	18.82	24.96
COSMO-crCLIM-MPI	18.78	31.96	25.50	18.49	27.59	33.62	24.46	16.27	23.46
REMO2009-MPI	21.81	33.04	28.35	22.39	32.63	23.50	30.18	21.92	27.22
CCLM4-CNRM	34.53	18.35	25.45	33.01	31.69	37.74	34.53	28.08	29.72
COSMO-crCLIM-CNRM	29.75	23.36	29.21	29.31	36.52	32.75	35.54	38.21	33.11
COSMO-crCLIM-NCC	34.70	23.94	30.71	23.12	39.04	30.05	33.07	23.70	29.61
REMO2015-NCC	30.16	25.39	32.05	29.06	38.37	29.72	27.54	26.69	30.20
REMO2015-IPSL	30.39	41.20	30.57	31.56	35.26	38.26	36.73	31.75	34.40
REMO2015-NOAA	30.77	25.20	21.41	16.51	37.52	24.58	32.54	19.36	26.97

Table B2. Contribution of heat waves to the number of hot days [%]~~during 1976-2005 with respect to~~ , calculated from the ~~reference period 1961-1990~~total number of heat waves and hot days accumulated between 1976 and 2005, ~~in~~ for TSMP and the CORDEX ensemble~~of EURO-CORDEX climate change scenario RCM control runs~~, for the focus domain (FD) and the PRUDENCE regions: British Isles (BI), Iberian Peninsula (IP), France (FR), Mid-Europe (ME), Scandinavia (SC), Alps (AL), Mediterranean (MD), Eastern Europe (EA); see Fig. 9 for the spatial distribution.

RCMs \ Regions	BI	IP	FR	ME	SC	AL	MD	EA	FD
TSMP-MPI	0.118	0.189	0.246	0.233	0.193	0.145	0.171	0.148	0.193
CCLM-MPI	0.246	0.305	0.468	0.395	0.175	0.326	0.318	0.319	0.301
COSMO-crCLIM-MPI	0.181	0.246	0.361	0.216	0.152	0.213	0.262	0.318	0.241
REMO2009-MPI	0.173	0.156	0.207	0.230	0.211	0.125	0.180	0.218	0.202
CCLM4-CNRM	0.185	0.199	0.356	0.244	0.290	0.121	0.125	0.218	0.233
COSMO-crCLIM-CNRM	0.111	0.187	0.236	0.157	0.309	0.106	0.143	0.293	0.232
COSMO-crCLIM-NCC	0.160	0.188	0.234	0.163	0.193	0.105	0.165	0.268	0.204
REMO2015-NCC	0.181	0.173	0.163	0.166	0.267	0.082	0.123	0.184	0.205
REMO2015-IPSL	0.287	0.112	0.219	0.214	0.203	0.112	0.084	0.108	0.174
REMO2015-NOAA	0.213	0.094	0.120	0.197	0.294	0.101	0.144	0.141	0.213

Table B3. Frequency of heat waves with ~~intensity exceeding~~ intensities greater than 5 K based on data from 1976 to 2005 with respect to the reference period 1961-1990, in TSMP and the CORDEX ensemble~~of EURO-CORDEX climate change scenario RCM control runs~~, for the focus domain (FD) and the PRUDENCE regions: British Isles (BI), Iberian Peninsula (IP), France (FR), Mid-Europe (ME), Scandinavia (SC), Alps (AL), Mediterranean (MD), Eastern Europe (EA); see Fig. 10 for the spatial distribution.

Code and data availability. The TSMP v1.2.2 used in this work is available through https://github.com/HPSCTerrSys/TSMP GIT repository. The TSMP dataset forced by MPI-ESM-LR r1i1p1 can be accessed at https://datapub.fz-juelich.de/slts/regional_climate_tsmp_hi-cam/ as open access research data.

Author contributions. The study was designed by S.K. with contributions by K.G., L.P-S., and N.W.. L.P.-S. performed the model simulations and data processing, N.W. provided technical and programming support, C.H. provided setups, configuration, and workflow support. The analysis was developed and conducted by L.P.-S. with further inputs from S.K. and K.G.. L.P.-S. wrote the manuscript. All co-authors contributed to the interpretation of the results, active discussions, and revisions of the paper. The work was done under the supervision of S.K..

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This work was funded by the Helmholtz Association of German Research Centres (HGF) under the HI-CAM project (Helmholtz Initiative Climate Adaptation and Mitigation) and by the German Ministry of Education and Research (Bundesministerium für Bildung und Forschung, BMBF) under the ClimXtreme project. We ~~thank the EURO-CORDEX climate modelling groups for producing and making available their model output. We~~ are grateful to the Max-Planck Institute for performing MPI-ESM-LR r1i1p1 GCM experiment and the German Climate Computing Centre (DKRZ) for providing the MPI-ESM-LR dataset. We thank the EURO-CORDEX climate modelling groups for producing and making available their model output. The authors gratefully acknowledge the Earth System Modelling Project (ESM) for funding this work by providing computing time on the ESM partition of the supercomputer JUWELS at the Jülich Supercomputing Centre (JSC) under the ESM project ID JIBG35. In addition, we thank the Centre for High-Performance Scientific Computing in Terrestrial Systems (Geoverbund ABC/J, http://www.hpsc-terrsys.de) and the JSC for the computational support. Finally, we thank three anonymous reviewers for the constructive comments that helped improve the paper.

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