1 **The effect of forest cover changes on the regional climate conditions in Europe during the period**

2 **1986-2015**

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12 **Abstract**

13 Afforestation affects the earth's climate system by changing the biogeochemical and biogeophysical

14 characteristics of the land surface. While the regional effects of afforestation are well understood in

15 the tropics and the high-latitudes, its climate impact on the mid-latitudes is still subject of scientific

16 discussions. The general impact of afforestation on the regional climate conditions in Europe during

17 the last decades is investigated in this study. For this purpose, regional climate simulations are

18 performed with different forest cover fractions over Europe. In a first simulation, afforestation in

19 Europe is considered, while this is not the case for a second simulation. We focus on the years 1986-

20 2015, a period in which the forest cover in Europe increased comparatively strong, accompanied by a

21 strong general warming over the continent.

22 Results show that afforestation has both local and non-local effects on the regional climate system in

23 Europe. Due to an increased transport of turbulent heat (latent + sensible) into the atmosphere,

24 afforestation leads to a significant reduction of the mean local surface temperatures in summer. In

25 northern Europe, mean local surface temperatures were reduced about -0.3 K with afforestation, in

26 central Europe about -0.5 K and in southern Europe about -0.8 K. During heat periods, this local cooling

27 effect can reach to -1.9 K. In winter, afforestation results in a slight local warming both in northern and

28 southern Europe, because of the albedo effect of forests. However, this effect is rather small and the

29 mean temperature changes are not significant. In downwind direction, locally increased

30 evapotranspiration rates with afforestation increase the general cloud cover, which results in a slight

31 non-local warming in winter in several regions of Europe, particularly during cold spells. Thus,

32 afforestation had a discernible impact on the climate change signal in Europe during the period 1986-

33 2015, which may have mitigated the general warming trend in Europe, especially on the local scale in

34 summer.

35

1. Introduction

Afforestation is one of the most frequently debated strategies to mitigate the impacts of the anthropogenic climate change (Sonntag et al., 2016; Harper et al., 2018; Roe et al., 2019), because forests are able to remove large amounts of CO_2 from the atmosphere during their growth and store the carbon long-term in their biomass (Luyssaert, et al., 2010; Pan et al., 2011). Besides this beneficial biogeochemical effect on the global greenhouse effect, afforestation is also changing the biogeophysical characteristics of the land surface (Pielke et al., 2011; Bright et al., 2017). For instance, the evapotranspiration potential of forests is generally higher than of other vegetation types (Zhang et al., 2001), due to a higher biomass and a deeper root system. Thus, a comparatively large part of the incoming solar radiation is transformed into latent heat instead of heating up the land surface (Strandberg & Kjellström, 2019). This effect of afforestation is particularly relevant in regions with large amounts of available energy for evapotranspiration, like the tropics. Therefore, afforestation is known to have a regional cooling effect in the tropics (Lawrence & Vandecar, 2015; Zeppetello et al., 2020).

On the other hand, the surface albedo of forests is lower in comparison to other vegetation types (Bonan, 2008). A larger part of the incoming solar radiation is absorbed, and thus more energy is available to heat up the land surface. This albedo effect is further intensified by the presence of snow, since forests are only partially masked by snow, while other vegetation types are completely covered and reflect more solar radiation (Essery, 2013). The snow masking effect is therefore especially important in the high latitudes, where the land surface is over a large part of the year covered with snow. Afforestation has consequently a regional warming effect in the high latitudes (Bala et al., 2007, Li et al., 2015, Duveiller et al., 2018).

In the mid-latitudes, both the increased turbulent heat transport (sensible + latent) and the albedo effect are relevant (Bonan, 2008). In this geographical area, solar radiation is sufficiently available and thus, the albedo effect has a major impact on the regional climate conditions. In addition, the energy and water supply are generally high in the mid-latitudes, and the increased evaporative potential with afforestation has consequently an important effect on the surface energy balance. The arising question whether afforestation leads to a warming or a cooling of the regional climate conditions in Europe is therefore subject of current research and scientific discussions (e.g. Breil et al., 2023a).

Recent studies indicate that afforestation in Europe leads to a warming in winter, due to the snow masking effect of forests (Lejeune et al., 2017; Davin et al., 2020). In this season, large parts of the land surface are covered with snow in the mid-latitudes, and thus more solar radiation is absorbed by forests than by other vegetation types. In summer, surface temperatures are generally reduced, while boundary layer temperatures are increased with afforestation (Breil et al., 2020). Because of the higher surface roughness of forests in comparison to other vegetation types, the increased solar radiation with afforestation is efficiently transformed into sensible heat and transported away from the surface

71 into the atmosphere (Lee et al., 2011; Burakowski et al., 2018). Atmospheric temperatures are
72 consequently increased, and surface temperatures are reduced, although more solar radiation is
73 absorbed (Breil et al., 2020). Moreover, the commonly higher evapotranspiration rates of forests
74 increase the moisture content in the atmosphere and can therefore increase downwind precipitation
75 sums in Europe (Meier et al., 2021).

76 These effects of afforestation in the mid-latitudes are generally derived either from point
77 measurements of adjacent eddy covariance stations in forests and grasslands (e.g. Lee et al., 2011),
78 from satellite data (e.g. Li et al., 2015), from coarsely resolved global climate simulations (e.g. Bala et
79 al., 2007), or from idealized modeling studies (e.g. Davin et al., 2020). However, it is not possible on
80 the basis of these methods to quantify the effects of afforestation on the regional climate conditions
81 in the mid-latitudes. Although satellite data provide a high spatial coverage, they are not suitable to
82 analyze the underlying land-atmosphere interactions. Such interactions can be investigated with point
83 measurements of flux towers, but the arising atmospheric feedback processes cannot be analyzed with
84 such observations. While all these processes can be simulated with global climate models, the spatial
85 resolution of these simulations is generally too low to investigate all relevant processes in the
86 necessary detail. Although regional climate simulations have higher resolution, regional climate
87 models were until now, to our knowledge, only applied in idealized afforestation scenarios (e.g. Davin
88 et al., 2020; Breil et al., 2020). The actual effects of afforestation on the regional climate conditions in
89 Europe are therefore not yet comprehensively analyzed. This is especially the case for the impact of
90 afforestation on the European climate trend since the 1980s. During this period, the strongest
91 temperature increase in the last 2000 years took place (Gulev et al., 2021), while at the same time, the
92 forest cover increased comparatively strong.

93 Therefore, the goal of this study is to quantify how strong afforestation affected the regional climate
94 conditions during this period of intense regional warming in Europe, by considering the actual
95 afforestation between 1986-2015 in higher resolved simulations with a Regional Climate Model (RCM).
96 In this RCM experiment, a simulation is performed in which all land use changes during this 30 year
97 period (including afforestation) are implemented, and compared to an RCM simulation in which
98 afforestation is not considered. In this way, we are able to explicitly quantify the impact of
99 afforestation on the recent climate conditions in Europe, and analyze whether afforestation regionally
100 counteracted the general climate trend by e.g., an increased evapotranspiration rate and an enhanced
101 turbulent heat exchange, or if the increased absorption of solar radiation with afforestation even
102 intensified the regional climate trend in Europe.

103 The design of the modeling experiment is described in section 2. In section 3, the local (section 3.1)
104 and non-local (section 3.2) effects of afforestation on the climate conditions in Europe are assessed,

105 with a special focus on extremes (section 3.3) and climate variability (section 3.4). Results are discussed

106 in section 4 and conclusions are drawn in section 5.

107

108 **2. Methods**

109 **2.1. Model simulations**

110 In the framework of this study, regional climate simulations with the RCM COSMO-CLM (CCLM, Rockel

111 et al., 2008) coupled to the Land Surface Model VEG3D (Breil & Schädler, 2021) are used to analyze

112 the impact of afforestation on the regional climate conditions in Europe between 1986-2015. The

113 simulations are performed for the Coordinated Downscaling Experiment – European Domain (EURO-

114 CORDEX; Jacob et al., 2014) on a horizontal resolution of 0.11° (~12.5 km). The simulations are driven

115 by the ERA5 reanalysis (Hersbach et al., 2020) at the lateral boundaries and the lower boundary over

116 sea. The simulation period is 1986–2015, with a spin-up of 7 years before 1986.

117 During the first simulation, yearly updated land use maps of the land cover conditions in Europe are

118 implemented in CCLM-VEG3D in which all historical land use changes between 1986-2015 are

119 considered, excluding afforestation (Fig. 1a). This experiment constitutes the reference simulation

120 (REF). In the second simulation, the same land use dataset is used as in REF, but now afforested areas

121 are additionally implemented (AFF). Fig. 1b shows all grid cells, in which afforestation took place

122 between 1986-2015.

123 The underlying land use dataset was developed within the Land Use and Climate Across Scales (LUCAS)

124 project (Davin et al., 2020), based on the European Space Agency Climate Change Initiative Land Cover

125 (ESA-CCI LC) dataset (European Space Agency, 2017). The yearly changes in the land use map during

126 the simulation period are derived from the Land-Use Harmonization 2 (LUH2) dataset (Hurtt et al.,

127 2020). More information on how the applied land use map was constructed can be found in Hoffmann

128 et al., (2022).

129 In CCLM-VEG3D, only the dominant land use class in a grid cell is considered. Thus, afforestation is only

130 considered in our model setup in grid cells in which forest is becoming the dominant land use class.

131 The land use information in these grid cells is then completely assigned to forest. Although the spatial

132 resolution of the grid cells is rather small in our modeling experiment, this results in an overestimation

133 of the forest fraction in afforested grid cells. In return, afforested areas in which forest is not the

134 dominant land use class are not considered and the forest fraction is consequently underestimated in

135 the model.

136 By comparing the results of the AFF simulation with the results of the REF simulation, the effects of

137 afforestation on the regional climate conditions in Europe during the simulation period are assessed.

138 For the analysis, we differentiate between local effects and non-local effects. As local effects, we define

139 changes in the climate conditions in a grid cell in which afforestation took place. A non-local effect is

defined as a change in the climate conditions in non-afforested areas, which is indirectly caused by changes in the surface energy balance in afforested grid cells. The statistical significance of the temperature changes in AFF in comparison to REF is calculated with a Wilcoxon-Rank-Sum-Test, a non-parametric statistical test analyzing the differences between two paired datasets.

Beside the effects of afforestation on the general climate conditions in Europe, we also investigate its impact on climate extremes and the interannual climate variability. Changes in heat extreme intensities are expressed as differences in the days above the 90th percentile of the daily maximum temperatures in 2 m height in summer (JJA). In this context, we define the heat period intensities as the mean daily maximum 2 m temperature for these warmest 10 % of summer days, and compare these mean values for AFF and REF with each other. Changes in cold extreme intensities are expressed as differences in the mean daily maximum 2 m temperature for the coldest 10 % of winter days (DJF). Effects on the climate variability are analyzed by calculating the standard deviation of the mean seasonal surface temperatures.

2.2. Afforested areas

According to the land use dataset derived in the LUCAS project (Hoffmann et al., 2022), about 1.1% of the land mass in the EURO-CORDEX domain was afforested during the period 1986-2015. By converting these land use change information into CCLM-VEG3D with its dominant land use class approach, about 1,7% of the CCLM-VEG3D model domain was afforested. These land use changes were not homogeneous and evenly distributed, but were carried out on small-scales and on isolated locations. In Figure 1, all regions in CCLM-VEG3D are shown which were afforested during the 30 year period in Europe. Larger areas were afforested in the Balkan region, central and north-eastern Europe, while in Scandinavia and south-eastern Europe almost no afforestation took place. All over Europe, 63% of the afforested areas were converted from croplands, 31% from grasslands.

The main differences in the vegetation characteristics between different forest types and croplands and grasslands are summarized in table 1. While the surface albedo of forests is lower and the surface roughness is higher, croplands and grasslands are characterized by a shallow root system and a lower leaf area index (LAI). In this context, the vegetation characteristics of different deciduous tree species (e.g. beech, oak, etc.) and different coniferous tree species (pine, spruce, etc.) are all combined in one representative forest class, respectively. This means that for the different vegetation parameters, describing the characteristics of these different tree species, the mean values over the parameter space of the respective deciduous and coniferous trees are used. In CCLM-VEG3D, therefore, only one deciduous forest class and one coniferous forest class are considered. For the deciduous forest class, only deciduous broadleaved trees are taken into account, while in the coniferous forest class, only

174   evergreen needleleaved trees are included. Evergreen broadleaved trees (e.g., Mediterranean oaks)

175   or deciduous needleleaved trees (e.g. larch) are consequently not considered.

176

177   **3. Results**

178   First, we analyze the capability of CCLM-VEG3D to reproduce the general climate conditions in Europe.

179   Figure 2 shows the differences between the reference simulation (REF) and the ERA5-Land reanalysis

180   (Muñoz-Sabater et al., 2021) for (a) the yearly mean 2 m temperatures and (b) the yearly total

181   precipitation sums during the period 1986-2015.

182   A warm bias is simulated over most parts of Europe in the reference simulation, extending from

183   Southern Europe over Central Europe to Eastern Europe. However, these deviations to ERA5-Land are

184   in the same range as the biases of other RCMs, as demonstrated by Kotlarski et al., (2014). Regarding

185   Northern Europe and the British Isles, the simulation results agree well with the reanalysis data.

186   Total precipitation sums are underestimated in CCLM-VEG3D in southern and western Europe, but

187   overestimated in eastern and parts of northern Europe (shown as a percentual deviation in Fig. 2). This

188   is also true for the mountainous regions of the Pyrenees and the Alps. On the other hand, the simulated

189   precipitation sums agree well with the reanalysis data over large parts of Central and Eastern Europe

190   as well as of southern Scandinavia. Thus, the results of CCLM-VEG3D reflect the already known

191   precipitation pattern of regional climate simulations with CCLM (Kotlarski et al., 2014).

192   Therefore, although a certain model bias for the simulated 2 m temperature and the total precipitation

193   sums is found, the simulation results of CCLM-VEG3D are comparable with the results of other RCMs

194   (Kotlarski et al., 2014) and we conclude that the model is generally able to reproduce the general

195   climate conditions in Europe.

196

197   **3.1. Local effects**

198   **3.1.1 Winter**

199   The local effects of afforestation in Europe on different components of the surface energy balance are

200   analyzed for the period 1986-2015 (Figure 3). Since afforestation in Europe took place only on small-

201   scales and on isolated locations, local effects are summarized for three geographical sub-regions,

202   northern Europe (NE), central Europe (CE) and southern Europe (SE) for visualization purposes, which

203   are highlighted in Figure 1.

204   In winter, an important change with afforestation is that trees (particularly coniferous trees) maintain

205   a dense vegetation throughout the whole season (characterized by a high leaf area index (LAI)), while

206   the original vegetation types have only a low vegetation cover (especially croplands). Therefore,

207   forests are generally able to transpire more water than grasslands and particularly croplands during

208   winter (Fig. 3b). As a consequence, more energy is transformed into latent heat and less energy is

209   transformed into sensible heat in forests (Fig. 3c).

210   This feature is especially pronounced in central Europe. Within the period 1986-2015, mean local latent

211   heat fluxes were increased about 5.1 W/m² in winter (Fig. 3b), while mean local sensible heat fluxes

212   were reduced about -5.5 W/m² (Fig. 3c). At the same time, mean local net short-wave radiation was

213   slightly increased about 0.7 W/m² (Fig. 3a), leading to a positive surface energy budget (+1.1 W/m²,

214   Fig. 3d). Thus, afforestation led in central Europe to a slight local warming in winter for the period

215   1986-2015 (+0.2 K, Fig. 4a).

216   The same processes were also simulated in northern Europe. The mean local latent heat fluxes in

217   winter were increased (+1.9 W/m², Fig. 3b), while the mean local sensible heat fluxes were reduced (-

218   2.3 W/m², Fig. 3c). The increase in the mean local net short-wave radiation was with 0.1 W/m² (Fig.

219   3a) even smaller than in central Europe. The impact of the reduced surface albedo on the mean

220   radiative energy input, associated with the snow masking effect of forests in winter, must therefore

221   be rather small. The generally low insolation in this season consequently impeded stronger differences

222   in the mean local radiative energy input in central and particularly in northern Europe. As a

223   consequence, the surface energy budget was slightly increased in northern Europe (+0.5 W/m², Fig.

224   3d) and the mean warming with afforestation was small (+0.1 K, Fig. 4a).

225   Since the general insolation in southern Europe in winter is higher than in central and northern Europe,

226   a comparatively strong increase in the mean local net short-wave radiation was simulated with

227   afforestation (+2.0 W/m², Fig. 3a), due to the lower albedo values. Therefore, one could assume that

228   this enhanced radiative energy input should also have led to the strongest temperature increase in

229   Europe during winter. But this is not the case. On the contrary, afforestation resulted in a slight

230   reduction of the mean local surface temperature in southern Europe in winter within the simulated 30

231   year period (-0.1 K, Fig. 4a). This is because in southern Europe, not only the mean local latent heat

232   fluxes were increased with afforestation (+2.7 W/m², Fig. 3b), but also the mean local sensible heat

233   fluxes were high and on a level comparable to croplands and grasslands (-0.1 W/m², Fig. 3c). That

234   means the increased local radiative energy input was transformed into high latent heat fluxes as well

235   as high sensible heat fluxes. As a result, the surface energy budget was slightly negative (-0.6 W/m²,

236   Fig. 3d), resulting in a slight local cooling in southern Europe in winter (Fig. 4a).

237   Although these slight temperature changes in northern, central and southern Europe can be explained

238   consistently with changes in the surface energy budget, the local temperature effects of afforestation

239   are statistically not significant in winter, as calculated by a Wilcoxon-Rank-Sum-Test at a 95 % level.

240   Thus, random causes for the temperature changes cannot be excluded.

241

242   **3.1.2 Summer**

243 In summer, the most striking effect of afforestation is the general increase in absorbed solar radiation.
244 The mean local net short-wave radiation was increased all over Europe within the period 1986-2015
245 (Fig. 3a). However, this increased radiative energy input at the surface did not result in a warming of
246 the surface temperatures. Because of the higher surface roughness of forests in comparison to
247 croplands and grasslands (table 1) the absorbed solar radiation is, in general, more efficiently
248 transformed into turbulent heat with afforestation (e.g. Breil et al., 2020). Therefore, both the mean
249 local latent heat fluxes and the mean local sensible heat fluxes were enhanced in all subregions (Fig.
250 3b+c). As a result, more energy was released as turbulent heat into the atmosphere than was
251 additionally absorbed by solar radiation. Thus, the surface energy budget became negative (Fig. 3d),
252 although the mean local net short-wave radiation was increased. Afforestation led consequently to a
253 cooling of the mean local surface temperatures all over Europe in summer for the period 1986-2015
254 (Fig. 4b).

255 The strongest cooling was simulated in southern Europe, with a mean temperature reduction of -0.8 K
256 (Fig. 4b). However, at single locations, the cooling was pronounced more strongly. The maximum
257 cooling effect was about -3.1 K, with 20 % of the afforested areas showing a mean cooling of more
258 than -1.3 K with afforestation. This strong cooling was reached, although the albedo effect of
259 afforestation was highest in southern Europe, due to the high solar altitude in summer. But the
260 increase in mean local net short-wave radiation of 5.0 W/m² (Fig. 3a) was completely counteracted by
261 a considerably increased mean local sensible heat flux (+11.0 W/m², Fig. 3c) and a slightly increased
262 mean local latent heat flux (+0.6 W/m², Fig. 3b). The comparatively small increase in latent heat fluxes
263 and the pronounced increase in sensible heat fluxes were caused by the generally low soil water
264 contents in summer and the resulting soil moisture limitation of evapotranspiration in southern Europe
265 (Seneviratne et al., 2010).

266 In central and northern Europe, the soil moisture limitation in summer was not as strongly pronounced
267 as in southern Europe. The mean local latent heat fluxes were consequently on a higher level (+4.9
268 W/m² in CE and +3.3 W/m² in NE, Fig. 3b), although the additional radiative energy input with
269 afforestation was not as high as in southern Europe (+4.1 W/m² in CE and + 2.9 W/m² in NE, Fig. 3a).
270 Since the mean local sensible heat fluxes were also increased (+2.1 W/m² in CE and + 1.0 W/m² in NE,
271 Fig. 3c), afforestation in central and northern Europe led to a mean local surface cooling of -0.5 K and
272 -0.3 K, respectively. The maximum mean local cooling effect in central Europe was about -2.6 K, and -
273 1.6 K in northern Europe.

274 In contrast to the local effects of afforestation in winter, local temperature changes in summer are in
275 fact statistically significant, as calculated by a Wilcoxon-Rank-Sum-Test at a 95 % level. In northern
276 Europe, 22 % of the afforested areas show statistically significant temperature changes. In central
277 Europe, 34 % of the temperature changes with afforestation are statistically significant, in southern

278   Europe as much as 63 %. However, this also means that for 78 % of the afforested areas in northern

279   Europe, for 66 % in central Europe, and for 37 % in southern Europe simulated temperature changes

280   are not significant. Although for these non-significant regions afforestation has the same physical

281   effects and the same process chain is simulated as for the significant areas, random causes for the

282   temperature changes in the non-significant regions cannot be excluded.

283

284   **3.2. Non-local effects**

285   **3.2.1 Winter**

286   The non-local effects of afforestation in Europe on the mean climate conditions in winter are now

287   investigated (Fig. 5). In the period 1986-2015, local afforestation led to a slight warming in Scandinavia,

288   central Europe and parts of southern Europe, more precisely Italy and the Balkan region (Fig. 5a). The

289   locally increased evapotranspiration rates with afforestation (Fig. 3b) enhanced the moisture content

290   in the atmosphere, with the consequence that the mean cloud cover in winter was slightly increased

291   over these regions (Fig. 5b). From the perspective of the surface energy balance, the effects of clouds

292   are stronger in winter on the outgoing long-wave radiation than on the incoming short-wave radiation,

293   due to generally short sunshine duration. Therefore, the net short-wave radiation was just slightly

294   reduced in these regions (Fig. 5c), while the reduction in the net long-wave radiation was stronger (Fig.

295   5d). This reduction in outgoing long-wave radiation led consequently to a decreased nocturnal cooling

296   and thus, to higher mean surface temperatures in Scandinavia, central Europe and parts of southern

297   Europe for the period 1986-2015. The mean non-local warming in these regions was +0.06 K, with a

298   warming less than +0.14 K in 90 % of the area. However, only a small proportion of these non-local

299   temperature changes are statistically significant. Only in southern Europe, the non-local warming with

300   afforestation was significant at 15 % of the affected area. For the other regions, no statistically

301   significant temperature changes were simulated. Thus, random causes for the differences between

302   AFF and REF cannot be excluded.

303   The local temperature changes with afforestation are clearly larger than the surrounding non-local

304   changes, as can be seen in Figure 5. In addition, the local temperature changes show often an opposite

305   sign and thus, are detached from the large-scale temperature patterns.

306

307   **3.2.2 Summer**

308   As already described for the winter season, the locally increased evapotranspiration rates in afforested

309   areas (Fig. 3b) enhanced also the atmospheric moisture content in summer under the dominant west-

310   wind circulation. The mean downwind cloud cover (Fig. 6b) and precipitation sums (Fig. 6c) were

311   consequently slightly increased over large parts of central and eastern Europe in the period 1986-2015.

312   Exceptions were an area north of the Black Sea and parts of north-eastern Europe. In the upwind areas

of western Europe, however, no systematic changes with afforestation were simulated for the mean seasonal cloud cover and the mean seasonal precipitation sums.

The increased mean precipitation sums in downwind direction slightly enlarged the amount of available water for evapotranspiration in these regions. As a result, the mean seasonal evapotranspiration rates were also enhanced in non-afforested regions of Europe (Fig. 6d), and thus, more radiative energy could be transformed into latent heat instead of heating up the land surface in summer.

In addition, the increased mean cloud cover slightly reduced the incoming mean solar radiation in summer (Fig. 6e) and thus, the radiative energy input in the respective regions. Therefore, the local afforestation in Europe led mainly to a slight cooling in the non-afforested areas of central and eastern Europe in summer for the period 1986-2015 (Fig. 6a). The mean non-local cooling effect in these regions was -0.06 K, with a cooling less than -0.13 K in 10 % of the area. Exceptions are the areas north of the Black Sea and parts of north-eastern Europe where the mean cloud cover and the mean precipitation sums were reduced. The mean non-local warming in these areas was +0.05 K, with a warming less than +0.11 K in 90 % of the area. Just like in winter, the non-local temperature changes in summer are not statistically significant, although these non-local effects can be explained by a physically consistent process chain. Therefore, random causes for the temperature changes cannot be excluded. Furthermore, the local temperature changes are again pronounced more strongly than non-local changes and detached from the large-scale temperature pattern.

3.3. Extremes

3.3.1. Temperature extremes

The non-local effects of afforestation on heat extremes (Fig. 7a) showed the same spatial patterns as for the mean temperature effects in summer (Fig. 6a). The daily maximum temperatures during heat extremes were slightly reduced over large parts of Europe, but slightly increased in an area north of the Black Sea and in parts of north-eastern Europe. However, the regional warming in these areas is pronounced more strongly than for the mean conditions in summer.

During heat periods, the surface energy budget strongly depends on the available amount of soil water for evapotranspiration. A reduction of the soil water availability has the consequence that less solar radiation can be transformed into latent heat and more energy is used to heat up the surface. The reduction of the mean seasonal precipitation sums north of the Black Sea and in north-eastern Europe during summer (Fig. 6c), leads in these regions to such a soil water limitation. The heat period intensities were therefore enhanced in these areas.

In the regions in which afforestation had a non-local cooling effect, the daily maximum temperatures during heat extremes were reduced in mean by -0.1 K, with no cooling below -0.2 K in 90 % of the area.

Comparable temperature effects were simulated for the regions in which afforestation had a non-local warming effect. North of the Black Sea and in parts of north-eastern Europe, heat extremes were in mean intensified by +0.1 K with a 90th percentile of +0.2 K. The non-local effects of afforestation on heat extreme intensities were consequently low.

The local effects of afforestation on the daily maximum temperatures during heat extremes were partly stronger. All over Europe, the intensities of heat extremes were locally reduced with afforestation. Although the mean local cooling effect was with -0.2 K comparable to the non-local effect, at some locations in southern Europe, temperature reductions as strong as -1.9 K were simulated during heat extremes.

Fig. 7b shows the effects of afforestation on cold extreme intensities in Europe for the period 1986-2015. In general, afforestation had the same spatial effects on cold extreme intensities as on the mean surface temperatures in winter (Fig. 5a). In Scandinavia, central Europe and parts of southern Europe (Italy and the Balkan region) cold extremes were reduced, while they were slightly increased in eastern Europe. However, the warming effect of afforestation on cold extreme intensities in Scandinavia, central Europe and southern Europe was more pronounced than the changes in the mean temperature conditions. Although the mean non-local warming was with +0.1 K rather small, maximum warming effects of up to +0.8 K were simulated in these regions.

Furthermore, the local effects of afforestation on the mean cold extreme temperatures were intensified. Particularly, the intensification of the local winter cooling in southern Europe is clearly evident during cold extremes. On average, the local daily minimum temperatures were reduced by -0.3 K in this region, while 10 % of the local temperature reduction were even larger than -0.8 K. Thus, local temperature responses had an opposite sign and were detached from the large-scale temperature pattern in southern Europe (Fig. 7b).

3.3.2. Precipitation extremes

In summer (S1) as well as in winter (S2), the number of small and moderate precipitation intensities was just slightly increased with afforestation. As shown in Fig. 3, evapotranspiration rates were locally increased with afforestation throughout the year all over Europe and particularly in central Europe. The atmospheric moisture content in Europe was consequently increased and downwind precipitation events became slightly more extensive. However, these increased evapotranspiration rates with afforestation did not affect the number and intensity of extreme precipitation events themselves. For precipitation events larger than 10 mm/day, no significant changes between AFF and REF were simulated over the simulated 30 years, indicating that the contribution of the slightly increased evapotranspiration rates with afforestation to the total precipitated water amount is negligible for such strong events.

383

3.4. Variability

The effects of afforestation in Europe on the interannual climate variability in winter and summer for the local and the non-local scales are shown in Figure 8. On average, afforestation did not change the interannual climate variability in Europe within the period 1986-2015. In both seasons, the mean change in the standard deviation was almost zero, both for the local and the non-local effects. However, a wider range of interannual variability were simulated for both, the summer and the winter season. On the local scale, the spread in variability is higher in summer than in winter. But in both cases, positive as well as negative variability changes with afforestation are evenly distributed and do not show any consistent spatial patterns. Thus, interannual variability changes with afforestation are balanced on the local scale, indicating on random effects caused by the natural climate variability. On the non-local scale, the changes in the interannual variability are almost negligible. Therefore, afforestation did not have systematic effects on the interannual climate variability in Europe in our experiments.

4. Discussion

The results of our study reflect the well-known effects of afforestation on the surface temperatures (e.g. Bonan et al., 2008), which are already documented in several measurements (e.g. Li et al., 2015; Duveiller et al., 2018) and modeling studies (e.g. Strandberg & Kjellström, 2019; Davin et al., 2020). On the local scale, European afforestation led to a slight warming of the surface temperatures in winter within the period 1986-2015, with the strongest warming effect in central Europe (Fig. 4a). However, statistically significant local effects of afforestation could only be simulated in summer, where afforestation resulted in a slight local cooling of the surface temperatures, with the strongest cooling effect in southern Europe (Fig. 4b). These general effects of afforestation on the surface temperatures in summer seem to be independent of the afforested area, as shown by the results of coordinated model intercomparison studies with idealized afforestation scenarios. For instance, Davin et al., (2020) and Breil et al., (2020) show that afforestation would have the same local temperature effects if the whole European continent would be afforested.

In contrast, the small local warming effect in winter is quite astonishing, since it is generally assumed that afforestation is associated with a pronounced warming in the mid-latitudes in boreal winter, as for example shown by Lejeune et al., (2017) for North America. Using Land-Use and Climate, Identification of Robust Impacts (LUCID) models and Phase 5 of the Coupled Model Intercomparison Project (CMIP5) models, Lejeune et al., (2017) provided evidence that the snow-masking effect of forests (e.g. Essery, 2013) is clearly pronounced in North America. In combination with slightly increased evapotranspiration rates, winter temperatures of forests are about 0.3 K (LUCID) and 0.4 K

418 (CMIP5) higher than those of other vegetation forms. However, the snow-masking effect is less

419 pronounced in Europe than in North America, as shown by Asselin et al., (2022) within the framework

420 of an idealized afforestation experiment for Europe and North America. They could show that snow-

421 masking reduces the surface albedo on both continents in a similar way, but the reduced surface

422 albedo effect on the surface temperatures is in North America much stronger than in Europe. For the

423 same latitude, European climate is warmer than the climate in North America, and snow cover in

424 winter is consequently restricted only to higher latitudes, notably central and northern Europe. There,

425 insolation is low in winter and thus, the albedo effect on surface temperatures is small. The same

426 conclusions were drawn by Strandberg & Kjellström, (2019) from regional climate simulations with an

427 idealized afforestation scenario for Europe.

428 In southern Europe, where insolation is higher, snow cover plays a minor role for the surface energy

429 balance. Surface temperatures are typically higher than for central and northern Europe, and

430 therefore, buoyancy is generally stronger in this region. In combination with the higher surface

431 roughness of forests and the associated increased wind shear, afforested areas in southern Europe are

432 consequently able to transform this increased energy input from solar radiation efficiently into

433 turbulent heat and release the energy into the atmosphere (e.g. Breil et al., 2020), counteracting the

434 increased solar radiation. Thus, afforestation did not have a warming effect in southern Europe in

435 winter (Fig. 4). These described general effects of afforestation on the different components of the

436 surface energy balance are intensified in summer and also take place in central and northern Europe

437 (Fig. 3; Breil et al., 2020). A general reduction of the surface albedo, an increased release of turbulent

438 energy into the atmosphere and a resulting local cooling in summer are also described by Burakowski

439 et al., (2018) for North America. This indicates that the results of this study may be representative for

440 afforestation in the mid-latitudes and transferable to other regions.

441 Beyond these local effects, afforestation affects the climate conditions in Europe also on the non-local

442 scale (Fig. 5 and Fig. 6). As already demonstrated by Meier et al., (2021), afforestation can increase

443 downwind cloud cover and precipitation sums in Europe by increased evapotranspiration rates and

444 thus, a higher moisture content in the atmosphere. These findings are confirmed by the results of this

445 study (Fig. 6b-d). Although the non-local effects of afforestation can be explained by a physically

446 consistent process chain, simulated non-local temperature changes are statistically not significant in

447 Europe.

448 However, a missing significance does not necessarily mean that there is no causal relationship

449 (Wasserstein & Lazar, 2016) between afforestation and the simulated non-local temperature changes.

450 On the contrary, the traceability of the complete physical process chain is, from our point of view, a

451 strong indicator that the non-local afforestation effects are not random. Particularly downwind

452 processes are spatially and temporally highly variable. Thus, locally induced changes in the

453 atmospheric moisture conditions do not always lead to precipitation and cloud cover at the same
454 downwind locations (Perugini et al., 2017). This high spatial and temporal variability, has the
455 consequence that the mean downwind effects are small and difficult to detect, resulting in not
456 significant temperature changes. Nevertheless, during extreme events, like heat periods in summer or
457 cold spells in winter, the described effects of afforestation on the local and the non-local surface
458 energy and water balance are pronounced more strongly than for the mean climate conditions, so that
459 afforestation had a notable impact on the characteristics of these extremes within the period 1986-
460 2015 (Fig. 7, Breil et al., 2023b).

461 However, the presented work is a modeling study and therefore associated with certain modeling
462 uncertainties. Even though CCLM-VEG3D is able to properly reproduce the observed regional climate
463 conditions in Europe during the simulated 30 years (Fig. 2), the effects of afforestation on the surface
464 temperatures may locally differ from measurement studies (e.g. Li, et al., 2015; Duveiller et al., 2018).
465 These differences to observations might result from the fact that in CCLM-VEG3D only the dominant
466 land use class is considered within a model grid box. This means that the local effects of afforestation
467 on the surface temperatures are overestimated at some places, and underestimated at other places.
468 However, the total afforested area in CCLM-VEG3D has with 1,7 % of the European continent nearly
469 the same extent as the real one with 1.1 % (Hoffman et al., 2022). The simulated total effects of
470 afforestation on the regional surface energy balance in Europe are therefore reasonable, and the
471 applied modeling approach is suitable to analyze the general impact of afforestation on the European
472 climate for the period 1986-2015. Nonetheless, regional variations in the described local and non-local
473 process chains have to be acknowledged.

474 In addition, the results of this study are only valid for evergreen needleleaved trees and deciduous
475 broadleaved trees that are characteristic for the mid-latitudes. Other tree species, like for example
476 evergreen broadleaved trees or deciduous needleleaved trees can of course have other effects on the
477 local surface energy balance and consequently induce other remote effects. The described
478 afforestation effects in this study could therefore be both, stronger and weaker.

479 On the other hand, the advantage of an idealized modeling study like this is that the effects of
480 afforestation on the surface energy balance can be locally isolated and comprehensively analyzed, by
481 performing and comparing simulations with and without afforestation. This is not possible in
482 observation based studies. Thus, the analyzed effects of afforestation on the surface energy balance
483 are in such measurement studies potentially superimposed by other processes, which are not easy to
484 separate from each other.

485 In conclusion, it is noticeable that the temperature changes with afforestation appear to be rather
486 small in Europe. However, in comparison to the mean temperature changes during the investigation
487 period 1986-2015, the impact of afforestation on the climate change signal is considerable. While the

488 mean temperatures in winter rose about 1.7 K in Europe during the simulated 30 years (Twardosz et
489 al., 2021), mean summer temperatures between 1986-2015 were 1.3 K warmer compared to pre-
490 industrial levels (Luterbacher et al., 2016). During the last decade of the investigation period, mean
491 annual temperatures were 1.5 K above pre-industrial levels (European Environment Agency, 2017).
492 Thus, the simulated non-local warming of up to 0.1 K in Scandinavia, central Europe and parts of
493 southern Europe in winter, additionally contributed to the general winter warming signal in these
494 regions. On the other hand, the local cooling effect of afforestation of about -0.3 K in northern Europe
495 and about -0.8 K in southern Europe in summer, may have mitigated the general warming trend in
496 summer. That means that without afforestation, the climate change signal would have been much
497 stronger in these regions for the period 1986-2015, especially in summer.

498

499 **5. Conclusions**

500 In this study, we analyzed the general effects of afforestation on the regional climate conditions in
501 Europe for the period 1986-2015, by performing long-term regional climate simulations, with one
502 simulation considering changes in forest cover and another simulation not accounting for changes in
503 forest cover. The comparison of these simulations reveals that afforestation led to a discernible
504 reduction of the mean local surface temperatures all over Europe in summer in the simulated 30 years.
505 In northern and central Europe local surface temperatures were reduced by -0.3 K and -0.5 K,
506 respectively. In southern Europe, this cooling effect is particularly pronounced and a mean local cooling
507 of -0.8 K was simulated. During heat extremes, the local cooling effect of afforestation is intensified.
508 At some locations in Europe, temperature reductions reached values up to -1.9 K. In winter,
509 afforestation did not have a significant local effect, due to a small general impact of the snow masking
510 effect.

511 Beyond these local effects, afforestation had also an impact on the downwind climate conditions. By
512 increasing the local evapotranspiration rates, afforestation led to an increase in the atmospheric
513 moisture content, and thus to a non-locally enhanced cloud cover and precipitation sums in
514 Scandinavia, central Europe and parts of southern Europe. These changes in the atmospheric water
515 cycle resulted in a slight warming of the mean non-local surface temperatures in winter and a slight
516 cooling in these regions in summer. Although these mean non-local temperature changes are not
517 statistically significant, non-local afforestation effects can be consistently explained by non-local
518 changes in the energy and water balance, which had especially during temperature extremes a notable
519 impact on the non-local climate conditions in Europe.

520

521 **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 VKMS 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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766 Table 1: Maximum parameter values of the surface roughness, leaf area index (LAI), surface albedo,

767 and root depth used in CCLM-VEG3D for deciduous forests, coniferous forests, croplands, and

768 grasslands.

	LAI	root depth (density < 2%)	albedo	surface roughness
deciduous forest	8	2.0 m	0.15	0.8 m
coniferous forest	9	1.0 m	0.11	1.0 m
croplands	3.5	1.0 m	0.2	0.07 m
grasslands	4	0.5 m	0.2	0.03 m

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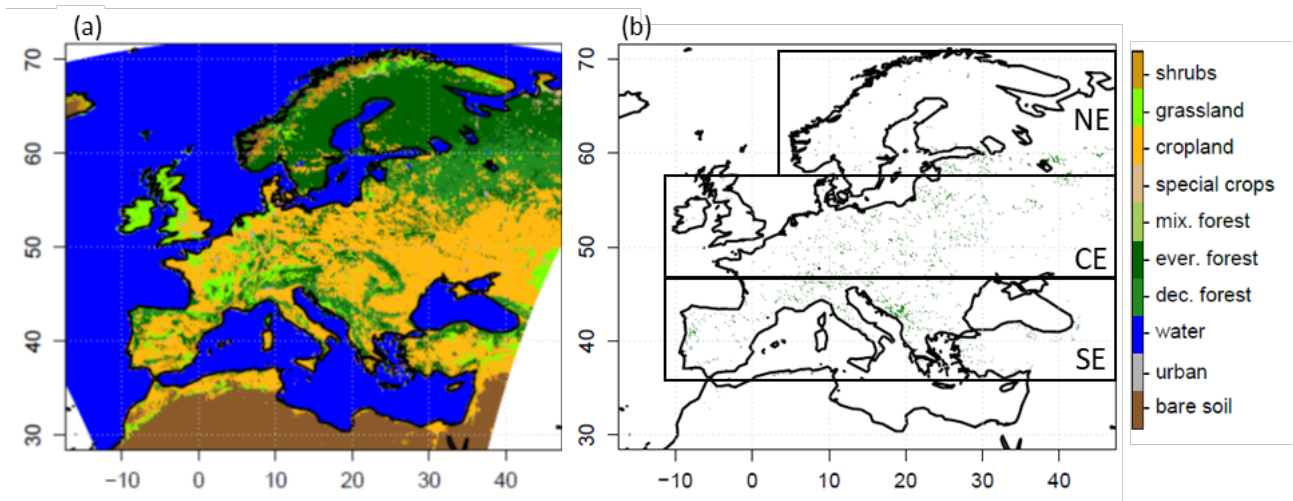
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793 Figure 1: (a) CCLM-VEG3D land use classes. (b) grid cells in which afforestation took place between
794 1986-2015 in the AFF simulation. The black boxes show the locations of the three geographical sub-
795 regions, northern Europe (NE), central Europe (CE) and southern Europe (SE).

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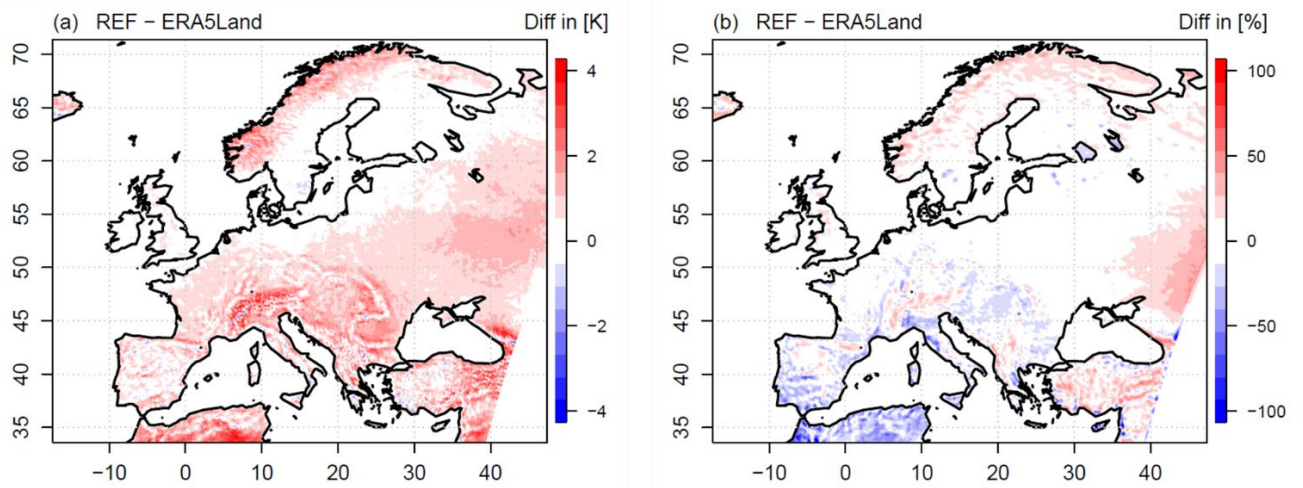
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829 Figure 2: Differences in the (a) yearly mean 2 m temperature and (b) the percentage deviation in the
830 yearly mean total precipitation sums between REF and the ERA5-Land reanalysis for the period 1986-
831 2015.
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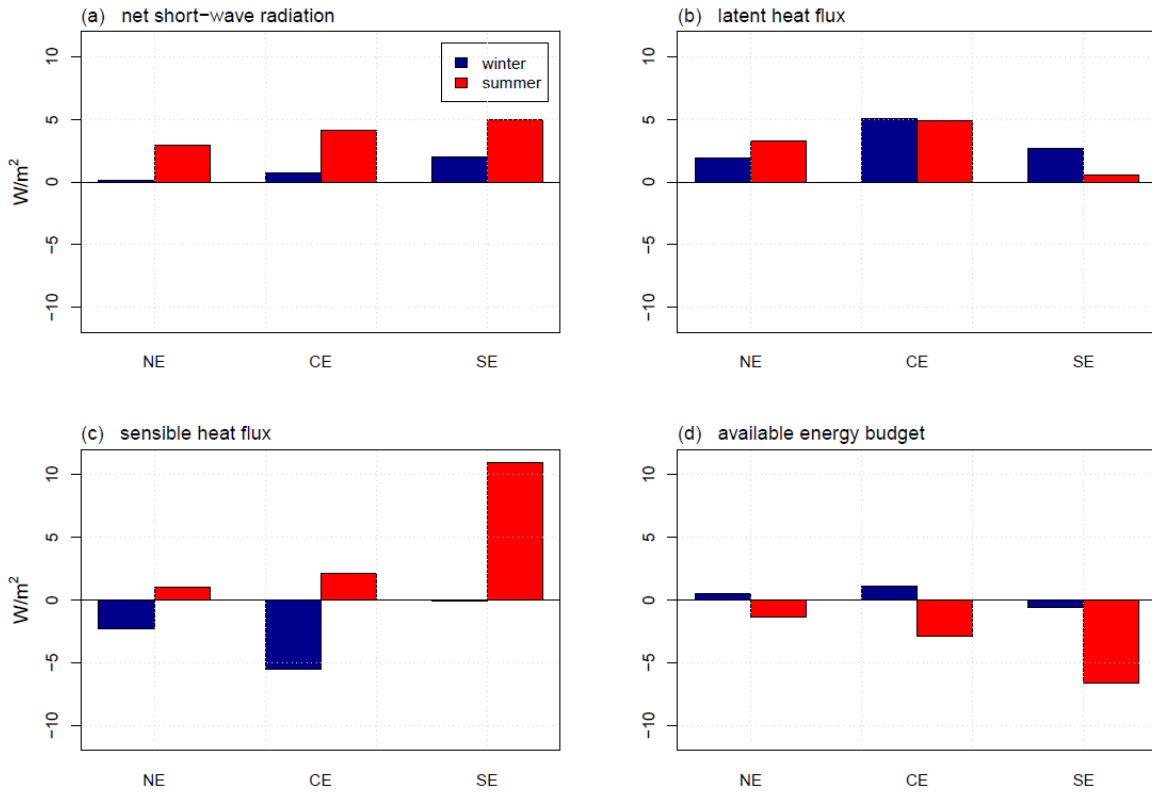
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846 Figure 3: Local effects of afforestation (AFF-REF) on (a) the mean net short-wave radiation (R), (b) the
847 mean latent heat fluxes (L), (c) the mean sensible heat fluxes (H), and (d) the available energy budget
848 at the surface (defined as R − (L+H)), for the three subregions NE, CE and SE. Local effects in winter are
849 shown in blue, local effects in summer are shown in red.
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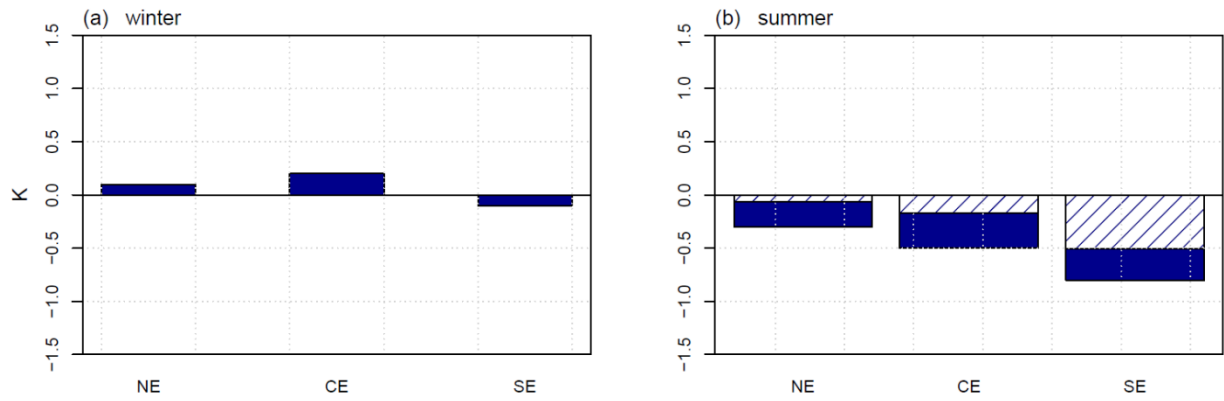
Figure 4: Local effects of afforestation (AFF-REF) on the mean surface temperature in (a) winter, and (b) summer for the three subregions NE, CE and SE. The fraction of significant local effects in the respective subregions (calculated with a Wilcoxon-Rank-Sum-Test at a 95 % level) are indicated by dashed lines.
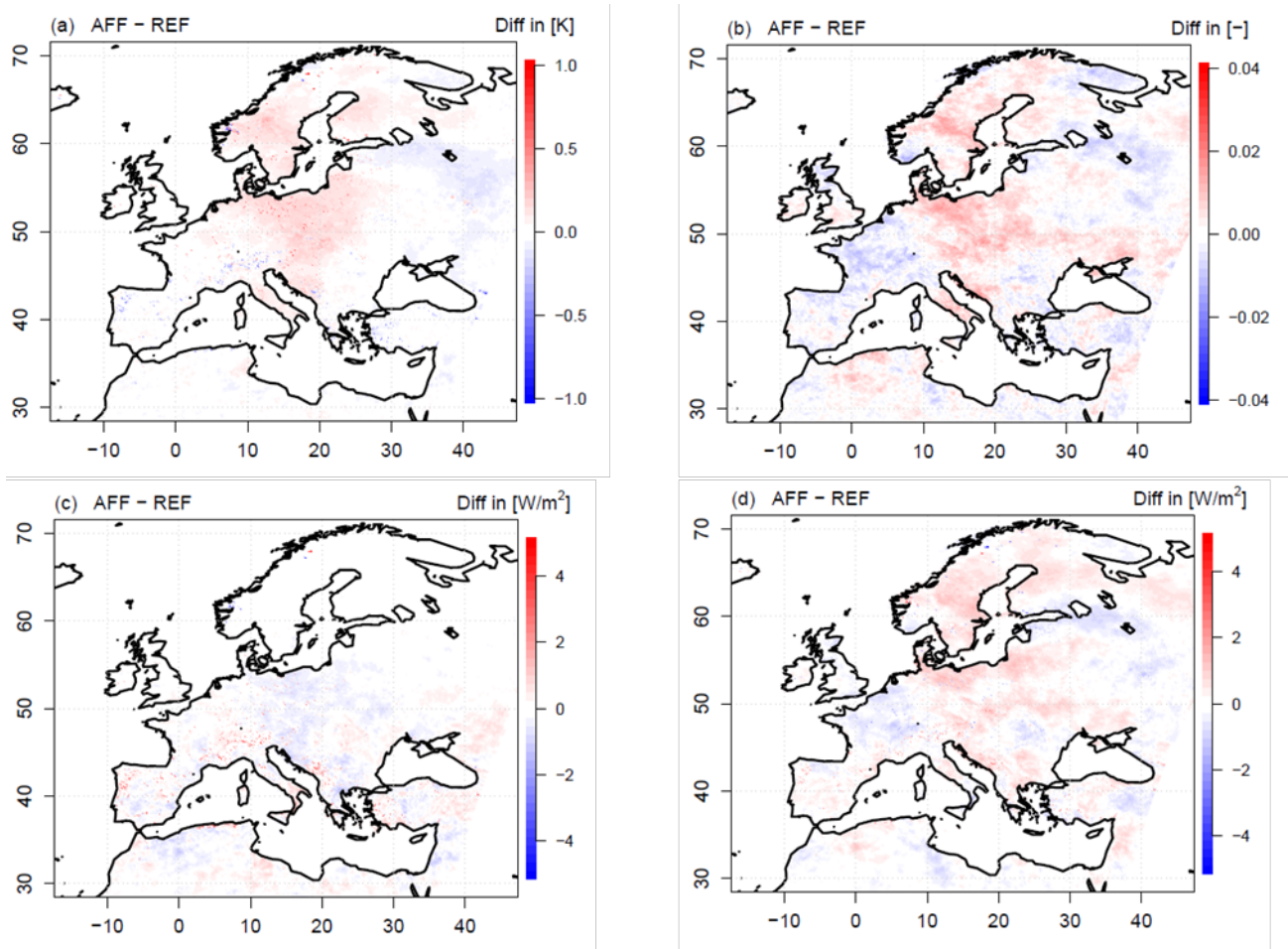
Figure 5: Non-local effects of afforestation in Europe on (a) the mean surface temperatures, (b) the mean cloud cover, (c) the mean net short-wave radiation, and (d) the mean net long-wave radiation in winter between AFF and REF.

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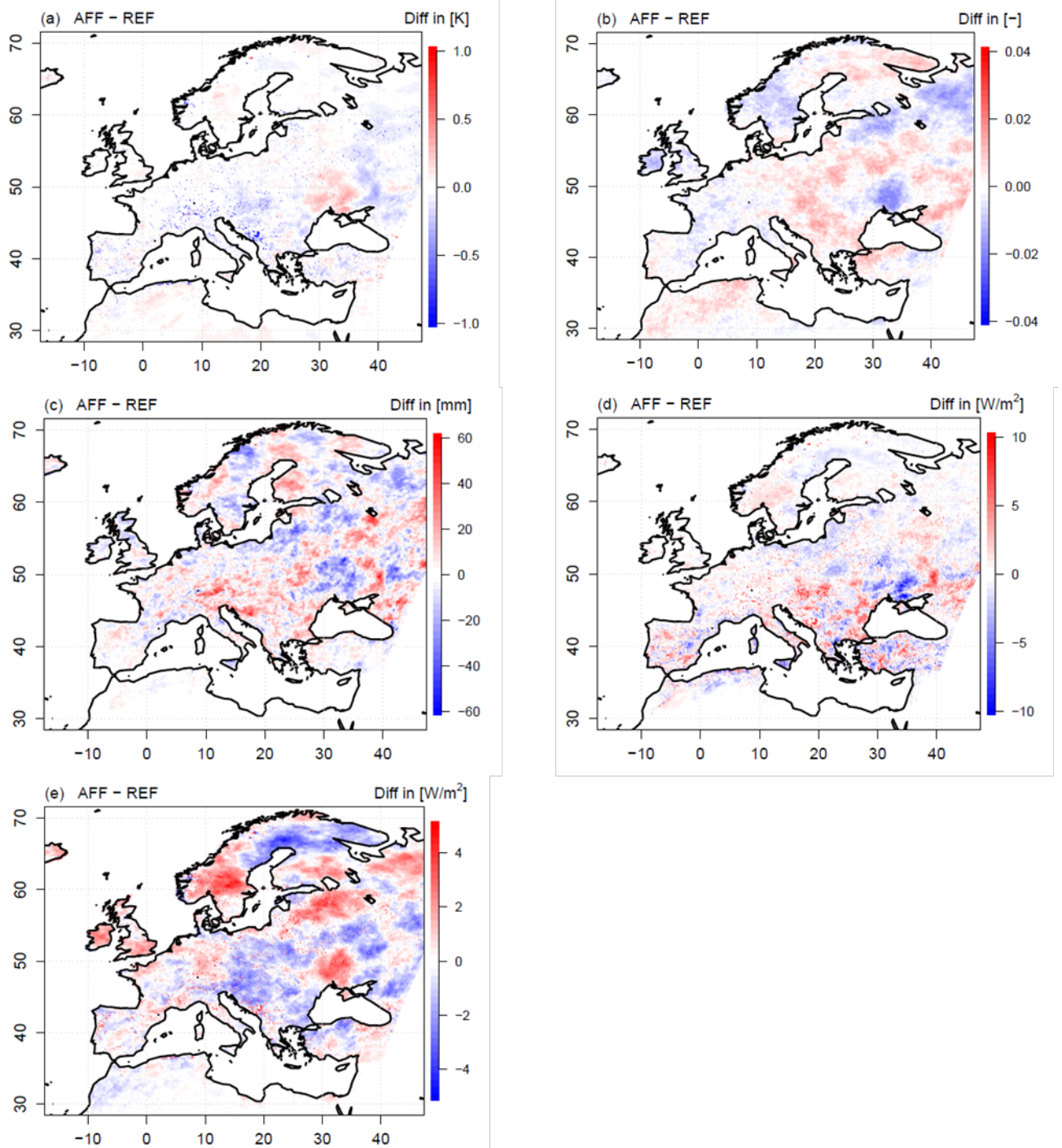
909 Figure 6: Non-local effects of afforestation in Europe on (a) the mean surface temperatures, (b) the
910 mean cloud cover, (c) the mean precipitation sums, (d) the mean evapotranspiration rates, and (e) the
911 mean net short-wave radiation in summer between AFF and REF.

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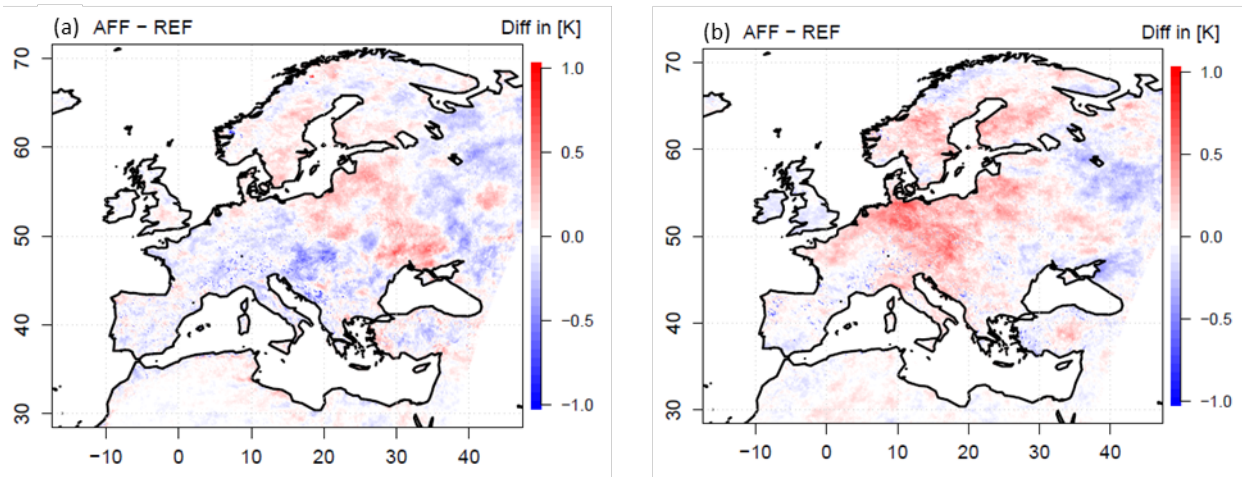
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920 Figure 7: Effects of afforestation on temperature extreme intensities in Europe for the period 1986-
921 2015. Changes in temperature extreme intensities are expressed as the mean temperature differences
922 in the days (a) above the 90th percentile of the daily maximum temperatures in 2 m height in summer
923 and (b) below the 10th percentile of the daily maximum temperatures in 2 m height in the winter season
924 between AFF and REF.
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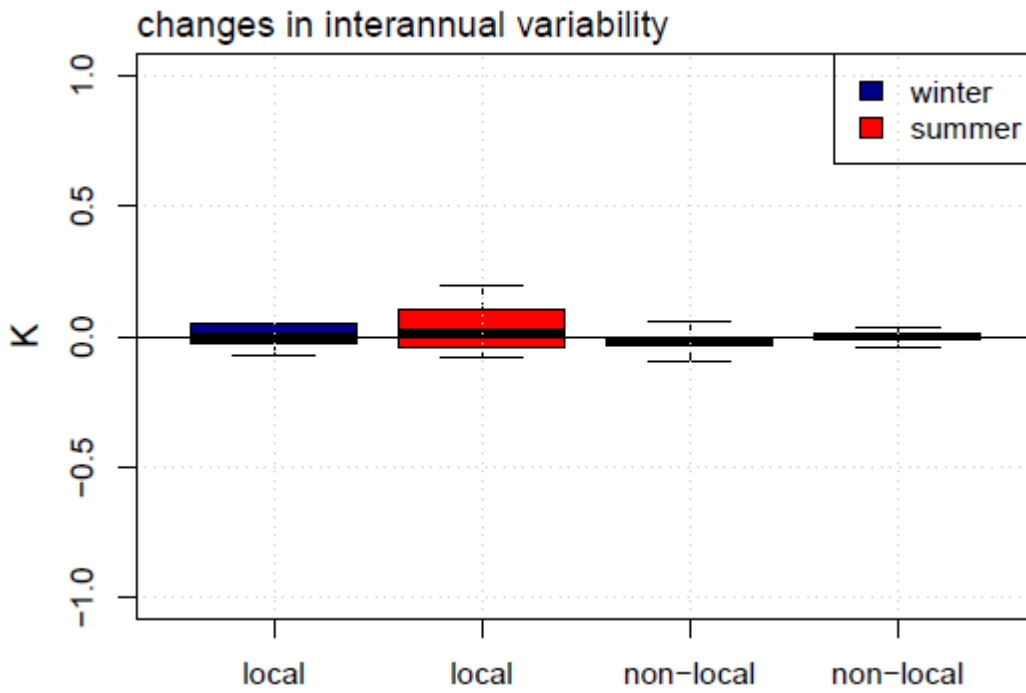
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938   Figure 8: The effects of afforestation in Europe on the interannual climate variability in winter and
939   summer for the local and the non-local scales, derived from the standard deviation of the mean
940   seasonal surface temperatures.
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