1 **The potential of an increased deciduous forest fraction to mitigate the effects of heat extremes in**
2 **Europe**

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12 **Abstract**
13 Deciduous forests are characterized by a higher albedo, a reduced stomatal resistance and a deeper
14 root system in comparison to coniferous forests. As a consequence, less solar radiation is absorbed
15 and evapotranspiration is potentially increased, making an increase in the deciduous forest fraction
16 potentially a promising measure to mitigate the burdens of heat extremes for humans and nature. We
17 analyze this potential by means of an idealized 30 years long regional climate model experiment, in
18 which all coniferous forests in Europe are replaced by deciduous forests and compared to a simulation
19 using the actual forest composition.
20 Results show that an increase in the deciduous forest fraction reduces the heat intensity during heat
21 periods in most regions of Europe. In mean, a slight reduction of the daily maximum 2 m temperatures
22 about 0.2 K is simulated locally, and 0.1 K non-locally during heat periods. Regions with a high cooling
23 potential are south-western France and northern Turkey, where heat period intensities are reduced
24 up to 1 K. Warming effects are simulated in Scandinavia and Eastern Europe.
25 Although the cooling effect on heat period intensities is statistically significant over large parts of
26 Europe, the magnitude of the temperature reduction is small. An increase in the deciduous forest
27 fraction has consequently only a limited potential to reduce heat period intensities in Europe and can
28 therefore only be considered as a supporting mitigation measure to complement more effective
29 mitigation strategies.

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1. Introduction

More frequent and more intense heat periods constitute one of the most serious impacts of anthropogenic climate change in Europe (Seneviratne et al., 2021). Since the 1950s, the number of days with extreme heat has tripled and the intensity of heat extremes has increased about 2,3 K in Europe (Lorenz et al., 2019). Although the intensities and characteristics of heat extremes depend on the applied heat extreme indices (Becker et al., 2022), the results of the latest CMIP6 projections indicate that this trend will further continue within the next decades (Li et al., 2021). The resulting heat stress will entail enormous burdens for humans and nature. Therefore, in order to minimize future heat extreme impacts, effective mitigation strategies will be required.

In this context, one of the most frequently debated mitigation strategies to man-made climate change is afforestation (e.g. Sonntag et al., 2016; Harper et al., 2018). Forests actively remove CO_2 from the atmosphere and store the carbon long-term in their biomass (Pan et al., 2011). Thus, afforestation has a beneficial biogeochemical effect on the greenhouse effect. Furthermore, the capability of forests to transpire water is higher than for other vegetation types (Bonan, 2008). A larger part of the available energy at the surface can consequently be transformed into latent heat instead of heating up the land surface (Strandberg & Kjellström, 2019).

Beyond these beneficial effects on the local surface energy balance, afforestation can also affect climate conditions non-locally (Winckler et al., 2019). For instance, Meier et al., (2021) showed that forests increase downwind precipitation in most regions of Europe, partially counteracting the projected precipitation decrease from climate change. Afforestation is therefore an indispensable component of all shared socio-economic pathways (SSPs) to reach the target of the Paris agreement to keep the rise in mean global temperature well below 2 K above pre-industrial levels (Roe et al., 2019).

However, the efficiency of afforestation as a mitigation strategy strongly depends on the planted forest type (Jackson et al., 2008; Anderson et al., 2011). For instance, deciduous forests are brighter than coniferous forests (e.g. Breuer et al., 2003; Jackson et al., 2008; Otto et al., 2014). Thus, less solar radiation is absorbed and the energy input into the climate system is reduced. Moreover, deciduous forests are characterized by a deeper root system (e.g. Canadell et al., 1996) and a reduced stomatal resistance (Breuer et al., 2003; Carnicer et al., 2013). As a consequence, deciduous forests are able to extract water from deeper soil layers and the available amount of soil water for evapotranspiration is increased, reducing the water stress particularly during heat periods (e.g. Brinkmann et al., 2019). Due to the reduced stomatal resistance of deciduous forest, the release of this additional water amount into the atmosphere via transpiration is facilitated and surface temperatures are reduced. The general effects of different forest types on the climate conditions are already documented (e.g. Duveiller et al., 2018; Luyssaert et al., 2018). For instance, using a statistical model based on remote sensing data,

71 Schwaab et al., (2020) concluded that deciduous forests have an increased cooling effect on heat
72 extremes in comparison to coniferous forests.

73 However, the current composition of European forests is dominated by coniferous trees (Bartholome
74 & Belward, 2005), due to forestry reasons. The composition of primary European forests is different
75 and depends on the regional conditions. In boreal and mountainous regions, cold and wet climate
76 conditions cause a leaching and acidification of soils, favoring the dominant establishment of cold-
77 tolerant coniferous trees (Bohn et al., 2000). Otherwise, primary European forests are mainly
78 characterized by large deciduous tree fractions, like beech (Bohn et al., 2000). After humans started to
79 cultivate landscapes in the course of the Holocene, European forests were extensively cleared for
80 croplands, timber and firewood (Kaplan et al., 2009), particularly during the medieval period (Pongratz
81 et al., 2008). As a consequence, the forest cover on usable land for agriculture declined to under 6 %
82 in central and western Europe in the mid-19th century (Kaplan et al., 2009). The resulting scarcity of
83 timber and firewood made the management of forests necessary, which led to an intensive plantation
84 of coniferous trees (McGrath et al., 2015). The persistent cold climate conditions of the so-called "little
85 ice age" during this period, and the high yields of coniferous trees, favored their cultivation in Europe.
86 This yield-orientation is still driving forest management today (Ceccherini et al., 2020), and is the
87 reason why today primary forests cover only 0.7 % of Europe's forest area (Sabatini et al., 2021).

88 The resulting high proportion of coniferous trees in today's European forests and the associated dark
89 vegetation surface has the consequence that comparatively large amounts of solar radiation are
90 absorbed, and a relatively lower fraction of this available energy amount is transformed into latent
91 heat. The energy balance of European forests is consequently not ideal, potentially increasing the
92 intensity and duration of heat extremes. Therefore, a potential strategy to optimize this energy
93 balance, and thus, to mitigate hot temperature extremes in Europe is an increase in the broadleaf tree
94 fraction in European forests. The goal of this study is to investigate this mitigation potential and
95 quantify its effects in an idealized setup.

96 For this purpose, we designed an idealized multidecadal modeling experiment, in which the whole
97 coniferous forest fraction in Europe is replaced by deciduous forest. In order to simulate the complex
98 effects of such a forest replacement on the regional climate system as accurately as possible, a regional
99 climate model (RCM) is applied, by which global reanalysis data are downscaled over Europe. The
100 results of this RCM simulation are compared with the results of a reference simulation, in which the
101 actual composition of European forests is used. By means of this idealized modeling experiment, we
102 are able to quantify the general potential effect of an increase in the deciduous forest fraction on heat
103 extreme characteristics in Europe. The design of the modeling experiment is described in section 2. In
104 section 3, the general potential effect of an optimized composition of European forests on the intensity

105 (section 3.1) and duration (section 3.2) of heat periods is assessed. Results are discussed in section 4

106 and conclusions are drawn in section 5.

107

108 **2. Methods**

109 In the course of this study, the regional climate model COSMO-CLM (CCLM, Rockel et al., 2008) is two-

110 way coupled to the Land Surface Model VEG3D (Breil & Schädler, 2021) and used to simulate the

111 effects of an increased deciduous forest fraction on heat extremes in Europe. The CCLM-VEG3D runs

112 are performed for the Coordinated Downscaling Experiment – European Domain (EURO-CORDEX;

113 Jacob et al., 2014) on a horizontal resolution of 0.11° (~12.5 km). All simulations were driven by ERA5

114 reanalyses (Hersbach et al., 2020) at the lateral boundaries and the lower boundary over sea. The

115 simulation period is 1986–2015 and a spin-up of 7 years was performed before 1986.

116 In the first simulation, yearly updated maps of the actual land cover conditions in Europe are

117 implemented in CCLM-VEG3D (Fig. 1a). This experiment constitutes the reference simulation (REF).

118 The applied land use maps were developed in the framework of the Land Use and Climate Across Scales

119 (LUCAS) project (Davin et al., 2020), based on the European Space Agency Climate Change Initiative

120 Land Cover (ESA-CCI LC) dataset (ESA, 2017). Changes in the land use cover during the simulation

121 period were derived from the Land-Use Harmonization 2 (LUH2) dataset (Hurtt et al., 2020). A detailed

122 description of the method, by which this land use dataset was created, can be found in Hoffmann et

123 al., (2022a).

124 Since in VEG3D only the dominant land use class in a grid cell is considered, land use changes are only

125 taking place in CCLM-VEG3D if the dominant land use class in a grid cell is changing. In addition, the

126 vegetation characteristics of different deciduous tree species (e.g. beech, oak, etc.) and different

127 coniferous tree species (pine, spruce, etc.) are all combined in one representative forest class,

128 respectively. This means that for the different vegetation parameters, describing the characteristics of

129 these different tree species, the mean values over the parameter space of the respective deciduous

130 and coniferous trees are used. In CCLM-VEG3D, therefore, only one deciduous forest class and one

131 coniferous forest class are considered (see table 1). In this context, for the deciduous forest class, only

132 deciduous broadleaved trees are considered, while in the coniferous forest class, only evergreen

133 needleleaved trees are included. Evergreen broadleaved trees (e.g., Mediterranean oaks) or deciduous

134 needleleaved trees (e.g. larch) are consequently not considered. This approach is associated with a

135 certain degree of uncertainty, since the parameter spaces of deciduous and coniferous trees have a

136 certain overlap (e.g. Wright et al., 2005, van Bodegom et al., 2012). This means that the characteristics

137 of several deciduous tree species and several coniferous tree species do show a high level of

138 agreement. However, we assume in our approach that in general the parameter similarity is higher

139 within the respective deciduous and coniferous tree classes than between the two classes (e.g. Gitay

140   & Noble, 1997). The averaged parameter values of deciduous and coniferous trees can consequently

141   be used to differentiate between the general characteristics of these tree species. Therefore, the usage

142   of two representative forest classes in this study is assumed to be suitable to investigate the general

143   effects of deciduous and coniferous trees on heat period characteristics.

144   In the second simulation, all grid cells covered with coniferous forests in REF are replaced by deciduous

145   forests (DECID, Fig. 1b). As a consequence, deciduous forests in this simulation are located in regions,

146   in which their growth is ecologically limited to some extent (e.g. Högberg et al., 2017). For instance,

147   broadleaved deciduous forests have generally high nitrogen needs. However, soils are generally

148   nitrogen-poor in boreal regions, explaining why the ecological conditions are not optimal for the

149   growth of deciduous forests, and only deciduous tree species with low nitrogen demands are naturally

150   growing, like birch or poplar. Therefore, coniferous trees have a naturally high proportion in boreal

151   forests. However, these ecological limitations of an increased deciduous forest cover fraction are not

152   considered in this idealized sensitivity study, the focus is only on the potential climatological effects.

153   By comparing the results of this idealized DECID simulation with the results of the REF simulation the

154   general potential effect of an increase in the deciduous forest fraction on the intensity and duration of

155   heat periods in Europe is assessed. In order to quantify changes in the heat period intensities, days

156   above the 90th percentile of the daily maximum temperatures in 2 m height in summer (JJA) are

157   analyzed. In this context, we define the heat period intensities as the mean daily maximum 2 m

158   temperature for these warmest 10 % of summer days, and compare these mean values for DECID and

159   REF with each other. Changes in the duration of heat periods in both simulations are quantified by

160   counting the number of days, in which the daily maximum 2 m temperature exceeds the 90th percentile

161   of daily maximum temperatures in REF over at least three consecutive days (Russo et al., 2015). The

162   analyzed processes are separated in local effects; changes in the climate conditions in grid cells with

163   an increase in the deciduous forest fraction, which are directly caused by changes in the surface energy

164   balance, and non-local effects; changes in the climate conditions in grid cells with no increase in the

165   deciduous forest fraction, which are only indirectly caused by changes in the surface energy balance.

166

167   **3. Results**

168   **3.1 Heat Period Intensity**

169   **3.1.1 Local Effects**

170   We first analyze the local effects of an increased deciduous forest fraction on heat period intensities.

171   Fig. 2a shows the local changes in the net short-wave radiation for the regions, in which coniferous

172   forests were replaced by deciduous forests. Net short-wave radiation is in all these regions reduced,

173   due to the increased albedo of deciduous forests in comparison to coniferous forests. Thus, less

174   radiative energy is locally available at the land surface. At the same time, in central and southern

175 Europe, the latent heat fluxes of deciduous forests are increased (Fig. 2b) and the sensible heat fluxes

176 are reduced (Fig. 2c). This indicates that, in a deciduous forest in central and southern Europe, the

177 radiative energy input during heat periods is reduced and a larger part of this reduced available energy

178 at the surface is additionally used for evapotranspiration instead of heating up the land surface. During

179 heat periods, the replacement of coniferous forests with deciduous forests leads consequently to a

180 local reduction of the daily maximum 2 m temperatures, and thus the heat period intensities (Fig. 2d).

181 In northern Europe, or more precisely in the northern part of Scandinavia, this is not the case. In this

182 region, a warming of the mean daily 2 m temperatures during heat periods is simulated with an

183 increase in the deciduous forest fraction. This warming effect is directly caused by a reduction of the

184 evapotranspiration rates in Scandinavia (Fig. 2b).

185 During heat periods, different evapotranspiration responses to an increase of the deciduous forest

186 fraction are caused by a different weighting of opposing vegetation characteristics of deciduous and

187 coniferous forests. On the one hand, the stomatal resistance of a deciduous forest is reduced in

188 comparison to a coniferous forest (see table 1), and transpiration through the leaf stomata is

189 facilitated. Furthermore, the root system of deciduous forests reaches deeper than of coniferous

190 forests (table 1). Therefore, deciduous forests are able to extract water from deeper soil layers. The

191 available amount of soil water for evapotranspiration is consequently increased during phases of water

192 limitation, reducing the water stress and enabling an enhanced evapotranspiration particularly during

193 heat periods. These two characteristics of deciduous forests have a facilitating effect on

194 evapotranspiration during heat periods.

195 On the other hand, the albedo of a deciduous forest is higher than of a coniferous forest (table 1).

196 Therefore, less solar radiation is absorbed and the energetic forcing of evapotranspiration is reduced

197 (Fig. 2a). Additionally, the surface roughness of a deciduous forest is lower than of a coniferous forest

198 (table 1). Thus, the turbulent transport of water from the surface to the atmosphere is not as efficient

199 as for a coniferous forest. These two characteristics of deciduous forests have consequently an

200 attenuating effect on evapotranspiration during heat periods.

201 In most parts of Europe the weight of the reduced stomatal resistance and the reduced water stress

202 of deciduous forests is dominating the evapotranspiration response during heat periods and latent

203 heat fluxes are increased (Fig. 2b). But this is not the case in Scandinavia. In general, the net short-

204 wave radiation and the saturation deficit are lower in Scandinavia than in central and especially in

205 southern Europe. Thus, the energetic forcing of evapotranspiration and the atmospheric demand for

206 evapotranspiration are reduced in comparison to the southern parts of Europe, generally attenuating

207 evapotranspiration in Scandinavia (Breil et al., 2021). Now, by increasing the deciduous forest fraction

208 in Scandinavia, the already comparatively low energetic forcing of evapotranspiration is further

209 reduced (Fig. 2a). In addition, due to the generally low radiative energy input in Scandinavia, surface

temperatures are lower than in central and southern Europe, with the consequence that buoyance is comparatively small and wind sheer becomes more important for the turbulent exchange between the surface and the atmosphere. The surface roughness has therefore in Scandinavia a stronger impact on evapotranspiration rates than for the rest of Europe (Breil et al., 2021). In a deciduous forest, this surface roughness is lower than in a coniferous forest (table 1). Wind sheer is consequently reduced and the turbulent transport of water between the surface and the atmosphere is further attenuated in Scandinavia, leading to reduced latent heat fluxes (Fig. 2b).

On top of this, evapotranspiration is even during heat periods not water limited in Scandinavia, due to the generally high water supply and the low energetic forcing. This is shown by the higher correlation between latent heat fluxes and daily maximum 2 m temperatures during heat periods in Scandinavia in comparison to central and southern Europe (Fig. 2f). This means that also for a coniferous forest with its comparatively shallow root system, enough soil water is available to use its higher evaporative potential of an increased energetic forcing and surface roughness in Scandinavia entirely. The increased radiative energy input of a coniferous forest can consequently be transformed into higher evapotranspiration rates (Fig. 2b), although its stomatal resistance is higher (table 1). This increase in evapotranspiration is even so strong that lower daily maximum 2 m temperatures are simulated with coniferous forests, although more energy is available to heat up the surface in Scandinavia (Fig. 2a). Therefore, an increase in the deciduous forest fraction leads in Scandinavia to more intense heat periods (Fig. 2d).

The same weighting of processes leads also in the Alpine region and the low mountain ranges of central Europe to increased latent heat fluxes for coniferous forests (Fig. 2b). But in these regions, the effects of the increased evapotranspiration is just balancing and not exceeding the effects of the increased radiative energy input of coniferous forests. As a result, the local intensities of heat periods are of the same magnitude for coniferous and deciduous forests (Fig. 2d).

In central and southern Europe, the radiative energy input is generally higher than in Scandinavia and thus, also buoyance. The effect of wind sheer and the surface roughness on the turbulent water transport is consequently less pronounced (Breil et al., 2021), and the weighting of the stomatal resistance on evapotranspiration is increased. In addition, the water stress during heat periods is lower for deciduous forests than for coniferous forests, due to the deeper root system of deciduous forests (table 1), which is shown in Fig. 2e, by the higher temporal correlation between latent heat fluxes and daily maximum 2m temperatures in DECID than in REF. As a consequence, evapotranspiration of deciduous forests is increased, although the energetic forcing is lower than for coniferous forests. An increase in the deciduous forest fractions leads therefore to a local reduction of heat period intensities in central and southern Europe (Fig. 2d).

244   However, the absolute local effects of an increased deciduous forest fraction in Europe on the daily
245   maximum 2 m temperatures are quite small during heat periods (Fig. 2d). The mean local reduction in
246   the heat period intensity in Europe (except Scandinavia) is 0.2 K. Regions with a pronounced
247   temperature reduction are located in south-western France (0.6 K – 0.9 K) and northern Turkey (up to
248   1 K). The highest simulated temperature reduction is 3,7 K. But such strong local effects are absolutely
249   exceptional. At 95% of the grid cells, in which an increase in the deciduous forest fraction leads to a
250   local cooling, the reduction of the daily maximum 2 m temperatures is below 0.5 K.
251   Although this local cooling effect is just slightly pronounced, it is statistically significant for 45 % of all
252   grid cells in which an increase in the deciduous forest fraction resulted in reduced daily maximum 2m
253   temperatures, uniformly distributed all over Europe (except Scandinavia, Fig. 2d). This means that for
254   nearly half of these grid cells the process chain of reduced absorbed solar radiation and increased
255   evapotranspiration results in a significant reduction of local heat period intensities for deciduous
256   forests. However, this also means that for slightly more than half of these grid cells the simulated
257   reduction of the daily maximum temperatures is not significant. Thus, for these grid cells random
258   causes for the temperature reduction cannot be excluded.
259   The mean local warming in Scandinavia is 0.1 K, with a maximum warming effect of 0.4 K. Local
260   warmings with an increase in the deciduous forest fraction are statistically not significant.
261
262   **3.1.2 Non-local Effects**
263   An increase in the deciduous forest fraction has a non-local cooling effect on the heat period intensities
264   over large parts of Europe in non-forested areas (Fig. 3a). Over central, western and southern Europe,
265   a non-local cooling of the daily maximum 2 m temperatures is simulated in general. The local cooling
266   of air masses over deciduous forests is consequently also inducing a cooling of air masses in the
267   surrounding areas. This non-local cooling effect is further intensified by generally higher precipitation
268   sums in summer in regions showing a non-local cooling (Fig. 3b). Thus, the available amount of water
269   for evapotranspiration is during heat periods increased in these regions and the water stress is
270   reduced, resulting in higher evapotranspiration rates (Fig. 3c) and lower heat period intensities (Fig.
271   3a).
272   However, in eastern Europe, at the North Sea coast of central Europe and the Balkan Mountains higher
273   daily maximum 2 m temperatures are simulated in non-forested areas (Fig. 3a). These warmer non-
274   local temperatures arising with an increase in the deciduous forest fraction are also caused by non-
275   local differences in the summer precipitation sums between DECID and REF. In all these regions, mean
276   precipitation sums in summer are reduced (Fig. 3b), and thus, the available amount of water for
277   evapotranspiration during heat periods is also reduced. Lower evapotranspiration rates are the

278 consequence (Fig. 3c), which means that more energy is available at the surface to heat up the surface,

279 finally leading to non-locally intensified heat periods.

280 These changes in the spatial distribution of precipitation sums in summer are most likely caused by

281 local changes in the vegetation characteristics, associated with an increase in the deciduous forest

282 fraction in Europe. Deciduous forests are locally increasing evapotranspiration rates (Fig. 2b), and thus

283 the release of water into the atmosphere. Downwind precipitation is therefore potentially increased.

284 However, deciduous forests are also reducing local temperatures (Fig. 2d) and are characterized by a

285 lower surface roughness (table 1), potentially inhibiting the development of convective precipitation

286 events in summer in comparison to coniferous forests. Because of these opposing vegetation

287 characteristics, therefore, an increase in the deciduous forest fraction can lead to changes in the spatial

288 and temporal precipitation distribution over Europe (Fig. 3c).

289 For instance, the locally increased evapotranspiration rates in central Europe (Fig. 2b) are increasing

290 the water vapor content in the atmosphere. Thus, moister air masses are generally transported

291 eastward with the typical westerly flow in Europe (Fig. 3d). We hypothesize that due to the increased

292 water vapor content of this air mass, downwind rain is falling earlier and more extensively, leading to

293 increased precipitation sums in a region from Greece to the Baltics (Fig. 3b). Further east, air masses

294 are consequently drier and precipitation sums in summer are reduced (Fig. 3b), resulting in intensified

295 heat periods (Fig. 3a).

296 A slight non-local warming during heat periods is additionally simulated in the coastal regions of

297 Scandinavia (Fig. 3a). This warming is not caused by reduced precipitation sums, but is a direct

298 consequence of the warmer air masses above forested regions in Scandinavia. This is shown by the

299 fact that evapotranspiration rates are slightly increased instead of reduced (Fig. 3c). Thus, changes in

300 the evapotranspiration rates are here a result of warmer temperatures and not their cause, as it is the

301 case in eastern Europe.

302 Quantitatively, the non-local effects of an increased deciduous forest fraction in Europe are of the

303 same magnitude as the local effects, and thus quite small (Fig. 3a). The non-local warming effect in

304 eastern Europe, at the North Sea coast of central Europe and the Balkan Mountains is in mean 0.1 K,

305 and is statistically not significant. The warming at 95 % of the respective grid cells is again below 0.4 K.

306 The non-local cooling effect over central, western and southern Europe is in mean also 0.1 K with a

307 95th percentile of 0.3 K. As already identified for the local effects, non-local cooling effects are

308 statistically significant for 23 % of all grid cells with reduced daily maximum 2 m temperatures (Fig. 3a).

309 However, this also means that the simulated non-local reduction of the daily maximum temperatures

310 is statistically not significant for the other 77 % of these grid cells. Although for these non-significant

311 grid cells the same process chain is simulated as for the significant grid cells, random causes for the

312 temperature reduction during heat periods cannot be excluded.

313

3.2 Heat period duration

We finally analyze potential impacts of an increase in the deciduous forest fraction in Europe on changes in the heat period durations (Fig. 4). Therefore, a heat event is in both simulations defined as a period in which the daily maximum 2 m temperature exceeds the 90th percentile of daily maximum temperatures in the reference run over at least three consecutive days.

Results show that in mean the duration of heat periods is generally not affected by changes in the European forest composition. In eastern Europe isolated grid cells with a heat period extension of up to one day are simulated. In central Europe and northern Scandinavia a few grid cells with a shortening of heat periods are simulated. However, these grid cells are not systematically connected to local or non-local processes. Thus, no significant impact of an increase in the deciduous forest fraction on heat period durations is detected in Europe.

4. Discussion

The results of this study show that the benefit of an increased deciduous forest fraction on the heat period intensities in Europe strongly depends on the water availability for evapotranspiration. In northern Europe, evapotranspiration of (deciduous as well as coniferous) forests is under current climate conditions even during heat periods not water limited (Fig. 2e+f). By means of a higher energetic forcing (Fig. 2a) and a higher surface roughness, coniferous forests are consequently able to transpire more water than deciduous forests (Fig. 2b). This simulated property of coniferous forests in northern Europe depends of course on the considered vegetation parameters. As mentioned in section 2, the used vegetation parameters in table 1 are averaged values over the parameter space of deciduous and coniferous forests and vary consequently for specific deciduous and coniferous tree species. This variability in the vegetation characteristics is also reflected in observations. For instance, higher transpiration rates of deciduous forests are reported in Baldocchi et al. (2000), who reviewed several field studies in Canada, Siberia and Scandinavia, in Eugster et al., (2002) based on the analysis of several eddy-covariance stations in the boreal regions of Europe and northern America, and in Grossiord et al., (2013) for measurements in a boreal plantation in south-western Finland. On the other hand, contradictory results have been reported in Augusto et al., (2015), who reviewed studies on the water-use efficiencies of deciduous and coniferous forests in boreal regions, implying higher transpiration rates of coniferous forests, in Ewers et al., (2005) for a comparison between pines and poplar in the BOREAS Northern Study Area in Canada, and in Baumgarten et al. (2019), where higher transpiration rates of coniferous forests are measured in hemiboreal regions even during the warm summer months.

347 The increased transpiration rates of coniferous forest identified in our model study are consequently

348 within the range of the observed transpiration variability in boreal regions and lead in our simulations

349 to slightly increased heat period intensities for northern Europe (Fig. 2d). The low potential of an

350 increased deciduous forest fraction to reduce heat period intensities in northern Europe was already

351 suggested in Schwaab et al., (2020), who applied a statistical model. The application of a regional

352 climate model with its capability to account for all associated atmospheric feedbacks indicates that

353 this potential might be not only low, but even negative. However, considering the missing significance

354 of the warming effect of an increased deciduous forest fraction in Scandinavia in the model and the

355 observed variability in the sign of the transpiration response, a final assessment of the mitigation

356 potential for heat extremes in northern Europe is not possible.

357 Conversely, evapotranspiration is in central and southern Europe moisture limited during heat periods

358 (Fig. 2e+f). An increase in the deciduous forest fraction is beneficial in these regions for the heat period

359 intensities (Fig. 2d), because of the deeper root system of deciduous forests and the associated

360 increased evapotranspiration rates (Fig. 2b). However, in some regions of southern Europe, current

361 climate conditions are already so dry that the root system of a deciduous forest does not reach deep

362 enough to meet the atmospheric water demand during heat periods. Therefore, the benefit of an

363 increased deciduous forest fraction arises in these areas only from the reduced radiative energy input

364 (Fig. 2a). These effects of an increased deciduous forest fraction were already hypothesized by

365 Schwaab et al., (2020) and are now underpinned by this study.

366 However, the results of recent climate projections indicate that the water availability for

367 evapotranspiration will change in the future in Europe. For any climate change scenario, regional as

368 well as global climate models simulate a dipole in the projected precipitation changes in Europe

369 (Douville et al., 2021; Coppola et al., 2021). In northern Europe, precipitation will slightly increase,

370 while in southern Europe the opposite is the case, particularly during summer. Simultaneously, the

371 atmospheric water demand will increase in both regions, due to the generally increased atmospheric

372 temperatures. In northern Europe, this will likely lead to a slight reduction of the available soil water

373 amount, although precipitation sums are slightly increased (Cook et al., 2020). This might have the

374 consequence that the evapotranspiration of shallow rooted coniferous forests in northern Europe will

375 become water limited, and the cooling effect of coniferous forests on heat period intensities might get

376 smaller in comparison to deciduous forests.

377 In southern Europe, reduced precipitation sums and increased atmospheric water demand will result

378 in more frequent drought conditions (e.g. Mömken et al., 2022). It can therefore be concluded that in

379 southern Europe the cooling effect of an increased deciduous forest fraction on the heat period

380 intensities will even decrease, since progressing water limitation will further constrain

381 evapotranspiration also for deciduous forests in future, as it is already the case in the driest regions of

382   southern Europe (e.g. Forner et al., 2018). Thus, the climate benefit of deciduous forests will then be

383   restricted only on the reduced incoming solar radiation.

384   Central Europe is in the transition zone of this precipitation dipole (Giorgi & Coppola, 2007). Thus, in

385   this region the lowest changes in water availability are expected with climate change in annual mean

386   (Douville et al., 2021; Coppola et al., 2021). This means that also in the future an increase in the

387   deciduous forest fraction will have a slight cooling effect on the heat period intensities in central

388   Europe. However, the location of this transition zone is considerably varying between models (GCMs

389   and RCMs) and climate change scenarios (Coppola et al., 2021). Therefore, uncertainties on changes

390   in the spatial water availability in central Europe, and thus on the projected changes in

391   evapotranspiration rates are quite large (Douville et al., 2021), whereby a small decrease in water

392   availability is projected in the ensemble mean (Samaniego et al., 2018; Cook et al., 2020). This indicates

393   that particularly during very extreme heat events, the likelihood of water stress will increase for

394   deciduous forests also in central Europe and the cooling effect of an increased deciduous forest

395   fraction on heat period intensities will likely decline.

396   Non-local changes in heat period intensities are also caused by changes in the available water amounts

397   for evapotranspiration. In non-forested areas, these changes are obviously not caused by changes in

398   the vegetation characteristics, but are a result of changes in the mean summer precipitation sums. The

399   interrelation between evapotranspiration rates of forests and downwind precipitation sums was

400   already investigated by Belušić et al., (2019), Strandberg & Kjellström (2019) and Meier et al., (2021).

401   While Strandberg & Kjellström (2019) could find almost no connection, Belušić et al., (2019) and Meier

402   et al., (2021) provided evidence that increased evapotranspiration rates of forests can lead to

403   increased downwind precipitation sums. It is therefore evident that a change in the forest composition

404   and associated evapotranspiration rates also affects downwind precipitation sums in Europe.

405   However, beside the local increase in evapotranspiration rates, deciduous forests are also

406   characterized by lower local temperatures and surface roughness, inhibiting the formation of

407   convective precipitation. Therefore, an increase in the deciduous forest fraction changes the spatial

408   and temporal distribution of precipitation sums over Europe (Fig. 3c) and leads, in this way, either to

409   an increase or a decrease of the non-local heat period intensities (Fig. 3a).

410   However, in our study, the effects of an increased deciduous forest fraction on heat period intensities

411   are not as clearly pronounced as one could expect from the results of other studies like Schwaab et al.,

412   (2020). On the one hand, this might be due to the different methodological designs of the studies. In

413   contrast to statistically based approaches as used in Schwaab et al., (2020), relevant atmospheric

414   feedback processes are explicitly simulated in our regional climate model approach, potentially

415   attenuating the impact of different vegetation characteristics on heat period intensities.

416   On the other hand, this might be related to the general representation of these vegetation
417   characteristics in the regional climate model itself. In CCLM-VEG3D, different species of deciduous and
418   coniferous trees are all aggregated in one representative forest class, respectively (see table 1).
419   However, not everywhere in Europe the same species of deciduous and coniferous trees are growing
420   (Bohn & Gollub, 2006), and these different tree types do not all have the same vegetation
421   characteristics. An example for such differences, are the different vegetation characteristics of beech
422   trees and oaks. The stomatal resistance of beech trees is lower than of oaks (Jonard et al., 2011), while
423   the root system of oaks reaches deeper than of beech trees (Leuschner et al., 2001). It is therefore
424   possible that the vegetation characteristics of deciduous and coniferous forests in CCLM-VEG3D are
425   slightly overestimated at some locations or slightly underestimated at others. Thus, an increase in the
426   deciduous forest fraction can have slightly deviating effects on the heat period intensities locally in a
427   regional climate model.

428   Another model constraint of CCLM-VEG3D is that only the dominant land use class is considered in a
429   grid cell. This means that grid cells in which forest is the dominant land use class are completely
430   assigned to forest in the model and the forest fraction is overestimated in these areas. In return,
431   forested areas with a lower percentage in a grid cell are consequently not considered in the model and
432   the forest fraction is underestimated. The spatial distribution of forests in Europe is therefore not as
433   extensive in CCLM-VEG3D as in reality (Hoffmann et al., 2022b), leading potentially to an
434   underestimation of the spatial extension of local effects. However, the goal of this study is to
435   disentangle the general feedback processes of an increased deciduous forest and its general effects on
436   local and non-local heat period intensities and not to analyze the effects of realistic transformations in
437   the forest composition in Europe. Against this background, the use of the dominant land use class is
438   from our point of view reasonable and suitable to investigate general deciduous forests effects on heat
439   periods. Of course, the simulated responses of other modeling systems to changes in the forest cover
440   composition might be different.

441   Beyond these model constraints, the advantage of our modeling approach is that both local and non-
442   local effects of an increased deciduous forest fraction can be analyzed in detail, under the
443   consideration of all relevant feedback processes represented in the regional climate model. This is not
444   possible with studies, focusing on plant physiological differences of trees and their effects on the local
445   energy budget of forests. Thus, our study contributes to complementing our knowledge on the general
446   effects of deciduous forests on heat period intensities, by deriving a comprehensive understanding of
447   the associated local and non-local process chains. With this in mind, we could show that an increase
448   in the deciduous forest fraction has significant as well as non-significant effects on local and non-local
449   heat wave intensities. While for the grid cells with significant effects, consistent physical process chains
450   are the reason for the local and non-local temperature reductions during heat periods, random causes

451   for the temperature reductions in non-significant grid cells cannot be generally excluded. However, a

452   missing significance does not necessarily mean that there is no connection (Wasserstein & Lazar, 2016)

453   between an increase in the deciduous forest fraction and reduced heat period intensities in these grid

454   cells. On the contrary, also for the non-significant grid cells with reduced daily maximum temperatures,

455   the same process chains were identified as for the significant ones. From our point of view, this high

456   physical consistency of the simulated processes is a strong indicator that the reduced heat period

457   intensities are also not random in the non-significant grid cells. Particularly downwind processes are

458   spatially and temporally highly variable. Thus, locally induced changes in the atmospheric moisture

459   conditions do not always lead to precipitation at the same downwind locations (Perugini et al., 2017).

460   This high spatial and temporal variability, therefore, has the consequence that the physical processes

461   are difficult to detect and the temperature reductions are statistically not significant. However,

462   comparing the potential reduction of heat period intensities with the substantial intensification of heat

463   extremes of about 2,3 K in Europe since the 1950s (Lorenz et al., 2019), the effect of an increased

464   deciduous forest fraction is small.

465

466   **5. Conclusion**

467   In the course of idealized regional climate simulations, the general potential effects of an increased

468   deciduous forest fraction on heat period characteristics in Europe are quantified. Results show that an

469   increase in the deciduous forest fraction has significant as well as non-significant effects on the local

470   and non-local scale. Locally, mean heat period intensities are slightly reduced about 0.2 K, except for

471   Scandinavia, where a mean warming of 0.1 K is simulated. The simulated temperature reductions in

472   grid cells with replaced coniferous forests are statistically significant at 45 % of the grid cells and not

473   significant at 55 % of the grid cells. The simulated local warming in Scandinavia is not statistically

474   significant.

475   Non-locally, mean heat period intensities are slightly reduced in central, western and southern Europe

476   about 0.1 K, but slightly increased in Eastern Europe, the North Sea coast of central Europe and the

477   Balkan Mountains also about 0.1 K. Significant results are only simulated for 23 % of the grid cells in

478   which an increase of the deciduous forest fraction leads to a cooling. The duration of heat periods is

479   not affected by a change in the forest composition in Europe.

480   These results indicate that an increase in the deciduous forest fraction has no potential to reduce the

481   intensity of heat periods in Scandinavia. This might change in future to a certain extent, since a slight

482   decrease in water availability is projected in this region by regional as well as global climate models.

483   This might limit evapotranspiration rates of shallow rooted coniferous forest during heat periods, and

484   the cooling effect of coniferous forests on heat period intensities might get smaller in comparison to

deciduous forests. Furthermore, an increase in the deciduous forest fraction leads in several regions of Europe to reduced precipitation sums and non-locally intensified heat periods.

In central and southern Europe, deciduous forests have a cooling effect on heat period intensities. Although this effect is in parts significant, its magnitude is rather small in comparison to the intensification of heat periods since the 1950s. In addition, the cooling effect is likely to decrease with climate change, due to a projected reduction in water availability during heat periods. However, not all deciduous forest types must necessarily have such small effects. For instance, species which have an optimal balance between a reduced absorption of solar radiation and an increased transformation of the solar radiation in turbulent heat fluxes might reduce heat period intensities stronger at certain locations. But such species are not considered in the general forest classes of CCLM-VEG3D, and their impact on heat period intensities is consequently not simulated in the model. Therefore, a next step will be to implement more forest classes in the regional climate model, enabling a more detailed differentiation of the respective vegetation characteristics. However, the results of our study indicate that a replacement of coniferous forests with common deciduous forest types has only a limited cooling effect on heat periods in Europe. Thus, the method can only be considered as a supporting mitigation measure to complement other, more effective mitigation strategies to reduce heat extreme intensities.

Data availability

The applied land use dataset is accessible at the World Data Center for Climate (WDCC) at DKRZ (https://doi.org/10.26050/WDCC/LUC_hist_EU_v1.1). The ERA-5 reanalysis data are obtained from the ECMWF (https://apps.ecmwf.int/data-catalogues/era5/?class=ea). The CCLM-VEG3D data is available upon request from the corresponding author.

Author contributions

MB designed the study, performed the CCLM-VEG3D simulations and wrote the paper. MB and AW analyzed the data and MB prepared the figures. All authors contributed with discussion, interpretation of results and text revisions.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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799   Table 1: Vegetation parameters of deciduous and coniferous forests in CCLM-VEG3D

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	Minimum stomatal resistance	root depth (density < 2%)	albedo	surface roughness
Deciduous forest	100 s/m	2.0 m	0.15	0.8 m
Coniferous forest	120 s/m	1.0 m	0.11	1.0 m

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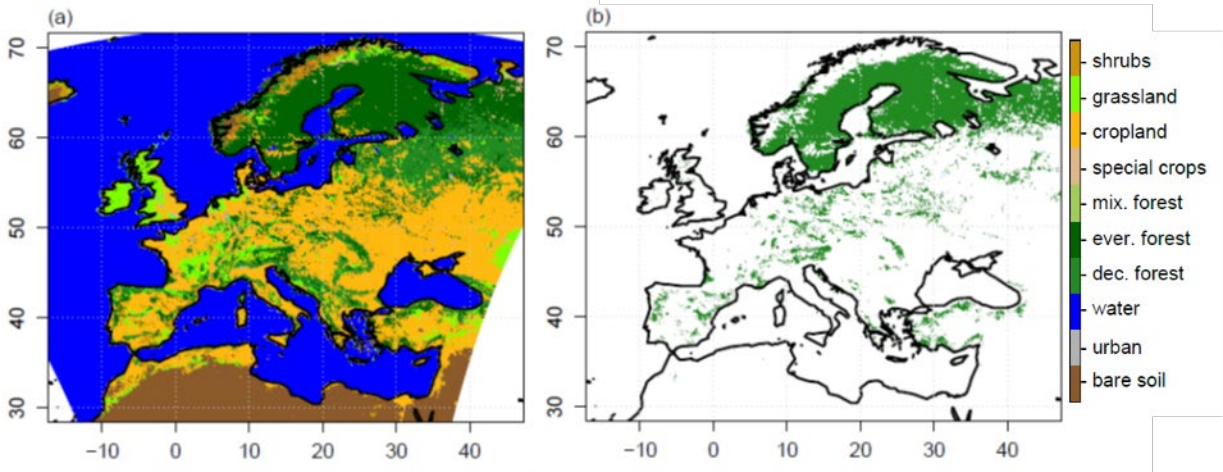
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843 Figure 1: (a) CCLM-VEG3D land use classes. (b) grid cells in which coniferous forests were replaced by
844 deciduous forests in the DECID simulation.

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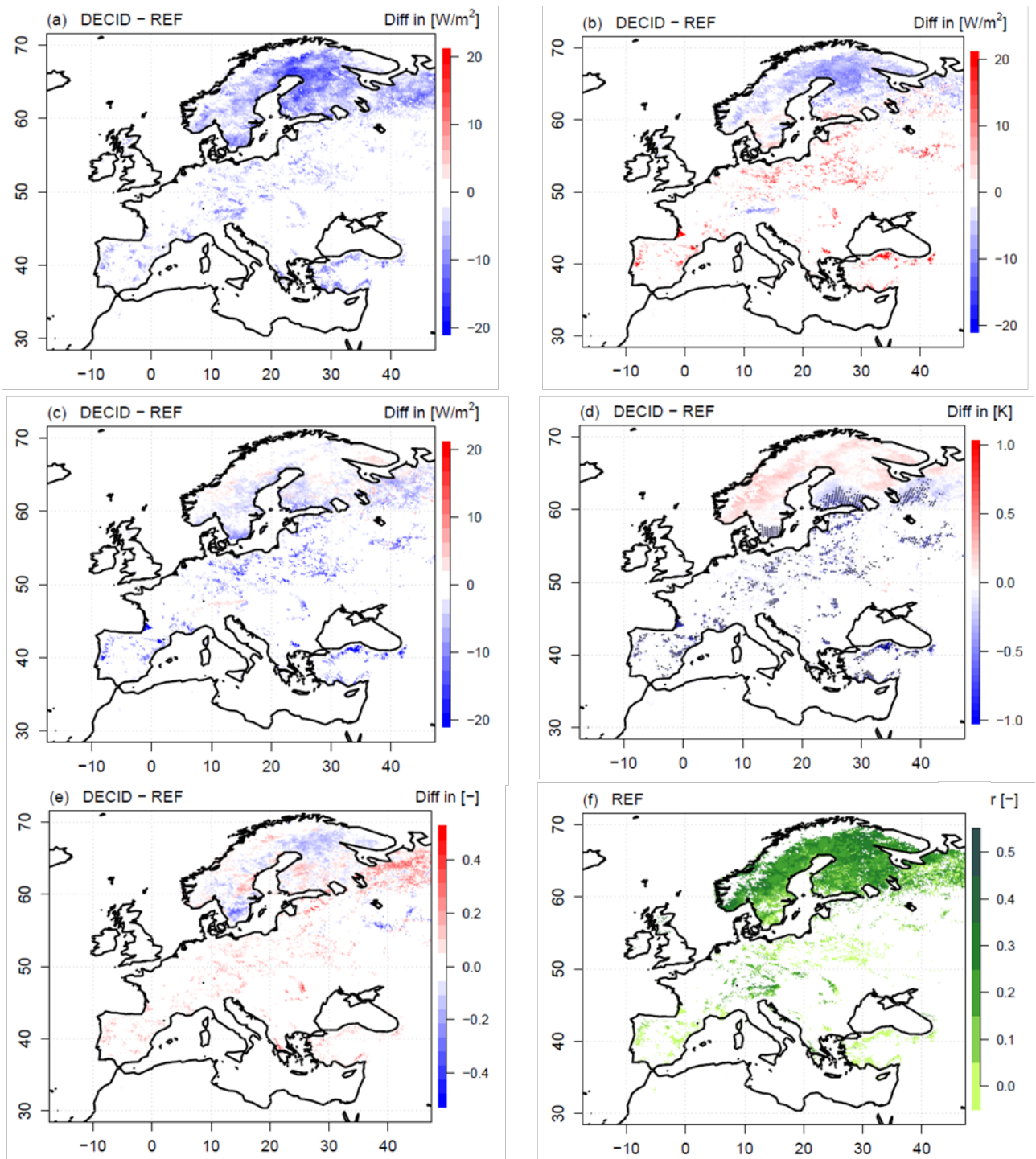
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880 Figure 2: Local differences between DECID and REF for (a) net short-wave radiation, (b) latent heat
881 fluxes, (c) sensible heat fluxes, (d) daily maximum 2 m temperatures, (e) temporal correlation between
882 latent heat fluxes and daily maximum 2m temperatures during heat periods. (f) shows the temporal
883 correlation between latent heat fluxes and daily maximum 2m temperatures of coniferous forests in
884 REF during heat periods. The black circles in (d) indicate significant results calculated with a Wilcoxon-
885 Rank-Sum-Test at a 95 % level.
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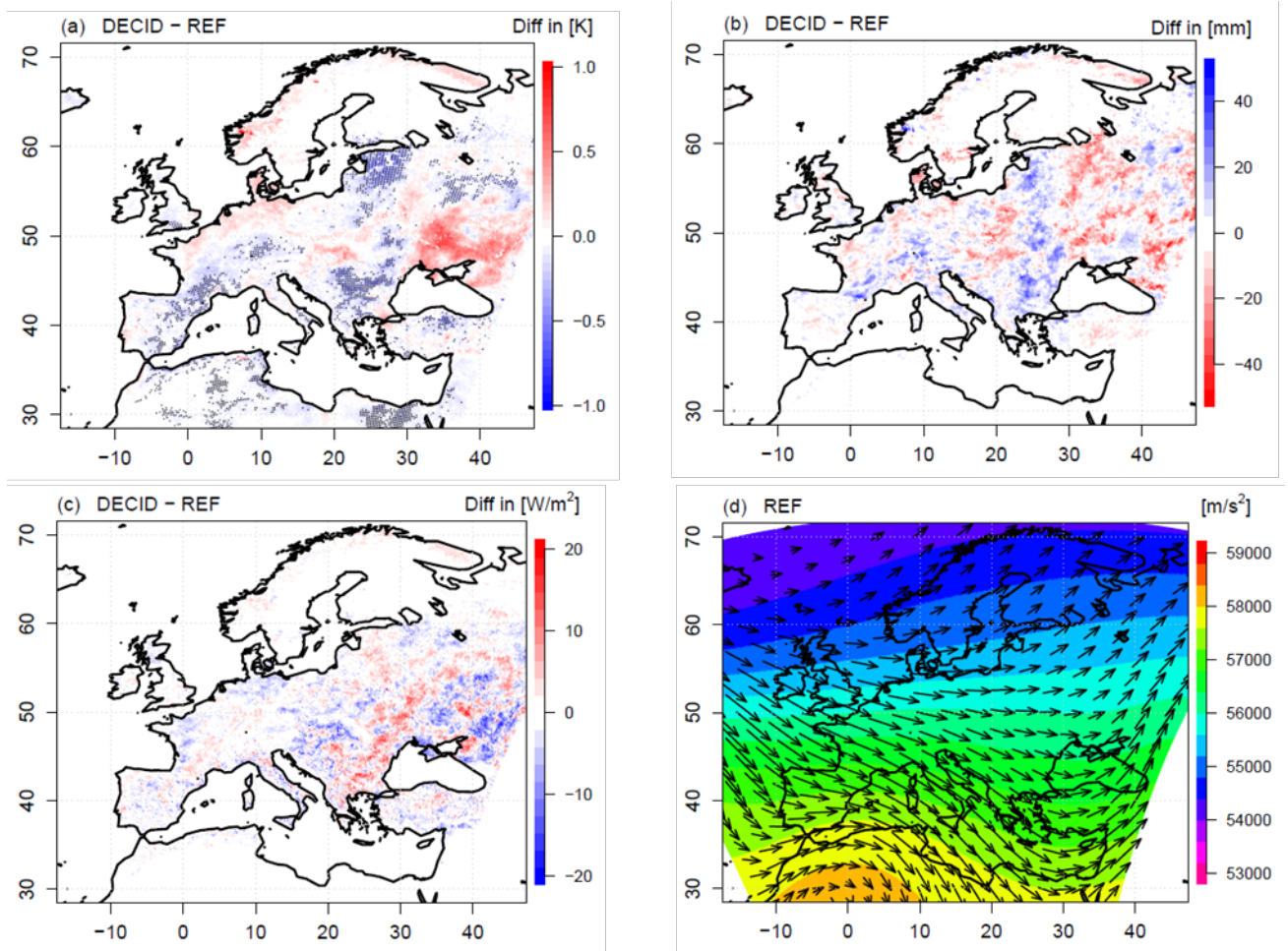
Figure 3: Non-local differences between DECID and REF for (a) daily maximum 2 m temperatures during
heat periods, (b) mean precipitation sums in summer, and (c) latent heat fluxes during heat periods.
(d) shows the geopotential height in 500 hPa and the mean wind direction (arrows) in REF in summer.
The black circles in (a) indicate significant results calculated with a Wilcoxon-Rank-Sum-Test at a 95 %
level.
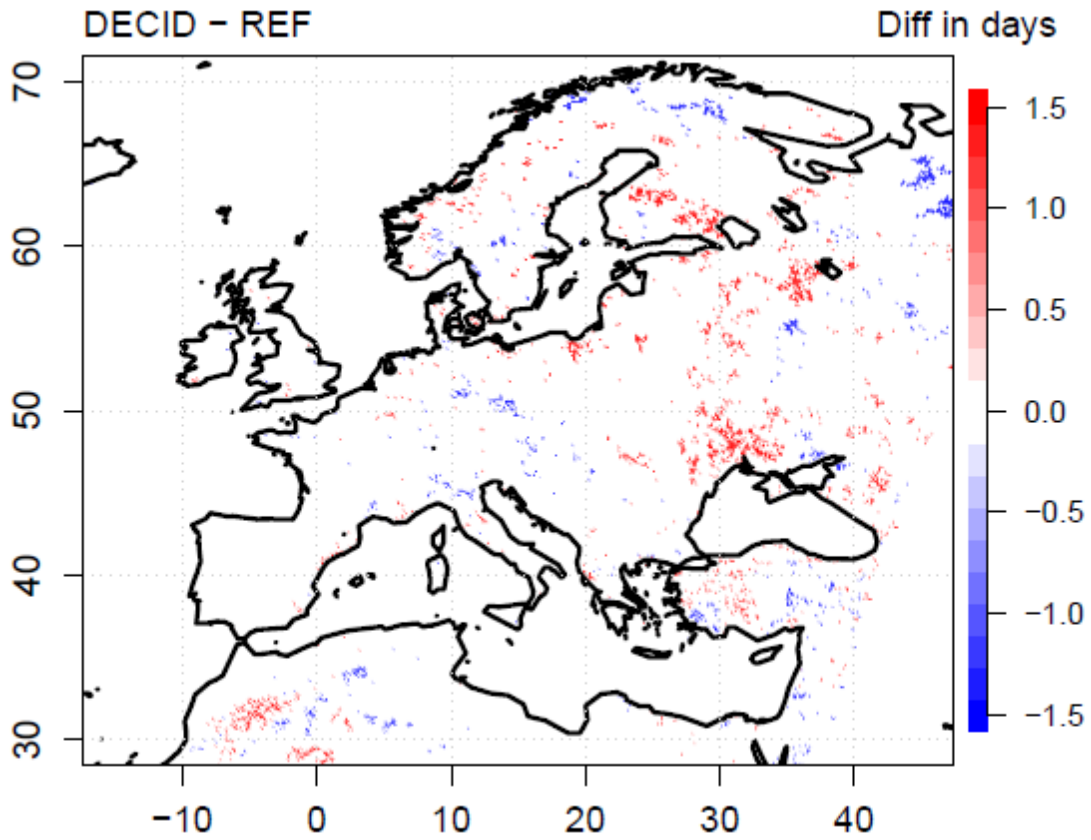
Figure 4: Differences between DECID and REF for the mean heat period durations over the whole simulation period from 1986-2015.