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Afforestation reduces cyclone intensity and precipitation extremes over Europe

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E-mail: danijel.belusic@smhi.se**Keywords:** land cover change, cyclone tracking, climate extremes, extratropical cyclonesSupplementary material for this article is available [online](#)

Abstract

Extratropical cyclones are the dominant weather pattern in the midlatitudes and cause up to 80% of precipitation extremes in some regions of Europe with a large societal and economical impact. Using a regional climate model and a cyclone-tracking algorithm, we study how idealized deforestation and afforestation of Europe affect long-term changes in the number and intensity of cyclones, and their effects on precipitation. The number of cyclones over Europe is smaller for afforestation compared to deforestation, with differences starting from 10% in regions near the west European coast and increasing towards the east to reach 80%. This decrease is caused by the larger surface roughness in afforestation. The winter precipitation extremes are considerably reduced with afforestation, without a large decrease in mean precipitation because of the balancing effect of increased weak and moderate precipitation. The mean precipitation increases over central and southern Europe as a result of the summer precipitation increase caused by larger evapotranspiration and access to deeper soil moisture in the presence of trees. These different region-specific effects of afforestation are generally positive and could provide an important mitigation tool in a changing climate.

1. Introduction

Changes in forest cover affect local climate via biogeophysical effects. These effects occur due to changes in the physical properties of the surface, such as albedo, heat fluxes, radiation and surface roughness. The influence on climate as well as the relative importance of the different effects depend very much on local conditions (Davin *et al* 2014, Alexandru and Sushama 2016). Factors that affect the local nature of land-atmosphere interactions include the latitude, soil and vegetation types, moisture availability, large-scale weather patterns, and size and spatial pattern of the area with forest cover change. A general rule is that afforestation increases winter temperatures in regions with long snow season as a result of albedo changes (Gao *et al* 2014, Strandberg and Kjellström 2019), and decreases summer temperatures as a result of increased evapotranspiration (Gálos *et al* 2011, Gao *et al* 2014, Stéfanon *et al* 2014, Perugini *et al* 2017, Strandberg and Kjellström 2019). Previous modelling

studies report only small effects of land use changes on precipitation; mostly on the timing and location of precipitation rather than the total precipitation within a larger area (e.g. Seneviratne *et al* 2013, Winchester *et al* 2017).

Probably the most straightforward effect of afforestation is increased surface roughness. At the same time, one of the most important weather patterns that affects local climate and extremes in the midlatitudes is extratropical cyclones (e.g. Hawcroft *et al* 2012, Pfahl and Wernli 2012). Extratropical cyclones can be responsible for up to 80% of precipitation extremes over some regions in Europe (Pfahl and Wernli 2012), thus having a large societal and economical impact both now and in the changing climate (e.g. Hawcroft *et al* 2018). Previous studies have shown that the presence of surface friction reduces the intensity of extratropical cyclones by about 40% compared to the frictionless case (Anthes and Keyser 1979, Boutle *et al* 2015). Ekman pumping has long been considered as the dominant mechanism for the cyclone intensity

reduction (e.g. Holton 2004, Beare 2007). It is a barotropic mechanism where the surface friction generates low-level flow convergence and consequently ascent at the top of the atmospheric boundary layer (ABL), forming secondary circulation that leads to the spin down of a cyclone (e.g. Holton 2004, Adamson *et al* 2006, Beare 2007). Adamson *et al* (2006) propose baroclinic potential vorticity generation in ABL due to surface friction as an additional mechanism for the cyclone spin-down that might in some cases have the dominant role. The current understanding is that both mechanisms may act in concert to produce the final intensity reduction (Boutle *et al* 2007, 2015). For the purpose of this study it is sufficient to conclude that surface friction considerably reduces cyclone intensity. It is important to note that the conclusions from previous studies are mostly based on idealized model simulations, achieved either by completely removing the surface friction or ABL mixing in otherwise realistic simulations (Anthes and Keyser 1979), or by simulating an idealized cyclone in a dry atmosphere (Adamson *et al* 2006, Beare 2007, Boutle *et al* 2007).

We take an approach where realistic simulations are performed in climate mode over 30 years, focusing on two extremes in forest cover over Europe: complete deforestation and potential afforestation. The extreme vegetation change is used to quantify the maximum possible effect on climate and is not considered as a realistic land cover change scenario. However, the realistic surface friction is always present and is either increased for increased forest cover or decreased in the absence of forests. The benefits of the realistic climate simulations are the large number of simulated cyclones which provides robustness of conclusions, and the inclusion of moist processes which allow us to infer the effects on precipitation and other climate characteristics.

2. Methods

2.1. Modelling setup

The regional climate model RCA4 (Strandberg *et al* 2014, Kjellström *et al* 2016), a successor of RCA3 (Samuelsson *et al* 2011) that is based on the numerical weather prediction model HIRLAM (Undén *et al* 2014), is used to simulate the climate response to different forest covers over the European domain (indicated in figure S1, which is available online at stacks.iop.org/ERL/14/074009/mmedia). The simulation period is 1980–2010, with the first year used for spin-up and not considered in the analysis. The initial and boundary data including the sea surface temperature are taken from the ERA-Interim reanalysis (Dee *et al* 2011). The modelling setup is the same as for the EURO-CORDEX simulations with horizontal grid spacing of 0.44° (e.g. Jacob *et al* 2014). This horizontal resolution is sufficiently high to allow reproduction of the most important aspects of

extratropical cyclones (e.g. Adamson *et al* 2006, Beare 2007, Boutle *et al* 2007, 2015), and at the same time low enough for reasonably fast computation of several 30 year simulations on a supercomputer. Other details about the model set-up and simulations can be found in Strandberg and Kjellström (2019).

Four experiments have been performed, differing only in the land cover characteristics (see also figure S1):

- Control, with the current vegetation cover.
- Afforestation, with the potential afforestation of Europe, i.e. vegetation is allowed to grow freely without human intervention (Strandberg and Kjellström 2019). The surface roughness length (z_0) in this experiment varies between 1 and 3 m.
- Deforestation, with all forest areas converted to open land. Here z_0 is between 0.01 and 0.1 m.
- z_0 , where all land cover characteristics are the same as in the deforestation experiment (i.e. open land), except for z_0 , which is the same as in the afforestation experiment. It is important to note that in RCA4, open land areas with snow cover automatically take the snow roughness length, while forests keep their roughness length irrespective of snow cover. This means that without snow cover the z_0 and afforestation experiments have the same roughness lengths, but in the presence of snow their roughness lengths are substantially different. Hence extra care is taken when analysing this experiment.

Note that the forest cover is rather similar in control and afforestation over most of Fennoscandia, while majority of other areas show considerable difference (figure S1).

The aim of this study is to explore the maximal possible effects of realistic, albeit not practically achievable in short-term, changes in the surface characteristics (Strandberg and Kjellström 2019). Thus, the deforestation and afforestation are used as the opposite extremes to help inform about the largest magnitude of climate response to such changes. The effects from more achievable surface changes will be explored in subsequent studies.

By using the same ERA-Interim forcing in all simulations, the differences in results are only due to the response of RCA4 to the change in surface characteristics. The main mechanism studied here is the model response to surface roughness change. Since different surface covers are always present in realistic domains, potential problems with the model behaviour over different surfaces would have emerged in previous model usage and validation. RCA4 and its predecessors have been amply validated against observations by many different groups, particularly within the CORDEX framework, and it has been found to perform within the expected limits of the state-of-the-

art models (e.g. Kjellström *et al* 2005, Nolan *et al* 2012, Pryor *et al* 2012, Belušić *et al* 2018). Specifically, in a model inter-comparison study over North America He *et al* (2010) found that RCA3 reproduces well the sensitivity to different surface types.

2.2. Cyclone tracking

A number of cyclone tracking algorithms exist in the literature. They use different techniques for cyclone detection, and also different variables, such as MSLP (e.g. Lionello *et al* 2002, Pfahl and Wernli 2012) or relative vorticity in the lower troposphere (e.g. Hodges 1994, Hawcroft *et al* 2016). The results can vary considerably between different techniques and the absolute number of detected cyclones is method dependent (Neu *et al* 2013, Lionello *et al* 2016). Here we are comparing the four different experiments listed above, and hence are only interested in relative changes in the number of cyclones between the experiments. This reduces the sensitivity of the results to the choice of a cyclone detection technique.

A modified version of the method developed for detecting and tracking tropical cyclones (Fuentes-Franco *et al* 2014, 2017) is applied here on 6-h model outputs to track extratropical cyclones. The modified method detects an extra-tropical cyclone at a grid point when the following conditions are satisfied:

- Sea level pressure < 1000 hPa.
- Wind speed at 850 hPa $> 5 \text{ m s}^{-1}$.
- A group of at least 15 grid points (a contiguous area) satisfying the previous conditions must have eccentricity < 0.95 and the maximum surface pressure gradient within the contiguous area of at least 0.04 hPa km^{-1} .

The tracking algorithm is the same as for the tropical cyclone version of Fuentes-Franco *et al* (2017). We choose 4×4 deg grid boxes for counting cyclones, as a trade-off between keeping more information about spatial structure and ensuring larger cyclone numbers and hence higher robustness in calculating differences for each grid box.

2.3. Precipitation distribution

The forest cover change affects the mean precipitation but also the shape of precipitation distribution. The changes of the precipitation distribution between different experiments are studied using the analyzing scales of precipitation (ASoP) method (Klingaman *et al* 2017, Berthou *et al* 2018) applied on 3-h accumulated precipitation data. ASoP gives a distribution of the contributions of each precipitation intensity bin to the mean precipitation rate. The distributions are calculated for each model grid point, and then averaged over desired regions. In the first step, the method defines the precipitation intensity

bins such that all bins have a similar number of events, except for the largest bins due to small number of events there. The frequency of events in each bin is then multiplied by the mean precipitation rate of the bin to obtain the actual contribution of the bin to the mean precipitation rate (an example can be seen in figures S8(a) and (c)). Note that the sum of all actual contributions gives the mean precipitation rate. Furthermore, dividing the actual contributions by the mean precipitation rate gives the fractional contributions to the mean precipitation. The sum of all fractional contributions equals one (exemplified in figures S8(b) and (d)), so the information provided by fractional contributions is predominantly about the shape of the distribution.

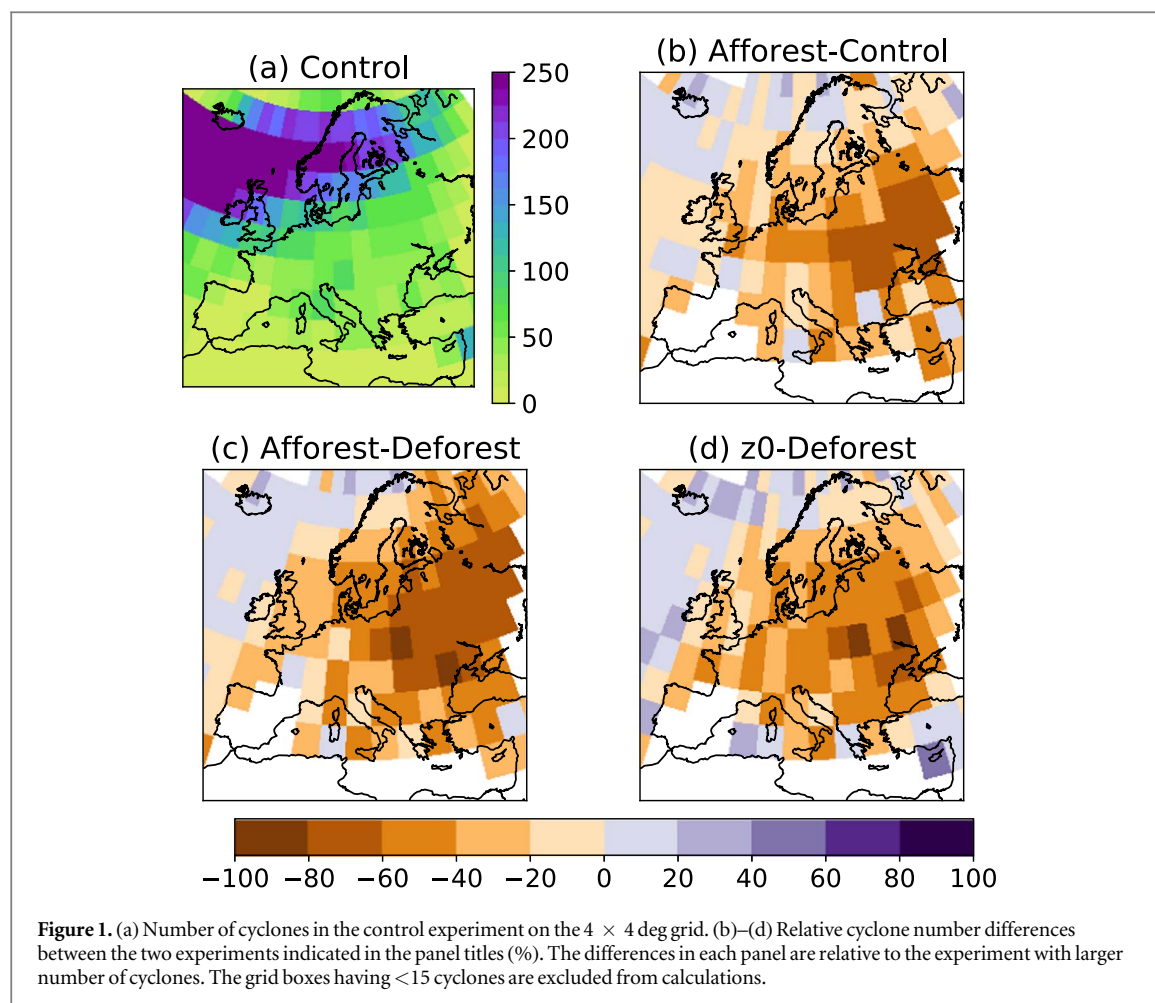
The main interest here is in precipitation differences between different experiments. In some cases the differences between distributions of two experiments are very similar for both actual and fractional contributions (exemplified for winter in figure 4). This indicates that the differences between the experiments are predominantly in the shape of the distribution, and not in the mean precipitation. On the other hand, if the mean precipitation is different, then the differences of actual contributions could be of the same sign for most of the intensity bins (exemplified for summer in figure 4(c)). In that case, the differences of fractional contributions are not similar to actual contributions, but indicate how the shape of distribution changes (exemplified in figure 4(d)).

An alternative to averaging the distributions over a certain region, which was illustrated in the above examples, is to plot spatial maps. In the subsequent analysis, spatial maps are created by integrating actual or fractional contributions at each grid point over four intensity bins: < 10 , $10\text{--}20$, $20\text{--}40$, and $> 40 \text{ mm d}^{-1}$.

3. Results

3.1. Forest cover effects on cyclones

The spatial distribution of the number of cyclones clearly shows the storm track (figure 1) and is consistent with other cyclone tracking studies (e.g. Pfahl and Wernli 2012). The most conspicuous effect of changing the forest cover is seen in the number of cyclones. In all experiments with increased forest cover or roughness, the number of cyclones is reduced over most of continental Europe. The reduction generally increases from west to east over the continental area, ranging from $< 20\%$ to 80% . This is because cyclones predominantly travel eastward and are thus longer exposed to land cover effects further east. The largest differences are between the afforestation and deforestation. The control experiment has relatively small differences from afforestation over Fennoscandia, because most of the current land cover there is close to potential afforestation (figure S1). Further south, the differences between control and

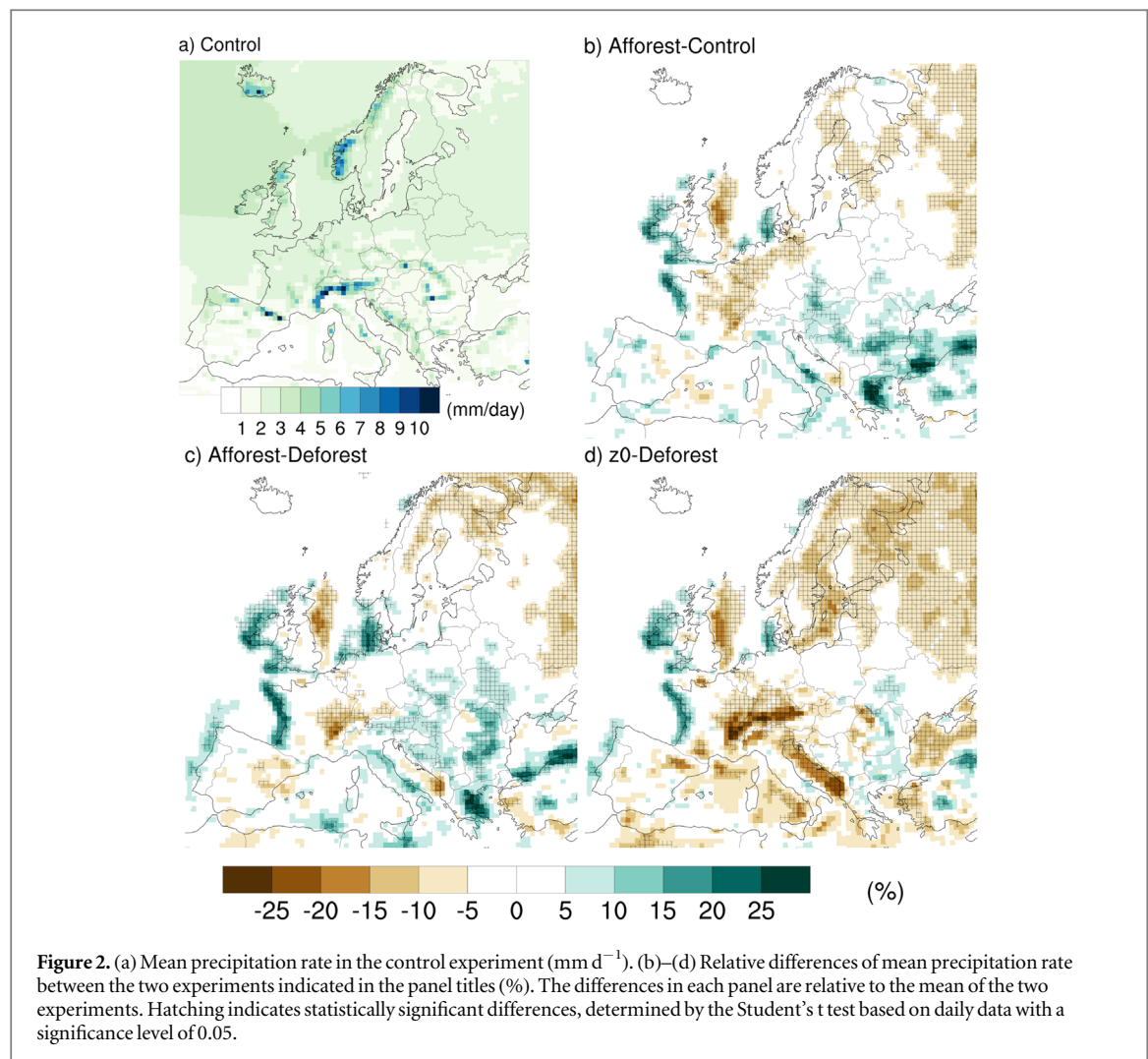


afforestation increase and are approaching the values and spatial pattern of the differences between deforestation and afforestation. The roughness (z_0) experiment is interpreted with caution because of the issue with snow cover explained in Methods: the roughness length is the same in both afforestation and z_0 experiments, except when snow cover is present. Since figure 1 includes cyclones from all seasons and there are many cyclones in winter, the effect of decreased roughness over snow is considerable for some areas. Nevertheless, the z_0 experiment indicates that a large part of the reduction in number of cyclones for afforestation is a consequence of the increased roughness, which is consistent with previous idealized studies (Anthes and Keyser 1979, Boutle *et al* 2015). This is seen more clearly for individual seasons: in the absence of snow over most of the domain (predominantly summer and autumn) the cyclone reduction is very similar in both afforestation and roughness experiments (figures S2–S5).

The number of cyclones is also reduced over the British Isles and the North Sea in all experiments with larger surface roughness. This is partially because eastern parts of eastward propagating cyclones reach land before their centres, so some reduction is expected over the seas west of the continent. Another reason is likely the increased roughness over the British Isles.

We are not aware of a study addressing the dependence of cyclone development on horizontal length scales of roughness change. However, the British Isles extend meridionally about 1000 km, which is the same order of magnitude as the typical cyclone size, so it is likely that they affect the cyclone development.

The increased roughness due to afforestation affects also the intensity of cyclones. The cases with cyclone weakening (i.e. filling; positive pressure change) dominate over land (figure S6). The entire frequency distribution of the pressure rate of change for afforestation is shifted toward larger values compared to deforestation, for both the intensifying and weakening cases, implying systematically weaker deepening and stronger filling of cyclones for afforestation. The median pressure change is 7.4 Pa h^{-1} for deforestation and 11.4 Pa h^{-1} for afforestation, so the cyclones in the afforestation case are weakening about 35% faster than for deforestation. This is consistent with the changes in the number of cyclones (figure 1). The control experiment is, according to expectations, between the two forest cover extremes, with the median pressure change of 8.4 Pa h^{-1} .



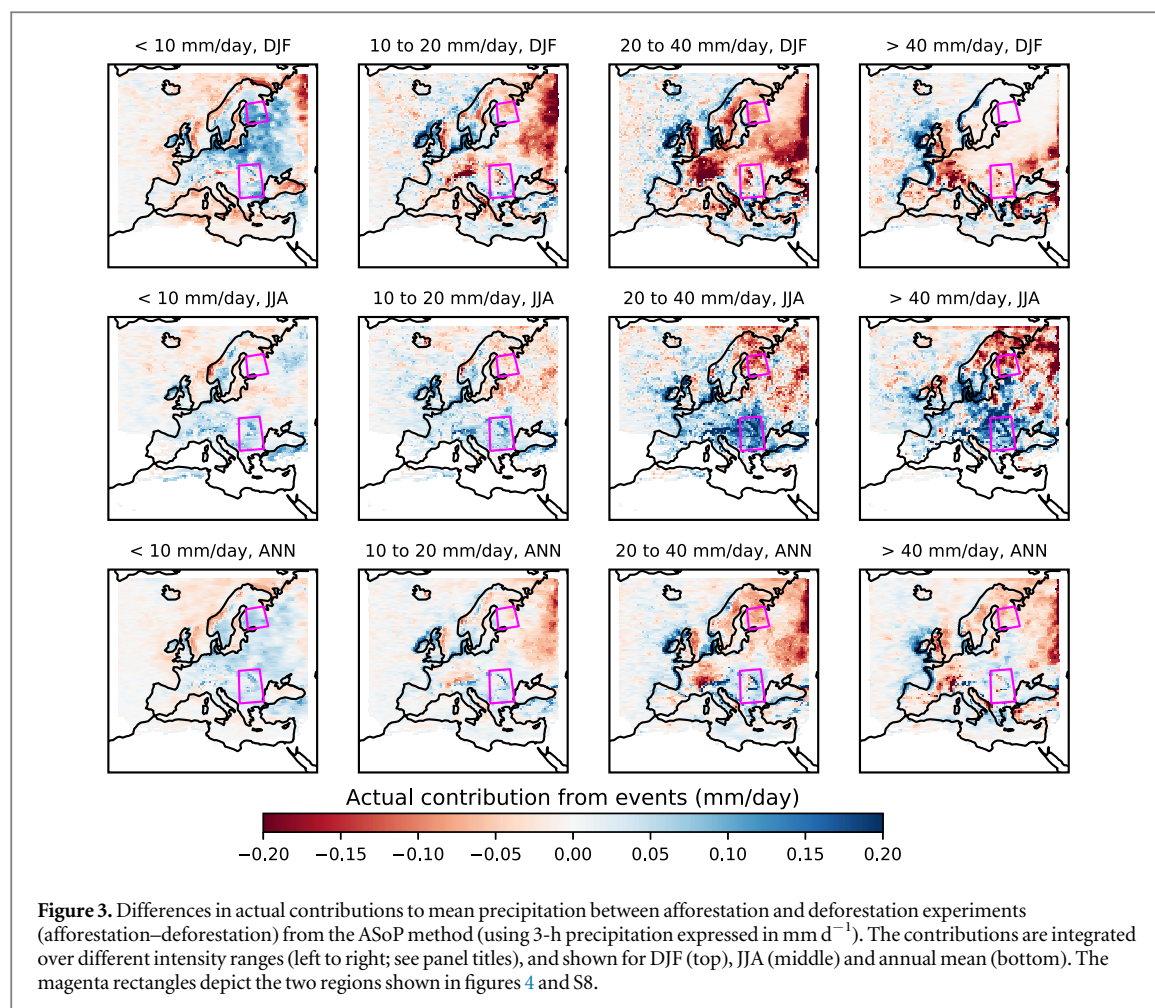
3.2. Forest cover effects on precipitation

3.2.1. Mean precipitation

Figure 2 shows that the large-scale spatial pattern of mean precipitation is related to the number of cyclones, with a clear maximum in the storm track region (figure 1), while the most conspicuous local and regional precipitation maxima are related to mountains. The forest effects are most clearly visible in the difference plots. Here it is instructive to compare the afforestation and z_0 experiments. Both afforestation and z_0 cause a decrease in the number of cyclones compared to deforestation, which has an effect on the mean precipitation. However, afforestation also has other effects that z_0 does not, which come from different albedo, soil moisture and evapotranspiration. A major part of Europe experiences decrease in precipitation with less cyclones in the z_0 experiment compared to deforestation (figure 2(d)). Areas in the southern and eastern Europe with weak increase in precipitation might be related to increased convergence and upward motion due to rougher surface, and are probably not related to changed cyclone activity since there are not many cyclones in that area. Precipitation decrease for afforestation (relative to deforestation, figure 2(c)) is considerably weaker and

occurs over smaller areas compared to the decrease in z_0 (figure 2(d)). The decrease for afforestation mostly occurs over parts of the northern Europe and the region north of the Alps. The decrease over the eastern part of the domain is too close to the lateral boundary and is not considered here. The northern Europe decrease is mostly caused by the decrease in the number and intensity of cyclones. The decrease north of the Alps could be caused by two effects: the reduction of cyclones and the local convergence effect described further below. The causes for the decrease over both of these regions are the same as for z_0 but are weaker, implying that other effects than the roughness are important. Likewise, large parts of the southern and eastern Europe experience increase in precipitation for afforestation, again as a result of other effects than roughness. Analysis of latent heat fluxes and soil moisture shows that these other effects are predominantly the increased evapotranspiration and deeper and longer access to water in the soil when trees are present, and thus occur in the warm part of the year (not shown).

An interesting local pattern emerges over the British Isles. With increased surface roughness, there is up to 20% more precipitation in a rather narrow band



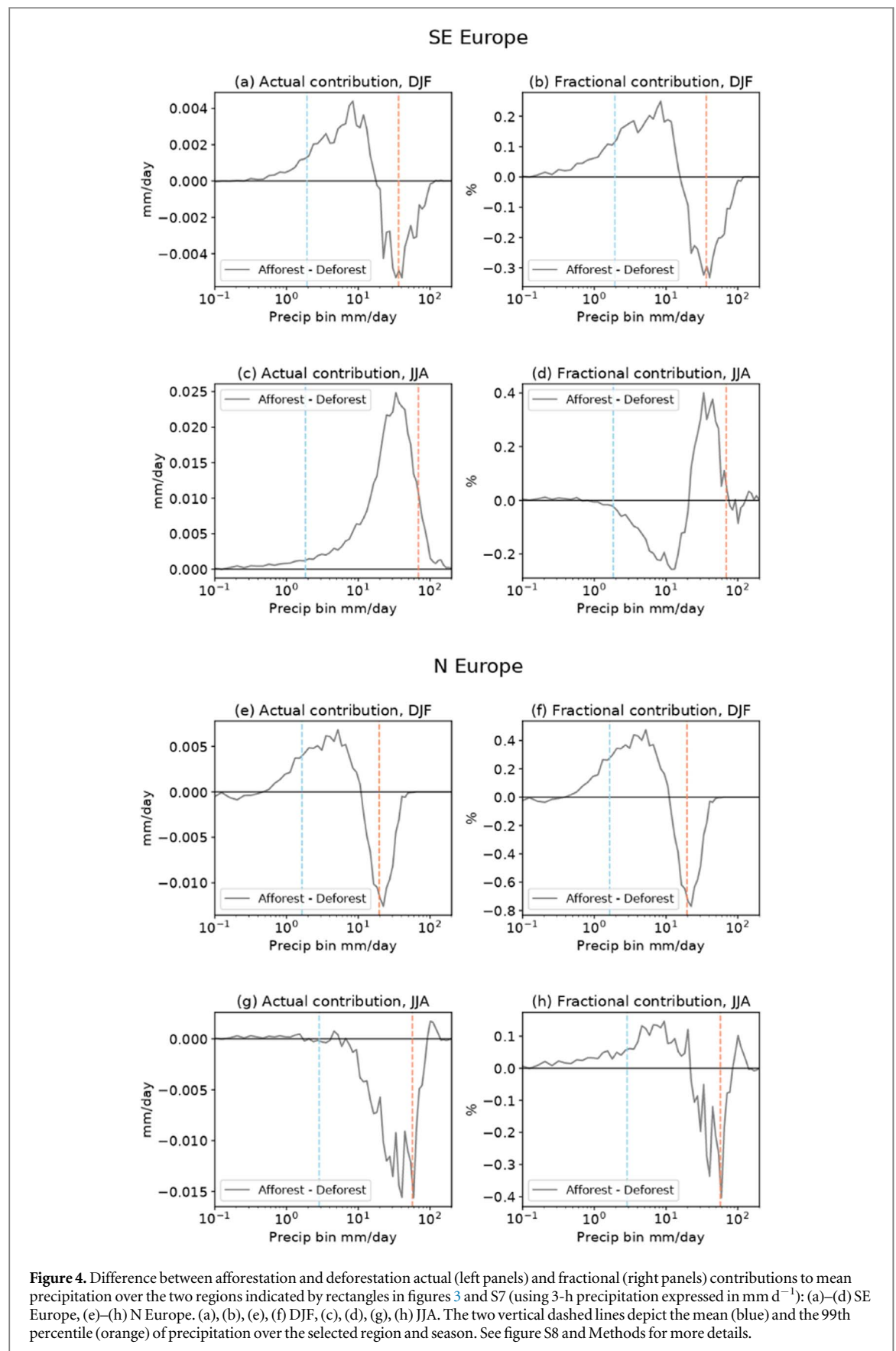
along the west coast, and likewise up to 20% less precipitation off the east coast. The west coast precipitation increase is caused by stronger upward motion resulting from stronger friction-induced horizontal convergence. Similarly, with the larger contrast between land and sea surface roughness at the east coast, the horizontal speed-up is larger resulting in horizontal divergence, subsidence, and consequently decrease of precipitation. Similar effect occurs over Denmark, the west coast of France and to a smaller extent Portugal and Spain. The effect is rather local and does not seem to affect cyclone development. As indicated above, the increased precipitation along the west coast of France could contribute to the weaker precipitation north of the Alps, assuming that the increased precipitation reduces the amount of water vapour in the air travelling westward.

3.2.2. Precipitation distribution

Here we focus on the afforestation and deforestation experiments. Figure 3 shows the differences between actual contributions to the mean precipitation for different intensity bins from the ASoP method. Precipitation changes between afforestation and deforestation in winter are dominated by mechanical effects of different roughness on cyclone intensity. There is less precipitation in the afforestation

experiment over most of the European continental area for intensities above 10 mm d^{-1} . This can be attributed to decreased frequency and intensity of cyclones with increased roughness, as evidenced by comparing with the z_0 experiment (not shown). It is not completely clear at the moment what causes the increase in precipitation for intensities below 10 mm d^{-1} for afforestation. A mechanical effect is ruled out because precipitation decreases in the z_0 experiment. Further study is needed to explain this effect but it is beyond the scope of this paper. The summer situation is quite different. There is more precipitation in the afforestation experiment in central and south Europe for all intensity ranges, which is consistent with the larger mean precipitation there (figure 2). There is relatively more precipitation at higher intensities for afforestation (figure S7), which is consistent with the convective nature of summer precipitation.

To study precipitation extremes, we use the 99th percentile as a reference. Two regions with different response of precipitation to forest cover change, one in SE and one in N Europe (indicated in figures 3 and S7), are used as examples. Both regions have a very similar response to afforestation in winter—while there is a rather small change in mean precipitation between afforestation and deforestation, the contribution of extreme precipitation to mean precipitation is



considerably reduced (figure 4). For N Europe, the actual contribution from the intensity bins around the 99th percentile is about 0.045 mm d^{-1} (figure S8(c)), while the decrease in actual contribution for

afforestation at those intensity bins is maximal and about 0.012 mm d^{-1} (figure 4(e)). Hence the maximum decrease of extreme precipitation is about 25% (10% for SE Europe; not shown). The decrease in

extreme precipitation is counterbalanced by the increase of a similar size in moderate and weak precipitation to keep the mean precipitation similar. Fractional distributions are very similar to the actual contributions, corroborating that the dominant change is in the shape of distribution and not mean precipitation.

The two regions show very different responses to afforestation in summer. In SE Europe, the precipitation increase occurs for all intensity bins (figures 4(c) and S8(a)), which is consistent with the increase in summer mean precipitation already implied from figure 3. The fractional contributions show that there is more stronger, but not extreme, precipitation in afforestation (figure 4(d)), which is consistent with the summer convection. There is a decrease of mean precipitation over N Europe in summer, with largest decrease occurring for strong to extreme precipitation (figures 4(g) and (h)).

4. Discussion and conclusion

The focus of this study is long-term effects of changing forest cover on extratropical cyclones over Europe and consequently on local climate. According to the authors knowledge, this is the first time that the effects of changed surface roughness on the climatology of cyclones are quantified. The regional climate model RCA4 and a cyclone-tracking algorithm are used to study the effects of four different forest covers: the current forest cover, potential afforestation, deforestation, and deforestation with afforestation roughness lengths. The extremes in forest cover are used to estimate the maximum impact of vegetation change on climate. It is found that the changes of forest cover considerably and consistently affect the number and intensity of cyclones over land. Afforestation reduces the number and intensity of cyclones everywhere over Europe compared to experiments with smaller forest cover. The reduction in number of cyclones increases towards the east, reaching up to 80% over some regions when compared to completely deforested Europe. The experiment with increased roughness length indicates that the dominant cause of the cyclone reduction is mechanical, which is consistent with previous idealized studies. Furthermore, previous studies obtained about 40% decrease in cyclone deepening in the presence of surface friction compared to the frictionless case (Anthes and Keyser 1979, Beare 2007, Boutle *et al* 2015), and about 30% decrease when z_0 was changed from the values over sea (10^{-4} – 10^{-3} m) to the typical land value of 0.1 m (Beare 2007). In this study, the overall decrease in the number of cyclones for afforestation compared to deforestation over all land points of the domain is 27%, and the cyclone filling is 35% faster. While the parameters and modelling setups between this and

previous studies are different, this consistency implies that the effect obtained here is realistic.

Extreme precipitation in winter is decreased up to 25% for afforestation compared to deforestation, while the balancing effect of increased weak and moderate precipitation keeps the mean precipitation similar. This is consistent with the overall reduction in cyclone number and intensity, knowing that cyclones and fronts cause majority of extreme precipitation over parts of Europe (Pfahl and Wernli 2012, Catto and Pfahl 2013). There is an increase in precipitation in the southern and eastern Europe for afforestation, caused by the increased evapotranspiration and deeper soil moisture access by trees. The effects of weaker cyclones are less pronounced there because of the on average smaller cyclone numbers. Since this precipitation increase occurs predominantly in summer, it is associated with convective precipitation and is consequently larger for higher precipitation intensities. Combining these two effects together, it is clear that the first-order effects of forests are positive for almost all regions of Europe: decrease of extreme and increase of weak and moderate precipitation in winter, and increase of summer precipitation in the southern and eastern Europe.

The changes of forest cover in this study were done over the entire European continent. However, it appears that the British Isles also affect the cyclone development, which is consistent with their meridional extent that is of the same order of magnitude as typical cyclones. It would be interesting to study in more controlled experiments the effects of horizontal length scale of changes of forest cover on cyclones. Since the main forest cover effect on cyclone intensity is due to the surface roughness, any other similar change in roughness over a sufficiently large area would have a similar effect on cyclones, albeit the effect on precipitation would not be the same. Furthermore, scales could affect another aspect of this study. The regional modelling setup uses specified lateral boundaries which do not allow for potential effects of the changing cyclone activity on larger scales. As suggested by one reviewer, it is imaginable that the reduced cyclonic activity and hence meridional transport of energy could increase the meridional temperature gradient and consequently the cyclonic activity, thus counteracting the mechanical effect from the increased roughness. Since these mechanisms act on different scales, the roughness change predominantly affecting local to regional scales, while the potential effect on meridional temperature gradient arguably occurring on larger regional to global scales, the plausibility of such feedback affecting specific local scales is rather limited. A corresponding study with a global climate model would be required to examine and quantify these effects.

In light of the recent work showing significant increase in cyclone-related extreme precipitation in a changing climate (Hawcroft *et al* 2018), the mitigating

role of trees is of interest. Based on the results presented here, forests selectively reduce extreme precipitation, predominantly in the storm track. Together with the changing nature of cyclones over Europe, where, unlike their weaker counterparts, intensely precipitating cyclones could triple by the end of the century (Hawcroft *et al* 2018), afforestation could provide an efficient way of reducing the intensity and frequency of extreme precipitation events. At the same time, the widely-documented decrease of (mostly summer) precipitation in the Mediterranean region in a warmer climate (e.g. Giorgi and Lionello 2008, Jacob *et al* 2014, Seager *et al* 2014, Donnelly *et al* 2017) could be mitigated by the increase in precipitation with afforestation.

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