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LETTER

Afforestation affects rain-on-snow climatology over Norway

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Abstract

Rain-on-snow (ROS) events are most commonly found in sub-polar and alpine climates where they pose a considerable threat to society and nature. While the relationship between ROS frequency and large-scale climate features have been identified, little is known about the role of localised factors, such as land cover, in ROS frequency. Importantly, the impact of future land cover changes, such as afforestation, on ROS frequency is also unknown. In this study, we use gridded observational products and kilometer-scale regional climate simulations to investigate the comparative roles of forests and open spaces in ROS frequency, and to identify the impact of afforestation on ROS frequency. The seNorge gridded observational products generally show that evergreen forests have a higher ROS frequency than open spaces despite the large discrepancies in land cover between different datasets. The observed behaviour was well simulated by a regional climate model, albeit with a more pronounced difference between ROS frequency in forests and open spaces. Model-based results show that future changes in ROS frequency are larger in evergreen forests than in open spaces, and afforestation will increase the frequency of ROS events. Our results demonstrate the relationship between land cover and ROS frequency, and highlight the need to include unique features of the local climate system, such as ROS events, in studies on climate and land use land cover change. Importantly, our study shows that afforestation policies in sub-polar and alpine regions should carefully consider the impacts of such policies on ROS frequency and the downstream consequences for society and nature.

1. Introduction

Rain-on-snow (ROS) events can occur anywhere with a significant snowpack, especially in sub-polar and alpine climates. These hydrometeorological events are of considerable societal importance as they can cause destructive flooding (McCabe *et al* 2007, Musselman *et al* 2018), increase avalanche risk (Hansen *et al* 2014), damage ecosystem services, and lead to the loss of wildlife (Putkonen and Roe 2003).

ROS events occur in many parts of the world, such as Alaska (Bieniek *et al* 2018, Crawford *et al* 2020), Conterminous United States (Musselman *et al* 2018, Yan *et al* 2018, Li *et al* 2019), the Canadian Arctic (Grenfell and Putkonen 2008), Greenland (Abermann *et al* 2019), Norway (Pall *et al* 2019) and Siberia (Bartsch *et al* 2010). Global studies such as that of Cohen *et al* (2015) have shown that some of these regions are ROS 'hotspots' i.e. regions where ROS events are most commonly found. Norway is one of these ROS 'hotspots', and a region already undergoing afforestation for the purpose of climate mitigation.

A recent study by Pall *et al* (2019) has shown that ROS frequency in Norway is declining at low elevations and increasing at higher elevations. Mooney and Li (2021) followed up this study to show that this change will continue until at least the middle of the century. Previous studies have shown that ROS frequency can be impacted by several factors such as low frequency atmospheric variability (e.g. Arctic Oscillation, North Atlantic Oscillation), proximity to the ocean and/or elevation (Cohen *et al* 2015, Pall *et al* 2019). However, little is known about the role of land cover in modulating ROS frequency. The potential of land cover as a factor in ROS frequency arises from previous observation-based studies which have shown that vegetation-snow interactions can extend or reduce the snowpack duration in evergreen forests compared to open spaces in many parts of the world (Gelfan *et al* 2004, Musselman *et al* 2008, Varhola *et al* 2010, Lundquist *et al* 2013, Roth and Nolin 2017).

Vegetation-snow interactions are highly complex and numerous observation- and model-based studies have examined the impact of vegetation on snow accumulation and snow melt. Factors that impact the vegetation-snow interactions include forest density, forest structure, tree species, elevation, air temperature, slope, aspect and wind exposure (Lundquist *et al* 2013, Harpold *et al* 2015, Dickerson-Lange *et al* 2017, Sun *et al* 2022). A common approach to observing vegetation-snow interactions is to use paired-site observations where an observational site is based in a forest and a similar site is based close by in an open space. These paired-site based studies have shown that under certain conditions, the onset of snow melt can be delayed in evergreen forests compared to open spaces. One consequence of this is that the snowpack duration would last longer in evergreen forests than in open spaces.

These results arise from the different physical processes that are more or less active in evergreen forests than in open spaces. Unlike open spaces, evergreen forests have canopies that can shade the underlying snowpack from incoming solar radiation and block winds, thus limiting loss through turbulence. This can delay snowmelt in forests compared to open spaces. However, the forest canopy can enhance snowmelt through longwave radiation processes as shown by Lundquist *et al* (2013). Conversely, the forest canopy can reduce the amount of snow accumulated and thus reduce the duration of snowpack under the canopy (Sun *et al* 2022). Although, this highly complex interplay between forests, snow and climate makes it difficult to determine whether forests will prolong or shorten snowpack duration in any region, it is clear from the literature that forests do impact the snowpack duration.

While these observational studies have demonstrated the impact of evergreen forests on the duration of the snowpack, much remains unknown about their role in ROS frequency. Additionally, little is known about the impacts of afforestation on ROS frequency. With the growing popularity of afforestation as a climate mitigation action, particularly in countries such as Norway, it is becoming increasingly important to understand and anticipate the climatic impacts of these policies (Mooney *et al* 2021).

In this study, we first use gridded observational products to identify the comparative roles of evergreen forests and open spaces in modulating ROS frequency. This is followed with kilometre-scale regional climate simulations to (a) identify the role of evergreen forests in the response of ROS frequency to 1.5 °C global warming and (b) determine the impact of a quasi-idealised afforestation scenario on ROS frequency under 1.5 °C of global warming. This afforestation scenario is based on Norway's proposed mitigation strategies.

2. Methodology

2.1. Kilometre-scale regional climate simulations

This study uses kilometre-scale regional climate simulations from the Weather Research and Forecasting (WRF; Powers *et al* 2017) model that have been analysed in earlier studies (Mooney *et al* 2020, 2021, Poujol *et al* 2020, 2021). The model setup is described comprehensively in (Mooney *et al* 2020) and only essential details are described here. The model setup uses one-way nesting to downscale ERA-Interim reanalysis over the period 1996–2005. The domain setup consists of two domains. The inner domain which is used in this study is shown in figure 1(a); it has a grid spacing of 3 km. An outer WRF domain with a grid spacing of 15 km covers the EURO-CORDEX domain. The following physical parameterizations in the WRF model were used based on previous assessments of WRF for regional climates over Europe (Mooney *et al* 2013): the Thompson microphysics (Thompson *et al* 2008), RRTMG longwave and shortwave radiation schemes (Iacono *et al* 2008), Yonsei University planetary boundary layer scheme (Hong *et al* 2006), the revised Monin–Obukhov surface layer scheme (Jiménez *et al* 2012), and the Noah multi-physics (Niu *et al* 2011) (Noah-MP) land surface model. The cumulus parameterisation scheme is turned off in the inner domain. The simulations use a 10 year soil spinup period.

Atmospheric and snow variables from these simulations have been comprehensively evaluated in Mooney *et al* (2020), and they have been used in numerous published works such as Poujol *et al* (2020), Mooney *et al* (2021), Mooney and Li (2021), Poujol *et al* (2021). Importantly the study of Mooney *et al* (2020) compared the WRF simulated snow cover fraction (SNC) and snow depth to the GlobSnow satellite product and ground-based observations from the Norwegian Meteorological Service. This study shows that the model represents snow cover reasonably well. Snow depth was well simulated in the east and north but there was a discrepancy between modelled and observed snow depth from stations in Western Norway. These deficiencies are likely due to (a) the WRF model's overestimation of precipitation in this region and (b) deficiencies in the seNorge data arising from the sparse observational network in the remote, mountainous areas of Western Norway (Mooney *et al* 2020). Previous studies such as Chen *et al* (2014) compared snow water equivalent (SWE) from NoahMP with *in-situ* observations,

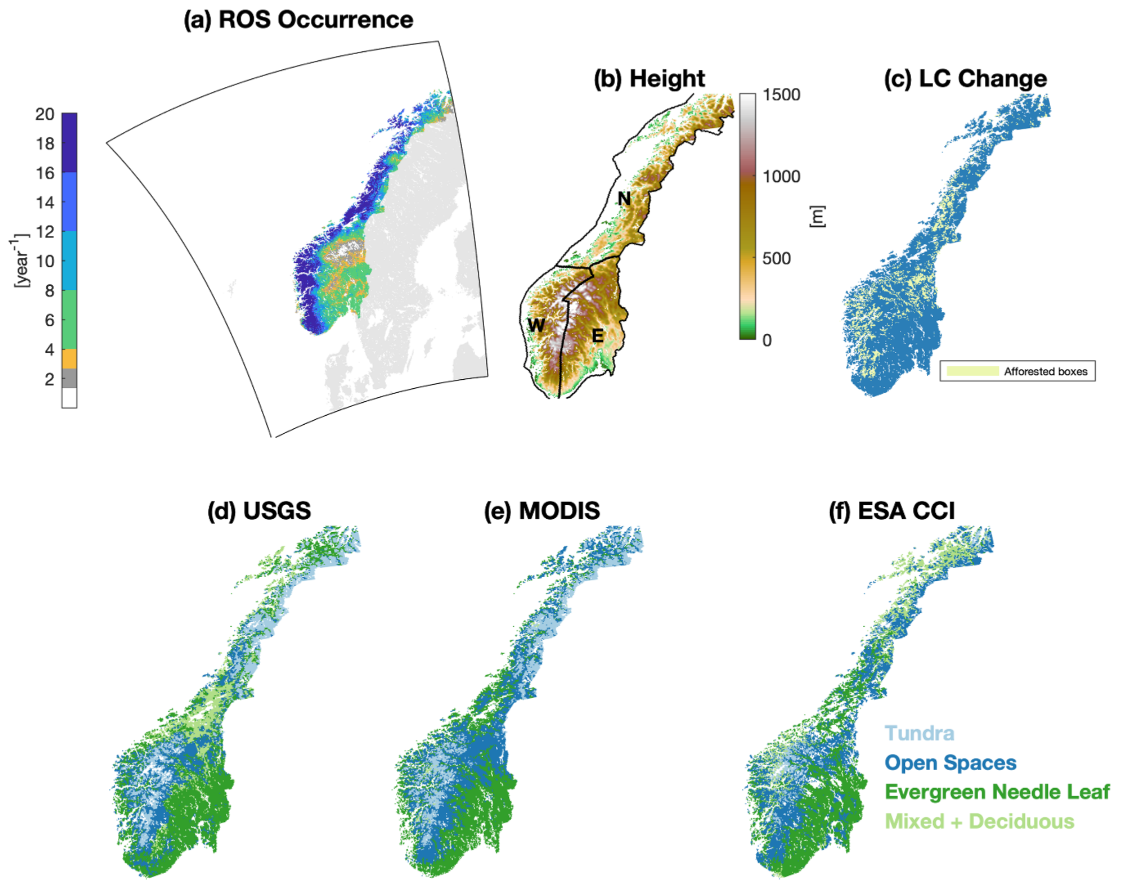

Figure 1. (a) The annual frequency of rain-on-snow (ROS) events derived from the seNorge gridded observational data, (b) terrain elevation and the three regions used in the analyses: West (W), East (E), and North (N), and (c) model grid boxes converted from grasslands/shrublands to evergreen needleleaf forests in the afforestation scenario. (d)–(f) Land cover over Norway obtained from three different data sets.

and showed that the NoahMP model performs well in forested regions.

The NoahMP land surface model (LSM) provides the WRF model with information about the current state of the land surface e.g. surface temperature and moisture, while the WRF model provides NoahMP with information about the state of the lower atmosphere e.g. radiative energy fluxes, temperature, and precipitation. This means that changes in the land cover are recognized by WRF and studies such as Mooney *et al* (2021) have shown that this impacts the surface air temperatures. However, the vegetation in the NoahMP model does not respond dynamically to the climate conditions. Instead, vegetation characteristics such as leaf area index vary monthly regardless of climate conditions.

In our simulations, snow canopy interactions are represented by the NoahMP LSM. NoahMP uses a separate layer for the vegetation canopy which allows both liquid water and ice to be intercepted by the canopy. Under the canopy, snow-vegetation-air turbulent fluxes are represented by stability functions based on the Monin–Obukhov Similarity Theory to determine the aerodynamic resistance with respect to the displacement and roughness lengths of the canopy. The canopy radiation transfer uses the two-stream radiation transfer approximation (Dickinson 1983, Sellers 1985). This scheme includes scattering and multiple reflections by the canopy and ground as well as the radiative effects of the canopy intercepted snow. NoahMP determines the albedo from the ratio of total reflected shortwave radiation to total downward shortwave radiation. In NoahMP the snowpack consists of a multi-layer physically based snow model (Yang and Niu 2003, Niu *et al* 2011). The model has up to 3 snow layers that vary depending on the total snow depth.

2.2. Pseudo-global warming approach

A PGW method was implemented to conduct a future climate warming simulation. For the PGW simulations, the boundary conditions from the historical period were perturbed by adding a mean monthly climate change between a reference 30 year period of 1976–2005 and a future period of 2036–2065. This perturbation uses the ensemble mean from 36 realisations across 19 different models from the Coupled Model Intercomparison Project (CMIP5). The future climate corresponds to approximately 1.5 °C warming globally from the climate sensitivity of the Representative Concentration Pathway 8.5

centred on the year 2050. A comprehensive description of the underlying assumptions for the PGW model configuration used here are provided in Mooney *et al* (2020) including a table of the CMIP5 simulations. The PGW perturbation consists primarily of changes to temperature and humidity in all seasons. For example, the 700 hPa temperatures increase by 1.5 °C–3.5 °C and humidity changes by −4% to 2% (Mooney *et al* 2020). The large-scale circulation remains largely unchanged compared to the reference period (Mooney *et al* 2020).

2.3. Experiment design

Three simulations were performed to elucidate the possible impacts of Norway's afforestation policy for climate mitigation. The three simulations consist of (a) present day climate and land cover, (b) future climate with present day land cover, and (c) future climate with afforestation. The United States Geological Survey land cover data was used as the present-day land cover. For the afforestation simulation, land cover currently identified as grasslands and shrublands below 1100 m were replaced with evergreen needleleaf forest (figure 1(c)). Grasslands and shrublands above the treeline (approximated to 1100 m based on Odland 2015) were left unchanged in order to create a realistic vegetation change. The land cover data set used in this study is the USGS data distributed with the WRF model.

2.4. Definitions for rain-on-snow, start of snowmelt season and snow day

This study follows the definition of ROS events described in Pall *et al* (2019) specifically for Norway. A ROS event is identified when each of the following criteria have been met: (a) rain > 5 mm d^{-1}, (b) SWE > 3 mm d^{-1}, and (c) SNC $> 25\%$. Analysis of results that use more conservative criteria agree qualitatively with those presented here but disagree quantitatively as the number of events are reduced when harsher criteria are applied (see supplementary figures S1–S3 available online at stacks.iop.org/ERL/17/054011/mmedia). ROS-related runoff is defined as the sum of snowmelt and rainfall. Start of the snowmelt season is determined when the five day mean of SWE reaches 80% of the five day season maximum in snow water equivalent. Snow days are defined as days when snow depth exceeds 10 cm.

2.5. Gridded observational datasets

Daily observational precipitation and temperature products on a 1 × 1 km grid covering Norway were used in this study are the seNorge2018 datasets (Lussana *et al* 2019). The precipitation data and the temperature data was obtained from https://zenodo.org/record/2082320#.YKvg2pMzarc and https://zenodo.org/record/2023997#.YKvg5ZMzarc, respectively. These products were produced by MET Norway, the national meteorological service, using statistical interpolation, analyses and *in situ* observations. Like most gridded observational products, the quality depends on the density of the underlying observations. Analysis by Lussana *et al* (2019) shows that the products agree well with observations but there are biases in mountainous areas in the west where the station density is sparse.

The gridded products for SNC and SWE were produced by the Norwegian Water and Energy Directorate by driving their snow model with the seNorge2018 products for temperature and precipitation, and assimilating snow observations. Details of the snow model and related procedures for creating these snow products can be found in Saloranta (2016), which also show that this product reproduces *in-situ* and satellite data very well. Like all gridded observational products, these seNorge products are best estimates of the observed system.

Three different land cover datasets are used for Norway. One of these datasets was obtained from the European Space Agency's Climate Change Initiative—Land Cover. The data was downloaded from http://maps.elie.ucl.acbe/CCI/viewer/download.php. The remaining two datasets are the USGS and MODIS land cover datasets that are distributed with WRF. The three land cover datasets, USGS, MODIS, and ESA's CCI Land Cover data, have an original resolution of 30 s, 30 s, and 300 m, respectively. They are remapped to a grid spacing of 3 km using the WRF model's pre-processing system which applied nearest neighbour interpolation. The remapped data for these land cover products are plotted in figures 1(d)–(f).

3. Results

3.1. Role of land cover in historical ROS climatology

As the gridded observational products show, ROS occurrence strongly depends on climatic conditions and elevation (figure 1(a)). This is clearly evident in Norway, which has diverse climatic regions. In this study, Norway is divided into three climate regions, namely East, West, and North (figure 1(b)). These regions were chosen based on the findings of Pall *et al* (2019) and used previously in Mooney and Li (2021). While the East exhibits alpine and inland continental climates, the West has a temperate maritime climate with autumn and winter precipitation dominated by cyclonic systems moving in off the Atlantic Ocean. The North is also modulated by the northeast extension of the Gulf Stream but inland areas exhibit an Arctic climate. The dominant influence of both regional climate and elevation on ROS frequency is especially evident in western Norway, which is one of the wettest regions in Europe (Stohl *et al* 2008), and is where lower elevations have considerably fewer snow days.

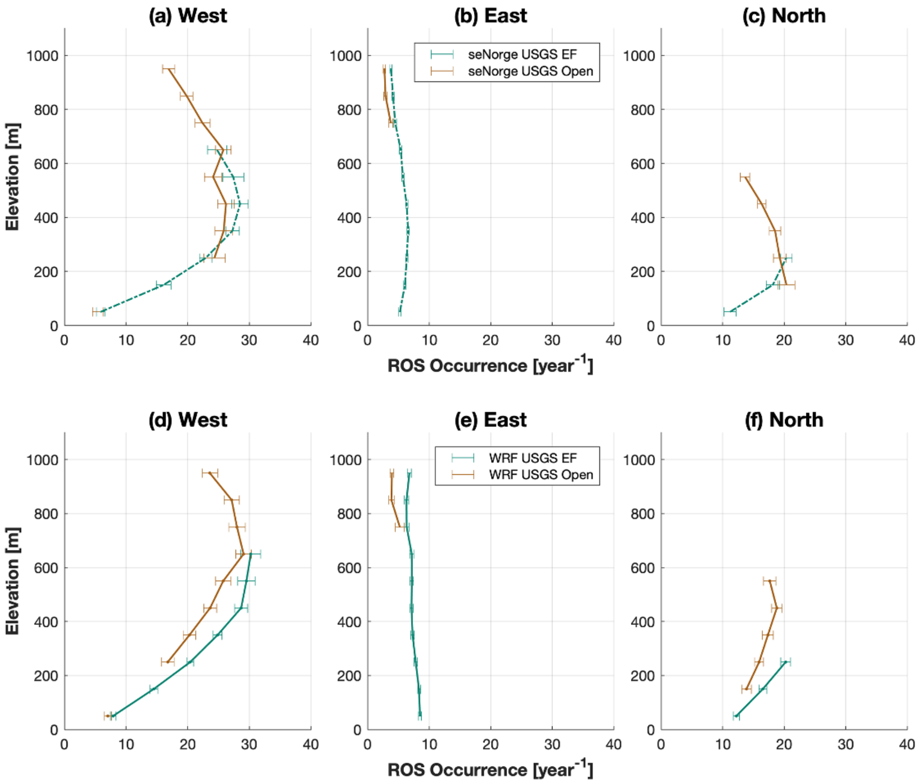

Figure 2. (a)–(c) Frequency of ROS events under current climate in evergreen forests (green lines) and open spaces (brown lines) as a function of elevation for each of the regions shown in figure 1(b) derived from seNorge gridded observational products. The separation into evergreen needleleaf forest (EF) and open spaces (Open) are taken from the USGS land cover dataset. (d)–(f) Same as (a)–(c) but derived from the regional climate simulations. Land covered by forests (green lines) show higher occurrence of ROS than open spaces (brown lines) in the historical climate. Error bars represent the 95% confidence interval.

Figure 2 shows the ROS frequency by elevation band and climate region for grid boxes with evergreen needleleaf and open spaces. Gridded boxes were identified as evergreen needleleaf and open spaces using three different land cover datasets. There are large discrepancies between these three different land cover datasets (see figures 1(d)–(f)) which leads to differences in the magnitude of the effect of land cover on ROS frequency. This is further compounded by the lack of information regarding forest density, and fraction of grid box covered by forest and/or open space in these observational datasets. Nonetheless, the analysis reveals a lesser but important role of vegetation in ROS frequency, particularly in the West and the North (figures 2(a) and (c)). Here evergreen needleleaf forests generally exhibit more ROS events per year than open spaces such as croplands, grasslands, and shrublands. This result is clearer in the regional climate model (figures 2(d)–(f)). Given the high level of disagreement amongst the different land cover datasets (figures 1(d)–(f)), the model results are used in figure 3 to understand the results shown in figure 2.

The primary reason for evergreen needleleaf forests to have more ROS events than open spaces is that evergreen needleleaf forests have more days with snow on the ground (snow days) than open spaces (figure 3(a)) as indicated by the linear regression model; the intercept and slopes are statistically significant for each line (p values are less than 0.001) and the Standard Errors on the model coefficients are low (see table S1 in the supplementary material). Table 1 shows the median value for open spaces and evergreen needleleaf forests in bands based on elevation: 0–200, 200–400, 400–600, 600–800 m). The medians of the evergreen needleleaf forests are consistently greater than open spaces in the West and East. A two-sided Wilcoxon rank sum test on the data showed that the distributions of open spaces and evergreen needleleaf forests differed significantly ($p < 0.05$) in the West and East. Analysis of the onset of snowmelt (figure 3(b)) shows that the additional snow days in forests occur during the snowmelt season. The prolonged duration of snowpack increases ROS frequency as the snowpack extends later in spring when precipitation has transitioned from snow to rain.

3.2. Influence of land cover in the response of ROS frequency to 1.5 °C global warming

Mooney and Li (2021) have already shown that in the near future (mid-21st century under 1.5 °C global warming), ROS frequency will decrease at low, coastal elevations while increasing at higher altitudes. This is also evident from figure 4 which shows the different responses of ROS frequency in evergreen forests and open spaces (croplands, grasslands and shrublands)

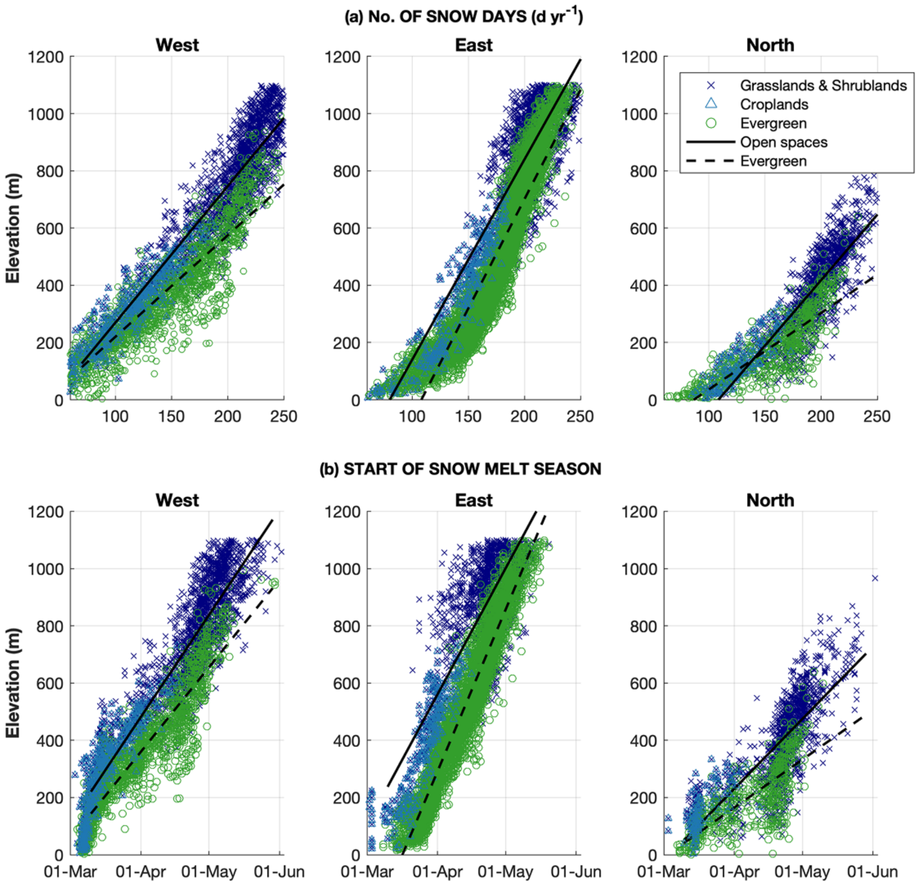

Figure 3. (a) The average number of snow days per year and (b) day of the year that snowmelt begins as a function of elevation in evergreen forests (green), grasslands and shrublands (dark blue) and croplands (light blue) for the regions West (W), East (E) and North (N) shown in figure 1(b). Snowmelt occurs later in evergreen needleleaf forests leaving them more vulnerable to ROS events towards the end of the snowpack duration. Lines are the best fit for each land cover type.

Table 1. The number of days with snow on the ground for different elevation bands in the three regions shown in Figure 1.

	West		East		North	
Elevation	Open	Evergreen	Open	Evergreen	Open	Evergreen
0–200 m	58	67	113	123	143	135
200–400 m	115	127	141	155	185	187
400–600 m	159	176	162	182	209	209
600–800 m	202	210	195	197	234	233

to 1.5 °C global warming as a function of elevation for each region shown in figure 1(b). Figure 4 shows that future changes in ROS occurrence are larger in evergreen forests than in open spaces. At low elevations there is a greater decrease in evergreen forests than open spaces as these forests have more ROS occurrences in the current climate than open spaces. Consequently, in the future when there is little snowfall at low elevations, ROS frequency decreases in evergreen forests more than in the open spaces.

3.3. Impact of afforestation on ROS frequency in a 1.5 °C warmer world

When afforestation under a warming climate is considered (i.e. open spaces below 1100 m are converted to forest—see methods for details), ROS frequency increases considerably (compare figure 5(a) to figure 5(b)). This shift is apparent over all regions of Norway and a strong elevational influence is evident. At lower elevations (under 400 m in east, west and 200 m in the north) ROS frequency decreases; though the new forests act to counter this. It is important to note that there are very few afforested grid points at lower elevations in the East (under 600 m) and West (under 400 m) and at higher elevations in the North (over 800 m). Across the remaining elevational bands, ROS frequency increases with the strongest response seen in the West (see figure S1). In this region the average ROS response to afforestation even undergoes a sign change in the 400–600 m band, switching from a decrease, when open spaces are maintained, to an increase. These shifts are considerable. Elevational bands that undergo substantial afforestation (i.e. those with 50 or more grid points

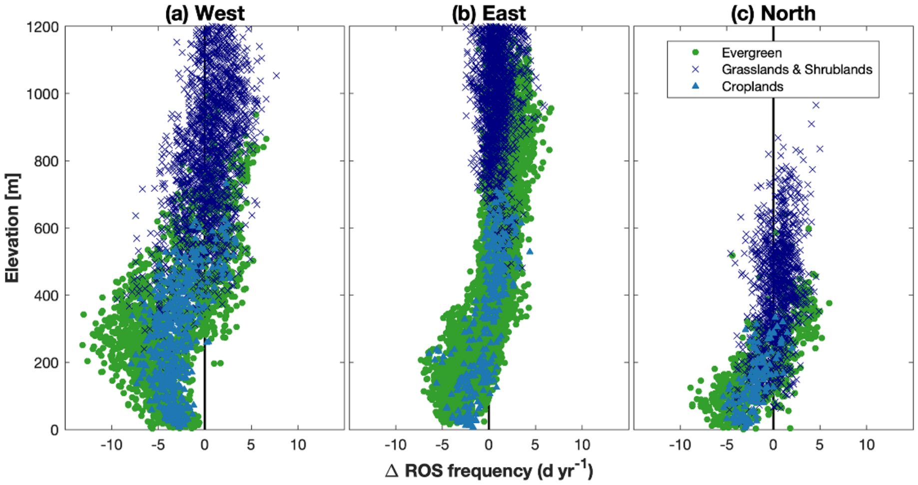

Figure 4. Changes in ROS occurrence under future climate change for the three different regions in Norway shown on the map in figure 1(b). Colours represent the three different land cover types: evergreen forests (green markers), grasslands and shrublands (dark blue), and croplands (light blue). Grasslands, shrublands, and croplands are considered open spaces during this time of year.

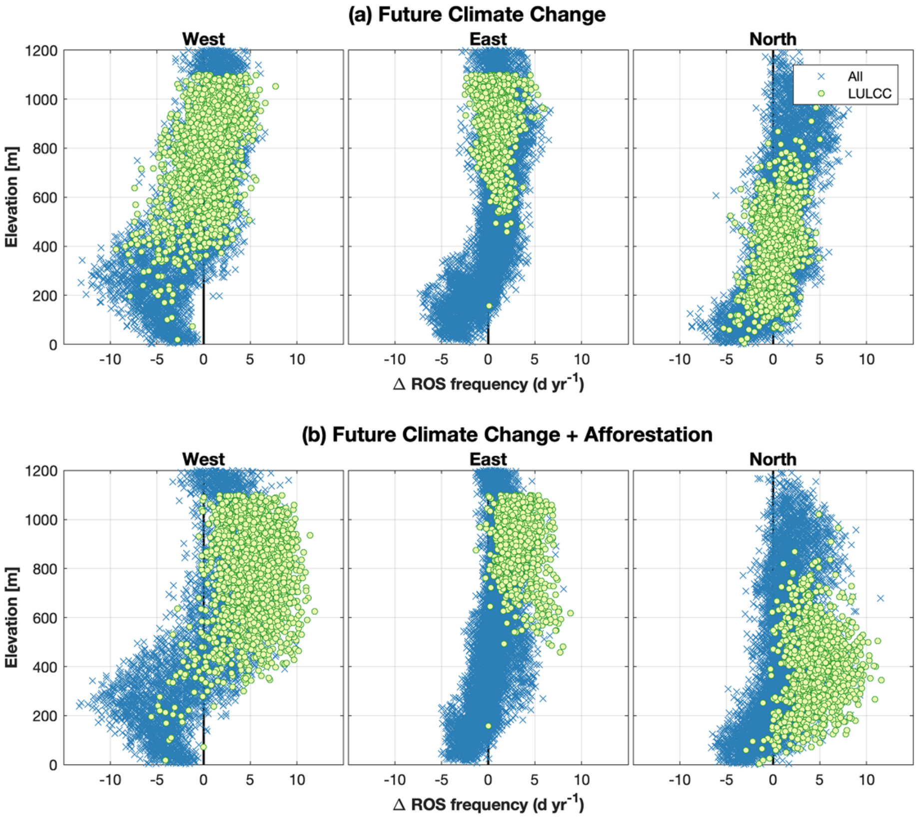

Figure 5. (a) Changes in ROS occurrence under future climate change for the three different regions in Norway shown on the map in figure 1(b). (b) Changes in ROS occurrence under future climate change and afforestation. Yellow circles are the grassland and/or shrubland grid boxes that undergo afforestation in the quasi-idealised simulations.

converted to forests) experience average increases in ROS events of ~2.8 (West), ~0.5 (East) and ~1.2 (North) days per year. This has implications for socio-economic and ecosystem exposure to hazards arising from ROS events. For example, in the West of Norway, this shift could result in additional risk exposure of up to 10 d per year at elevations between 400 and 1000 m.

3.4. Impact of afforestation on ROS-related runoff in a 1.5 °C warmer world

Although there are more than 100 basins in Norway, here the focus is on just 12 basins. Other basins were excluded because they were either too small for the model grid spacings used in this study, contained too few ROS events, or had little or no afforested grid boxes (<10% of the basin afforested).

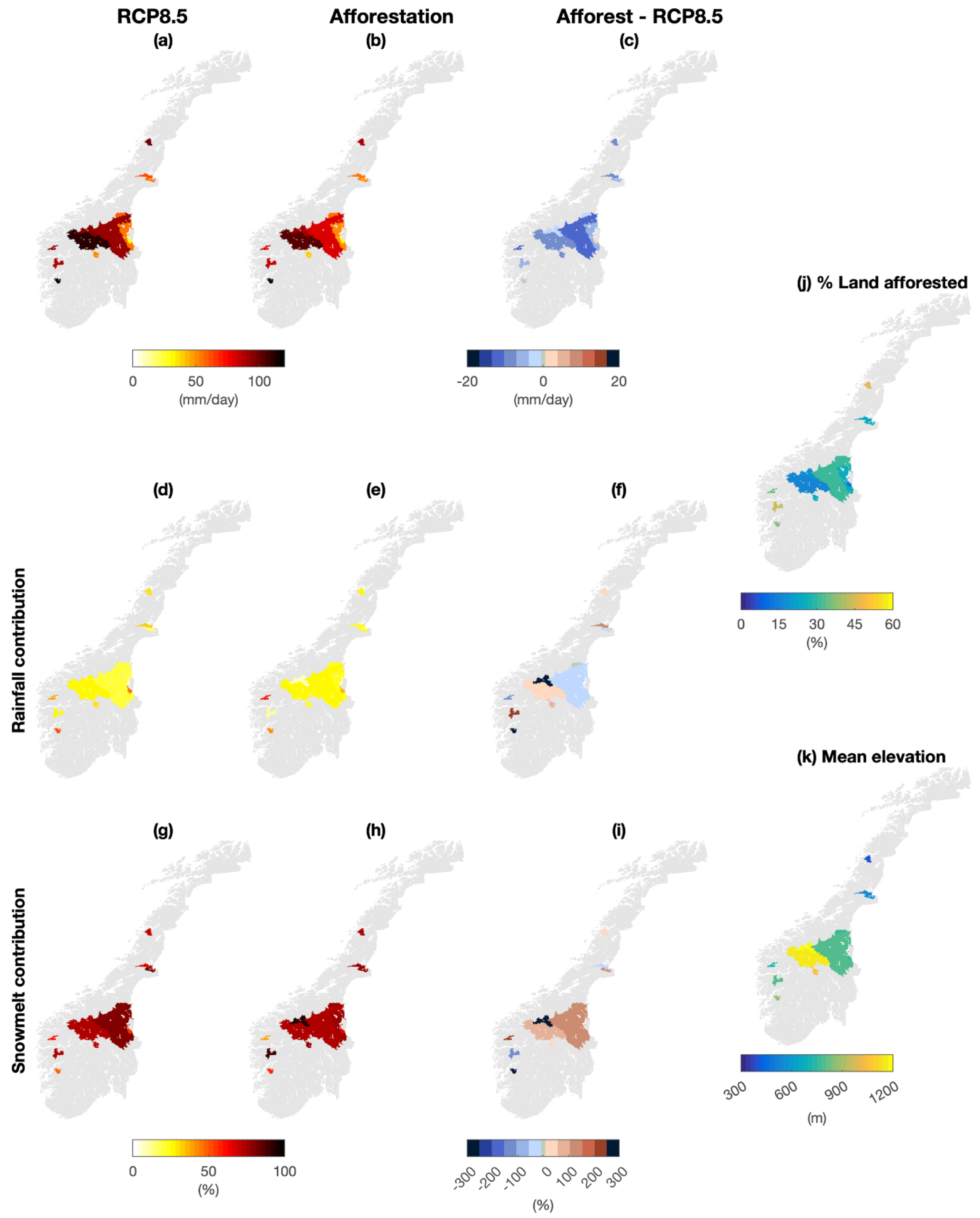

Figure 6. (a) Mean ROS-related runoff (snowmelt + rainfall) for the ten largest ROS-related runoff events in a 1.5 °C warmer world. (b) ROS-related runoff (snowmelt + rainfall) of the 10 largest ROS-related runoff events in a 1.5 °C warmer world with afforestation. (c) Response of ROS-related runoff for the ten largest ROS-related runoff ROS events to afforestation i.e. (b) minus (a). (d) Percentage contribution of rainfall to ROS-related runoff for ten largest ROS-related runoff events shown in (a). (e) Same as (d) but for the ten events shown in (b). (f) Contribution of rainfall to the ROS-related runoff response to afforestation (i.e. (d), (e)/(c)). Positive values indicate that this contributes to the response shown in (c) while negative indicates that it offsets some of the contribution from snowmelt. (g)–(i) Same as (d)–(f) but for snowmelt. (j) Percentage area of the basin afforested. (k) Mean elevation of each basin.

Analysis of the top ten daily ROS events in these 12 basins showed that ROS-related runoff will generally decrease in response to afforestation (figure 6). Most basins show a reduction in ROS-related runoff by 5%–15% regardless of how much of the basin is afforested (figure 6(d)). In both the afforested and non-afforested future climate, ROS-related runoff is dominated by snowmelt with considerable contributions from rainfall. In most basins, the reduction in the ROS-related runoff in response to afforestation can be attributed to the reduction in snowmelt, although some of the very small basins show that reduced rainfall dominates the response of ROS-related runoff to afforestation.

4. Discussion

Previous results have demonstrated a relationship between large scale climate features such as the NAO and the AO (e.g. Cohen *et al* 2015, Pall *et al* 2019), but none have identified the relationship with land cover. Here we present for the first time, evidence that land cover influences the frequency of ROS over Norway where evergreen forests have a higher frequency of ROS compared to open spaces. This builds on previous work (Hedstrom and Pomeroy 1998, Gelfan *et al* 2004, Lundquist *et al* 2013) that shows snow melt rates are different in forests and open spaces. Although this study focuses on Norway, ROS events occur in many other parts of the world (Cohen *et al* 2015). As such, it can be expected that land cover will also influence ROS frequency in these places. However, further studies are required to determine the exact nature of that influence. It is possible that the influence may be stronger or weaker, or can even have an opposite effect i.e. evergreen forests may decrease ROS frequency (Lundquist *et al* 2013).

Our study shows that afforestation will increase the frequency of ROS events in Norway and decrease ROS-related runoff. Previous studies on afforestation in Norway (Davin *et al* 2020, Mooney *et al* 2021, 2022) have explored the impacts on surface temperature, surface energy fluxes, and snow days. This study confirms the findings of previous studies that afforestation increases the number of snow days and extends those studies by analysing the impact of afforestation on ROS, which is largely driven by the increased snow days arising from afforestation. The role of precipitation is negligible in this case as previous work by Mooney *et al* (2021) showed that afforestation did not significantly impact precipitation. Results from observational and model-based studies (e.g. Gelfan *et al* 2004, Musselman *et al* 2008, Lundquist *et al* 2013) in other regions on the forest-snow relationship suggest that afforestation may impact ROS frequency in other parts of the world.

5. Conclusions

Here, we investigate the influence of afforestation on ROS events in Norway under a future warming scenario. In the current climate, we use gridded observational products and models to show that evergreen needleleaf forests have a higher frequency of ROS than open spaces (i.e. shrublands, grasslands and croplands). Analysis of future simulations show that future changes in ROS frequency are larger in evergreen needleleaf forests than open spaces. This has important implications for afforestation and further analysis shows that afforestation leads to increases in ROS frequency and decreases ROS-related runoff.

While the existing land cover datasets are sufficient for establishing a relationship between land cover and ROS frequency, the lack of consistency between observed land cover datasets makes it difficult to identify the magnitude of the differences between ROS frequency in forested and open spaces. This is further compounded by the lack of information on forest density, which is an important, influential factor on snowmelt rates in forests.

The use of km-scale modelling in this study is highly advantageous over models of coarser grid spacings as it improves the representation of various processes and effects, including precipitation processes. Indeed, the study of Mooney *et al* (2020) has shown that the simulations used here have good skill in simulating the observed precipitation and snow variables. As computational power increases and resources become more affordable, future studies should deploy multi-model km-scale ensembles for a more robust analysis of the response of ROS frequency to afforestation.

Future work on ROS in Norway should also develop observational campaigns and studies on the comparative roles of forests and open spaces in snow accumulation and ablation. This would provide valuable new insights and further evidence on the relationship between forests and snow in this region.

From a scientific perspective, future studies should analyse the influence of different land cover types, including different types of forests (different species, managed vs. natural) on ROS events. While the results presented here may be applicable in other sub-polar and alpine regions, additional studies and analysis are required to identify the response of ROS to evergreen forests in those regions.

Previous studies investigating the impact of land use land cover changes (LULCC) on climate have tended to focus on climatological and meteorological events more commonly found in warmer climates e.g. droughts and heatwaves. Even though studies have analysed the impact of LULCC in sub-polar and alpine climates, none have examined the influence of LULCC on ROS events which are uniquely found in these climates. A key recommendation from this study is that future LULCC and climate studies should develop a more tailored approach for the climatic region under investigation.

Finally, from a societal perspective, this study highlights the potential influence of afforestation on ROS frequency and intensity. ROS events can have a multitude of impacts for nature and society e.g. prevention of foraging by wildlife leading to a loss of wildlife through starvation (Putkonen and Roe 2003), increase avalanche risk (Hansen *et al* 2014), and flood risk. Our study shows that afforestation could reduce the intensity of the top ten ROS events and hence reduce the amount of water available for runoff during a ROS event. However, the reductions are small, and more studies are needed before clear conclusions can be drawn on the impacts for society. It is recommended that any future policy on afforestation in sub-polar and alpine climates perform additional studies to carefully consider the impacts of afforestation on the climatology of these societally relevant hydrometeorological events.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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