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Near future changes to rain-on-snow events in Norway

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Abstract

Rain-on-snow (ROS) events occur primarily in cold climates such as high latitudes and high elevations where they pose a considerable threat to nature and society. The frequency and intensity of ROS events are expected to change in the future, but little is known about how they will change in the near future (mid-century) and their link to hydrological extremes (e.g. 95% high flows). Here we use kilometre-scale regional climate simulations over Norway, a ROS 'hot spot', to determine potential changes in ROS frequency and intensity in the middle of the century under RCP8.5. Analysis shows that ROS will intensify in the future and ROS frequency will increase at high elevations and occur less frequently at lower elevations. Furthermore, high-flows that coincide with ROS events are expected to increase in winter and autumn. In general, this study shows that ROS changes in winter and autumn are related to changes in rain while ROS changes in spring and summer are related to changes in the snowpack. Since rainfall in Norway is dominated by large scale processes in autumn and winter (e.g. North Atlantic storm tracks), it is likely that future changes in ROS climatology in autumn and winter are related to changes in the large scale atmospheric system. This contrasts with spring and summer when local-scale processes drive snowmelt and hence future changes to ROS in those seasons.

1. Introduction

Rain falling on snow or frozen surfaces (hereafter called rain-on-snow or ROS) poses a considerable danger to nature and societies in regions susceptible to such weather extremes. For example, in spring, when the snow is at the melting point and saturated with water, all additional rainfall will generate runoff, which may trigger floods or slush floods (e.g. McCabe *et al* 2007, Hansen *et al* 2014, Musselman *et al* 2018). ROS events can also lead to other hazards, such as avalanches (Conway and Raymond 1993, Stimberis and Rubin 2011, Hansen *et al* 2014), can degrade permafrost (Westermann *et al* 2011) and restrict wildlife's (e.g. reindeer, elk) access to food when rain water freezes into ice on the surface (e.g. Putkonen and Roe 2003 and references therein).

ROS events usually occur in cold climate regions where snow cover persists for long periods of time. Global studies using reanalysis data (e.g. Cohen *et al* 2015) have shown that ROS events can occur in many parts of the Northern hemisphere. Such regions are often characterised by high latitude and/or high elevations such as Alaska (Bieniek *et al* 2018, Crawford *et al* 2020), Arctic Canada (Grenfell and Putkonen 2008), Western Siberia (Bartsch *et al* 2010), Greenland (Abermann *et al* 2019), Scandinavia (Pall *et al* 2019, Poschlod *et al* 2020), Svalbard (Hansen *et al* 2014), and North Western United States (Musselman *et al* 2018). However, the highest frequencies of ROS are generally found in coastal regions such as Norway, southern Alaska and Southeastern Greenland (Cohen *et al* 2015). Large scale climate modes, such as the North Atlantic Oscillation and Arctic Oscillation, have been shown to correlate with ROS frequency in Eurasia (Cohen *et al* 2015, Pall *et al* 2019).

Analysis of global datasets by (Cohen *et al* 2015) has shown that trends in ROS frequency have a strong regional variability. In Alaska, ROS frequency is expected to increase in most places but decrease in southern and southwestern Alaska (Bieniek *et al* 2018). Over the Rockies and western USA, ROS frequency is expected to increase at high elevations and decrease at lower elevations (Musselman *et al* 2018).

These studies attribute increasing ROS frequency to increasing rainfall and decreasing ROS frequency to declining snowpack.

A similar pattern was detected over Norway by Pall *et al* (2019). This analysis of gridded observational data over Norway for the 1961–1990 period showed that ROS events occurred more frequently in the lower elevations of southwestern Norway during the winter-spring period. This was attributed to the large frontal systems from the warmer Atlantic during winter. The frequency of ROS events in this southwestern region declines in spring as snow melts. This is broadly consistent with Poschlod *et al* (2020) who focused exclusively on southern Norway and showed that ROS events were more likely to occur on the southwestern coast of Norway compared to the rest of southern Norway.

The second most frequent occurrence of ROS identified by Pall *et al* (2019) was in the Mountain regions during the spring-summer period. Here snow cover persists into the summer when air temperatures are warmer and precipitation is transitioning from rain to snow.

Both Pall *et al* (2019) and Poschlod *et al* (2020) investigated changes in ROS with Pall *et al* (2019) focusing on the observed historical period and Poschlod *et al* (2020) focusing on the end of this century. Pall *et al* (2019) showed that during the 1981–2010 period, ROS events decreased in lower elevations where snow cover declined due to warming while ROS events increased at high elevations due to increasing occurrence of rain instead of snow. Poschlod *et al* (2020) used regional climate models to investigate changes in ROS occurrences over Southwestern Norway by the end of this century. Their study showed that ROS occurrence would be almost zero in coastal regions with only modest increases expected in the Mountain regions by the end of the 21st century.

None of the aforementioned studies on Norway have investigated changes in ROS in the near future, i.e. mid-century, which is more pertinent for current long term planning and investments in large infrastructure. Furthermore, no study has investigated future changes in the intensity of ROS events (snowmelt and rainfall) in Norway nor has any study linked changes in the ROS climatology to hydrological extremes at the basin scale.

A major challenge in closing these knowledge gaps has been the prohibitive computational costs needed to simulate the Norwegian climate at the necessary spatial scales. The Norwegian climate is strongly influenced by complex orography, a long coastline on the west and its expanse from the mid-latitudes into the Arctic Circle. For example, south western Norway has a maritime climate that receives significant amounts of precipitation and strong winds in autumn and winter from Atlantic storms with precipitation often enhanced by orographic lift. This contrasts with
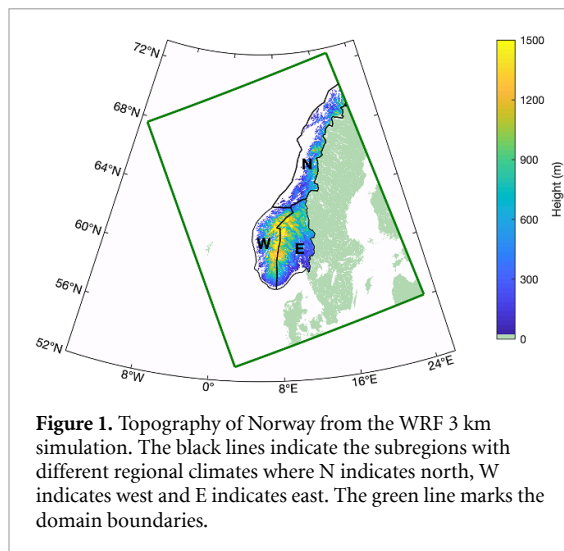
the south east which experiences significant amounts of rainfall in summer from convective activity. Given the spatial scale of these influential atmospheric processes and the complex orography, existing simulations from global Earth System Models (e.g. CMIP6 $\sim$ 100 km) and regional climate ensembles (e.g. Euro-CORDEX $\sim$ 11 km) are too coarse to properly represent the Norwegian climate (Pall *et al* 2019). As such it is essential to use regional climate simulations at convection permitting scales (<4 km) for climate change studies of ROS even though the computational expense prohibits ensembles (Prein *et al* 2015, Poschlod *et al* 2018).

This study uses convection-permitting simulations to determine for the first time 1) potential changes in ROS intensity and frequency in the middle of this century under RCP8.5 over Norway, and 2) the associated link between changes in ROS events and the potential changes in hydrological extremes (i.e. 95% high-flows) at basin scales. This manuscript is laid out as follows. Section 2 describes the data used in this study along with the definition of ROS events and intensity. Section 3 presents the expected future changes in the frequency and intensity of ROS events, and the changes in the ROS driven hydrological extremes (95% high-flows). Finally, in sections 4 and 5, the implications of these new findings for flooding are discussed and future directions for this work are presented.

2. Data and methods

2.1. High resolution regional climate simulations

The climate model data used in this study is described in detail in Mooney *et al* (2020) which also contains a comprehensive evaluation of the model's performance. For completeness, a brief description is provided here with an emphasis on details pertinent to this study. The Weather Research and Forecasting (WRF) model Version 3.9.1.1 (Skamarock *et al* 2019) was used to downscale the European Centre for Medium Range Weather Forecasting Interim Reanalysis for the 10 year period 1996–2005 over the Scandinavian Peninsula (see figure 1) at 3 km grid spacings using a one-way nested grid approach; the outer domain has 15 km grid spacings. Model physics include the Thompson microphysics scheme (Thompson *et al* 2008), Rapid Radiative Transfer Model for General Circulation Models 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), the Kain-Fritsch cumulus scheme (Kain 2004) on the 15 km domain only, and the Noah Multi-Physics (Noah-MP) land surface model (Niu *et al* 2011). Importantly, this land surface model uses the microphysics scheme's partitioning of precipitation into rain

Figure 1. Topography of Norway from the WRF 3 km simulation. The black lines indicate the subregions with different regional climates where N indicates north, W indicates west and E indicates east. The green line marks the domain boundaries.

and snow. This allows for better simulation of snow water equivalent (SWE) and snow cover fraction (SNC) by removing some of the uncertainty that arises in the more commonly used temperature-based approaches. Mooney *et al* (2020) compared the simulated 2 m air temperature (T2m), precipitation, and snow cover with a range of observations. The results of Mooney *et al* (2020) demonstrated reasonably good agreement between the simulated and observed variables.

High resolution future climate projections were obtained using a pseudo-global warming (PGW) approach (Schär *et al* 1996). The approach is described comprehensively in Mooney *et al* (2020) and only essential details to aid the reader are included here. This approach adds a monthly climate change signal to the same 6 h ERA-Interim data used in the present day simulation. The monthly climate change signal is calculated for each prognostic variable using the ensemble mean of 19 different CMIP5 models (see Table A1 in appendix A) with RCP8.5 covering a reference period (1976–2005) and a future period (2036–2065) that is centred on the middle of this century. This corresponds to approximately 1.5 °C of global warming. Hereafter, we use the term 'mid-century' to refer to the 10 years simulated by WRF using these perturbed boundary conditions.

Analysis of this perturbation by Mooney *et al* (2020) has shown that it contains only weak changes to the circulation pattern but clear enhancements to temperature and moisture. As such, this approach effectively applies primarily the externally forced thermodynamic response to global warming. A benefit to this approach is that it removes uncertainty arising from global model differences e.g. differences in the projected changes to the North Atlantic storm tracks. A limitation to this approach is that the variability is the same in both the present day and future simulations i.e. each simulation has the same weather at the lateral boundaries.

2.2. ROS definition

This study uses the same definition for a ROS event as that applied in Pall *et al* (2019). A ROS event is defined as a day when rain is greater than 5 mm d^{-1}, SWE is greater than 3 mm d^{-1}, and SNC is greater than 25%. Results that use more conservative criteria agree qualitatively with those presented here except the number of events is reduced when harsher criteria are applied (see figures S1 and S2 (available online at stacks.iop.org/ERL/16/064039/mmedia)).

ROS intensity is defined as the sum of rainfall and snowmelt during a ROS event.

Precipitation was separated into rain and snow using the temperature-based method described in Kienzle (2008). This method uses a S-shaped curve to describe the transition of precipitation from snow to rain. The shape of this curve is determined by a temperature threshold and a temperature range. The temperature threshold defines the temperature at which 50% of the precipitation falls as rain and it is the centre of the temperature range within which precipitation contains both rain and snow. Based on the results of Kienzle (2008) a temperature range of 13 °C was used in this study. A temperature threshold of 0.5 °C was chosen for Norway based on the work of Saloranta (2012).
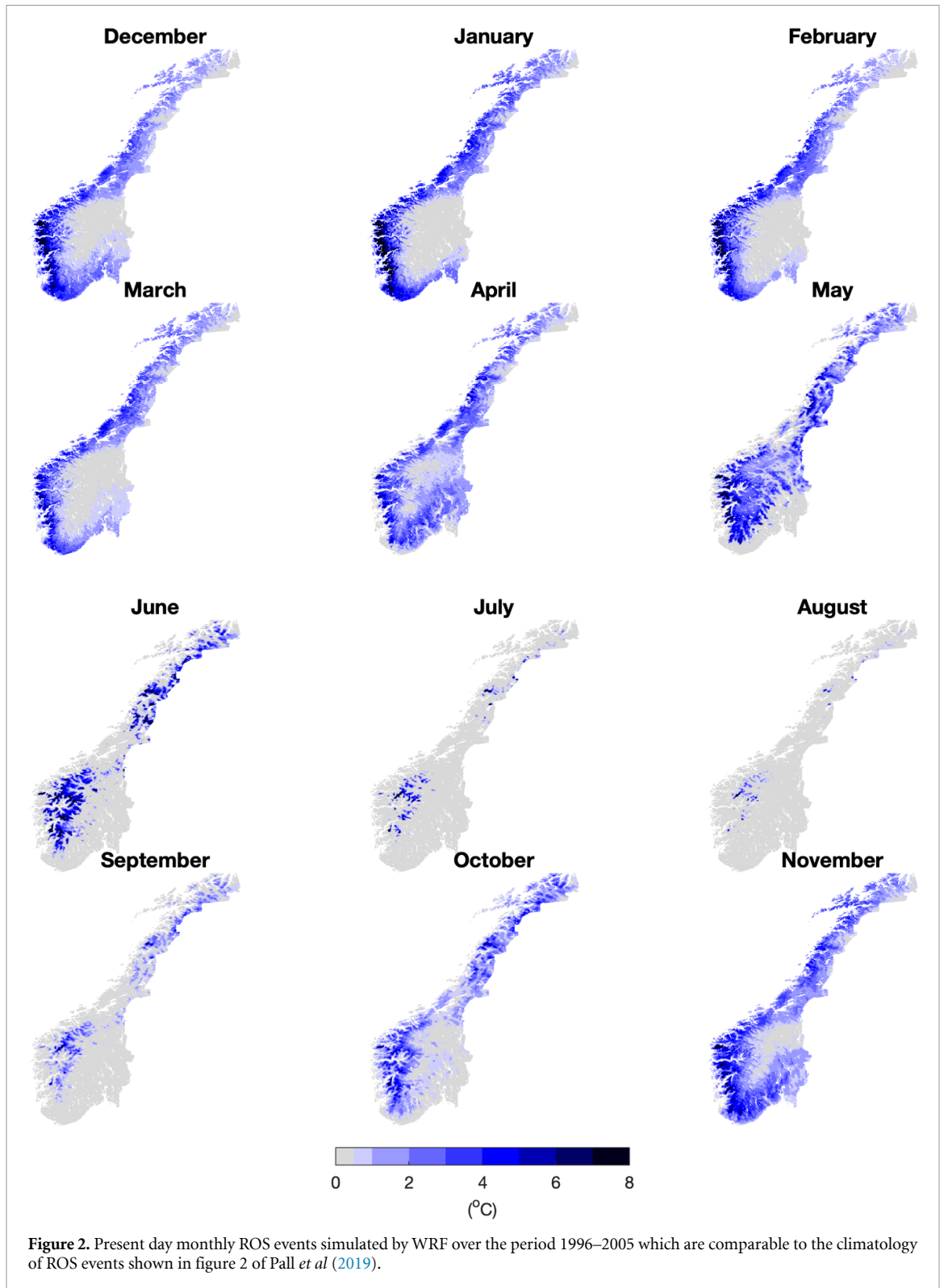
2.3. High flows (95th percentile) definitions and methods

The definition of high-flow used in the study is the 95th percentile of daily flow of the basins (see supplementary figure S6). This means the flow of daily runoff in mm d^{-1} equals to or exceeds 5% of the flow record. In addition, we also removed the high-flows (95th percentile), which have no ROS events counts. In this case, all the analysis of high-flow (95th percentile) changes between future and historical period is based only on those high-flows with a ROS contribution. Hereafter, these are called 'ROS high-flows'.

3. Results

3.1. Present-day ROS climatology

The mean number of monthly simulated ROS events is shown in figure 2. In winter and early spring, ROS events typically occur in the south west and in the north, with only a few occurrences in the east. This pattern results from the frequent and large amounts of rainfall in the west during this period, while the rain shadow in the east limits the occurrence of ROS. However, the frequency of ROS increases in the east from mid-spring to early summer. ROS also occurs more frequently at higher elevations during this time. This spatial shift in ROS frequency results from the persistence of snow at high elevations when precipitation transitions from snow to rain; during this time snow has already melted at lower elevations.

Figure 2. Present day monthly ROS events simulated by WRF over the period 1996–2005 which are comparable to the climatology of ROS events shown in figure 2 of Pall *et al* (2019).
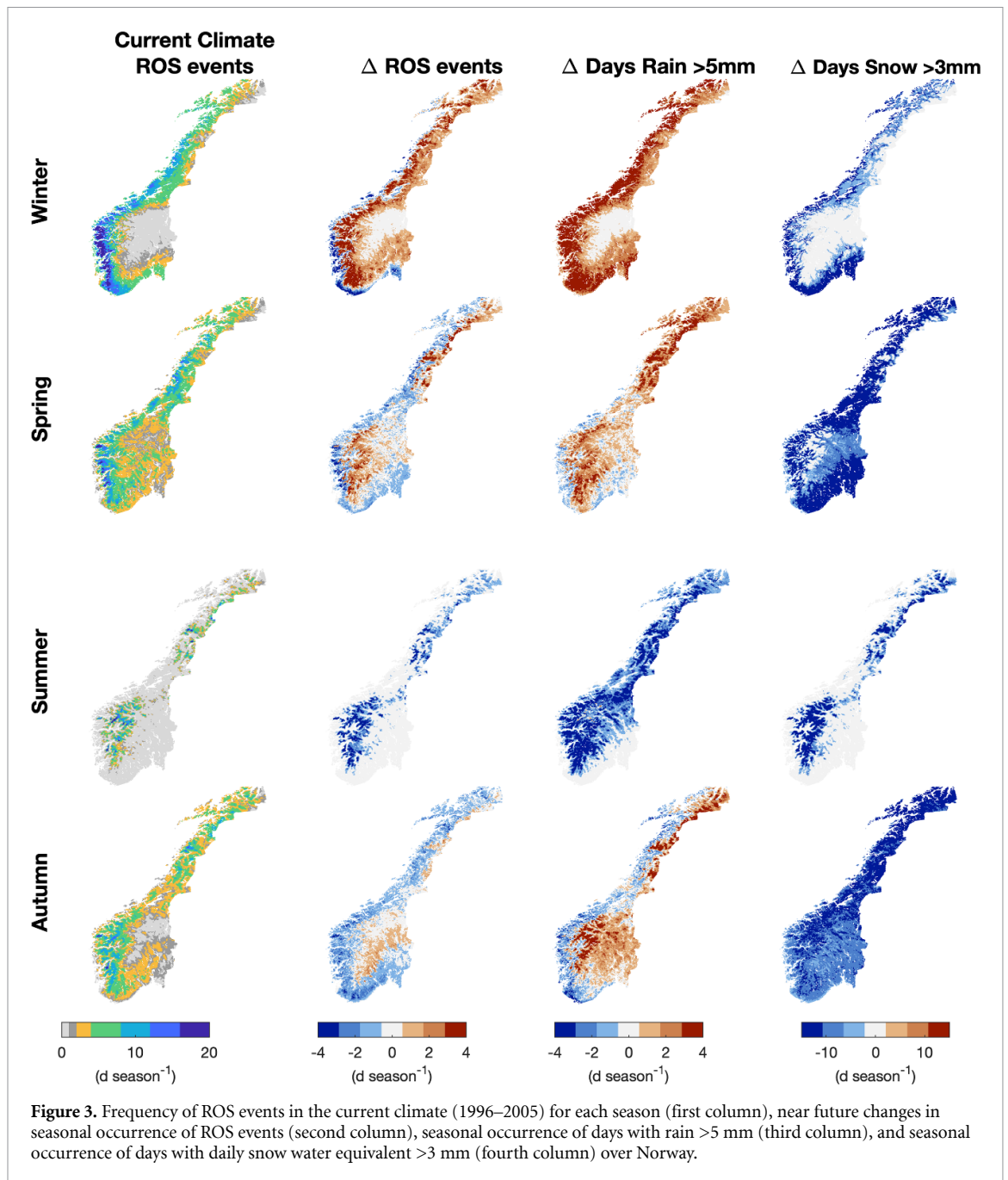
The occurrence of ROS is also greater in higher elevations in late Autumn when precipitation transitions from rain to snow. These ROS patterns show that both regional climate and elevation are key factors in ROS occurrence. The results are in good agreement with the observation-based results in figure 2 of Pall *et al* (2019); this adds confidence to the regional climate simulations used in this study.

3.2. Future changes in ROS occurrence

Figure 3 shows that there is a strong seasonality in the response of ROS frequency to global warming under RCP8.5 in the middle of the 21st Century. During winter, ROS frequency decreases at low elevations which are also coastal. This corresponds to a reduction in snow days at lower elevations in a warmer climate. The decrease in ROS frequency at low

Figure 3. Frequency of ROS events in the current climate (1996–2005) for each season (first column), near future changes in seasonal occurrence of ROS events (second column), seasonal occurrence of days with rain >5 mm (third column), and seasonal occurrence of days with daily snow water equivalent >3 mm (fourth column) over Norway.
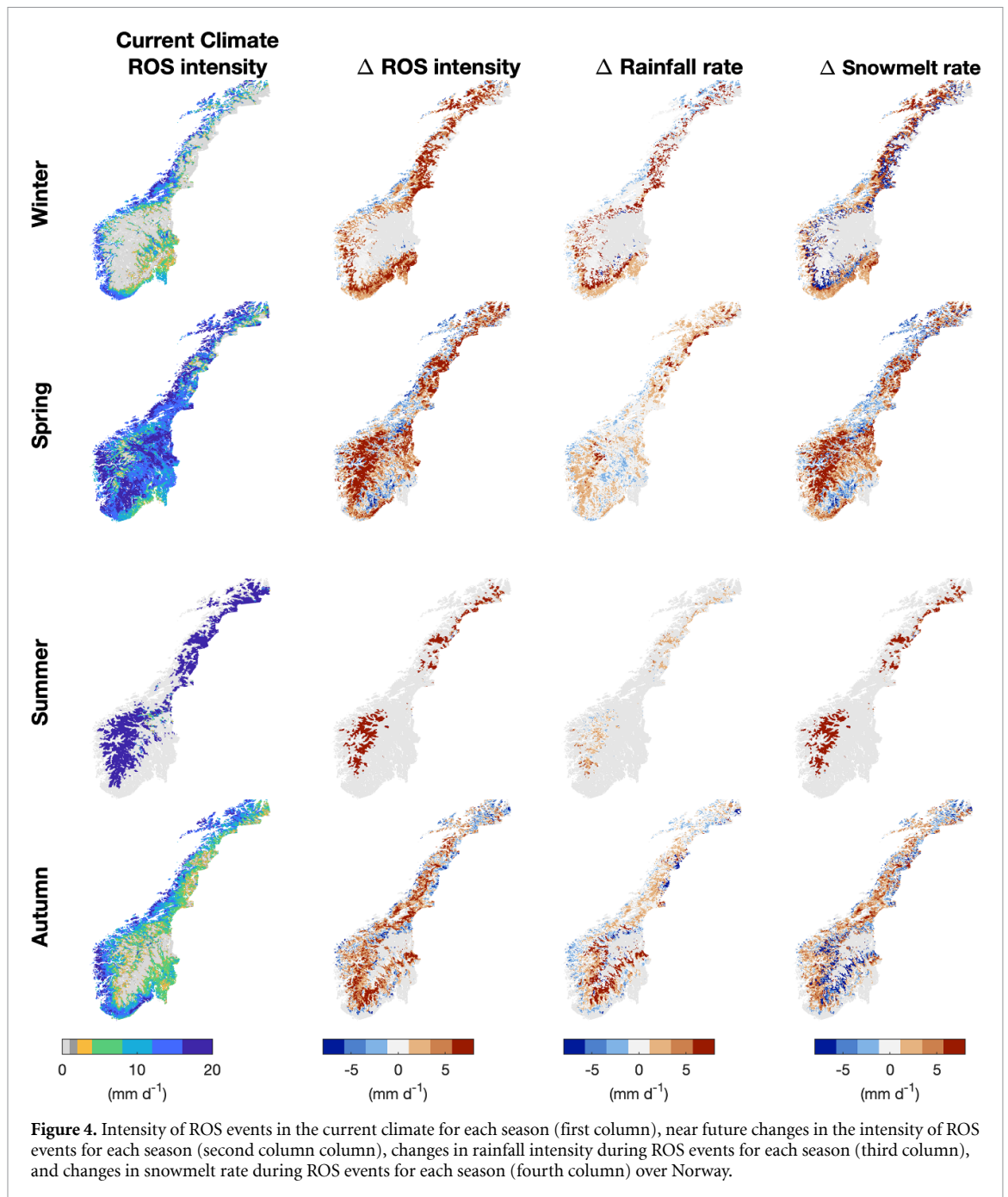
elevations contrasts with high elevations where ROS frequency increases. This coincides with increases in the number of days with moderate-to-heavy rainfall (i.e. days with rainfall >5 mm). In a warmer climate, it is expected that there would be more rainfall at the expense of snow. This increase in ROS events is largely attributable to the earlier transition of precipitation from snow to rain in spring despite decreasing snow cover.

In spring, ROS events will no longer occur at low elevations and ROS frequency will decrease at low-mid elevations (<800 m; see supplementary figure S03). This is due to the reduction in snow at these elevations. At mid-high elevations (>800 m), ROS frequency increases in the West and the North. This

corresponds to increases in days with moderate rainfall in the West combined with little to no reduction in snow days. Summer will experience a large reduction in the number of ROS events at high elevations (>1000 m) in the west and the north. This can be attributed to the loss of snow and the reduction in days with moderate-to-heavy rainfall in a warmer climate. ROS events do not occur at low elevations in summer under the current climate and this will continue in the future.

In Autumn, ROS frequency will decrease at low and mid-elevations (<1000 m). This is a consequence of the major reduction in snow during this season. Reductions in days with moderate-to-heavy rainfall are also a factor, albeit a secondary one. Small

Figure 4. Intensity of ROS events in the current climate for each season (first column), near future changes in the intensity of ROS events for each season (second column column), changes in rainfall intensity during ROS events for each season (third column), and changes in snowmelt rate during ROS events for each season (fourth column) over Norway.
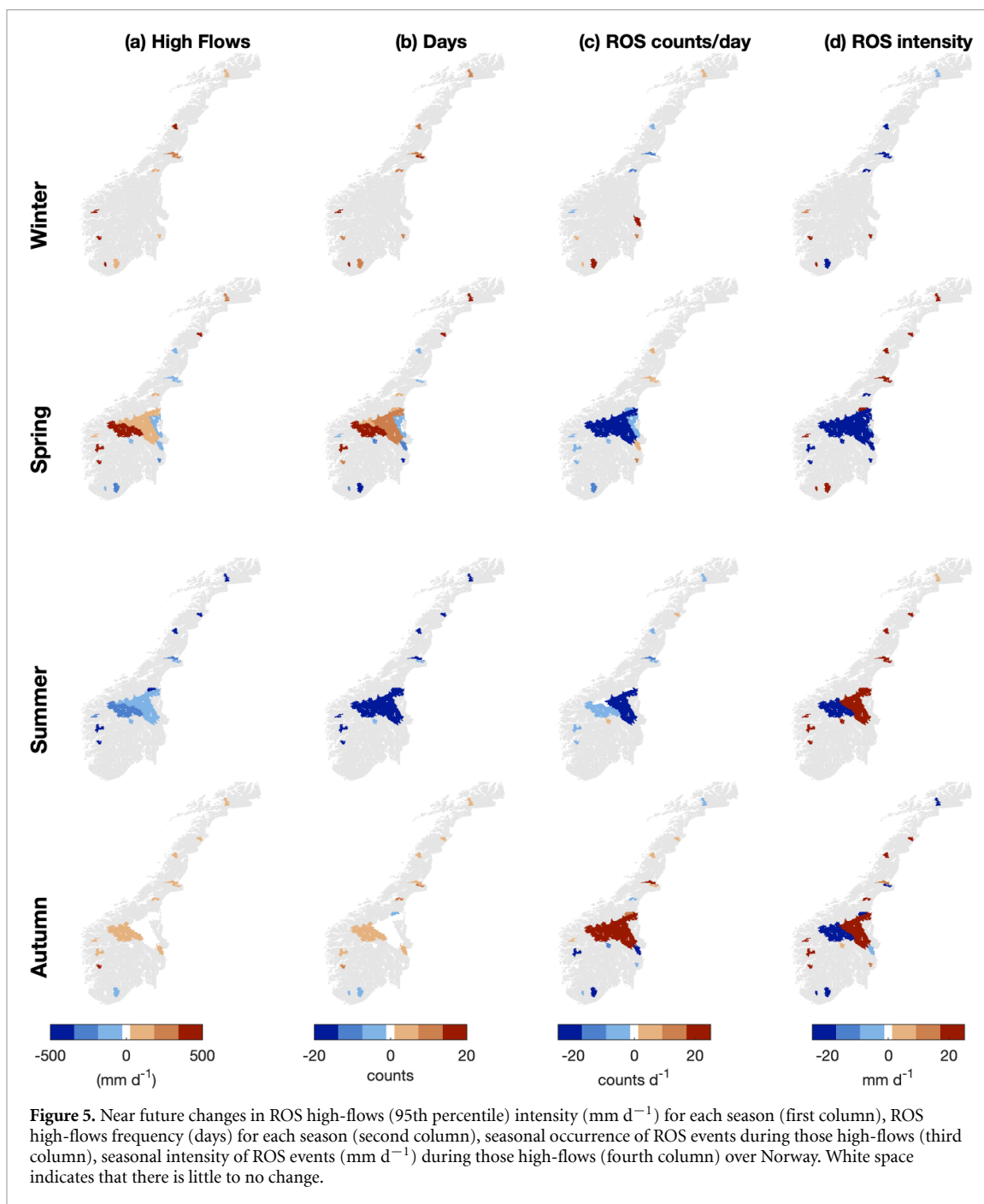
increases in ROS frequency occur at mid-high elevations in the East. This is a result of an increase in days with moderate-to-heavy rainfall.

3.3. Future changes in ROS intensity

Figure 4 shows that unlike ROS frequency, intensity has only a weak seasonality with seasonal changes in ROS intensity related to elevation. However, factors that influence the intensification differ between seasons. During winter, ROS events will intensify at low-to-mid elevations with no changes at higher elevations. This is primarily due to increased rainfall rate which has been highlighted in Poujol *et al* (2021). Increased rainfall rates will also intensify ROS events

in autumn. This increase in rainfall rate is also consistent with the recent analysis of Poujol *et al* (2021). Intensification of ROS in autumn primarily occurs at mid-elevations and higher.

ROS events will also intensify in spring, particularly at mid-high elevations in the West and the North. Unlike winter and autumn, this is largely due to increased snowmelt rates. In the East, there is intensification at low elevations and decreased intensity at mid-elevations. The increases at low elevations result from increased snowmelt rates while mid-elevations changes are driven by decreased snow melt rates. Rainfall does not play a role in changes to ROS intensity during this season. This is a consequence of the weak changes in rainfall rate that

Figure 5. Near future changes in ROS high-flows (95th percentile) intensity (mm d^{-1}) for each season (first column), ROS high-flows frequency (days) for each season (second column), seasonal occurrence of ROS events during those high-flows (third column), seasonal intensity of ROS events (mm d^{-1}) during those high-flows (fourth column) over Norway. White space indicates that there is little to no change.

are projected for this season in the future Poujol *et al* (2021). Enhanced snowmelt rates also drive the intensification of ROS events in summer.

3.4. Future changes in ROS high-flows

Figure 5 shows that basins which have ROS high-flows (95th percentile) during winter and autumn, will generally increase in both frequency (days) and magnitude (mm d^{-1}) in the near future. In winter, the increase of ROS high-flows (both frequency and magnitude) at basins in the South are related to the increases of ROS frequency or intensity. In autumn, increase of ROS events (frequency or intensity) result in an increase of high-flow of both frequency and

magnitude over the mountainous basins with median elevation >800 m (see table S1) (e.g. Losna and Rosten) in the East and west coast (e.g. Bulken, Sandvenvatn and Viksvatn), and basins (e.g. Junkerdalselv, Fustyatn and Trangen) in the North. This contrasts with Spring when high-flows increase at the basins in East and west coast but ROS frequency and intensity decrease. These increases in High-flow are more likely driven by non-ROS related rainfall increases for this region. Furthermore, in spring, ROS events increase over four basins in North while only the two basins in further North will have an increase of high-flows. In general, ROS high-flow will decrease in summer in Norway (both frequency and magnitude), as we see a wide decrease of ROS frequency at the basins in West,

East and North, although ROS will intensify in the regions (except Losna and Rosten).

4. Discussion

Results show that ROS events will intensify in all seasons and the intensification is largely driven by rainfall in autumn and winter, and by snowmelt in spring and summer. This ROS intensification results in high-flow increases in autumn over mountainous basins (elevation >800 m) in the East and west coast, and basins in the North, and in winter over basins in South. Seasonal changes in ROS frequency are also subject to the same influences. Changes in ROS events are influenced by the atmosphere in autumn and winter when stratiform precipitation is the dominant precipitation type (Poujol *et al* 2021). This type of precipitation most often arises from large scale atmospheric processes, such as atmospheric rivers and storm tracks, indicating that future changes in autumn and winter ROS events are strongly influenced by large scale atmospheric processes. This contrasts with spring and summer when changes in snowmelt dominate the changes in ROS events. Snowmelt is driven by surface energy fluxes such as radiative and turbulent heat fluxes which are primarily localised processes. In summary, changes in ROS events are mostly influenced by large-scale atmospheric processes in autumn and winter while in spring and summer, they are mainly influenced by local scale processes.

The ROS frequency results in this study are both consistent and complementary with the findings of both Pall *et al* (2019) and Poschlod *et al* (2020). The ROS frequency results in this study complements their findings by increasing the temporal coverage for future projections of ROS frequency in Norway in this century; Pall *et al* (2019) covers the start of this century, this study covers the middle of this century, and Poschlod *et al* (2020) covers the end of the century. Pall *et al* (2019) showed that ROS frequency has already increased at high elevations and decreased at lower elevations. The results in this study show that this trend will continue with ROS increasing even more at high elevations and decreasing at low elevations by the middle of this century when global temperatures have risen by ∼1.5 °C. By the end of the century, ROS frequency will decrease everywhere (Poschlod *et al* 2020). This study goes further than both Pall *et al* (2019) and Poschlod *et al* (2020) by also analysing the changes in ROS intensity and linking changes in ROS climatology to hydrological extremes at the basin scale.

5. Conclusions

In this study we used a regional climate model at convection permitting scales to project changes in

ROS events in the near future under RCP8.5 warming. The analysis shows that the magnitude of ROS frequency depends on the regional precipitation and surface elevation. It has been shown that these factors also play an important role in the response of ROS frequency to future warming. Furthermore, it is clear that there is a strong seasonality in the response of ROS frequency to future warming.

Overall, ROS events intensify in the future with decreases found mainly at mid-elevations in the East during Spring. The greatest intensification of ROS is expected at high elevations in the West and North during Spring and Summer. During these seasons changes in ROS intensity are driven by increased snowmelt rates. This contrasts with winter and autumn where changes in ROS intensity are dominated by changes in rainfall intensity.

In general, the ROS high-flow will increase in winter and autumn in Norway in the near future. The high-flow increase at the basins in the South in winter results from the increase of ROS events, as well as at the mountainous basins (elevation >800 m) in the East and west coast and basins in the North in autumn. The opposite happens in spring when the high-flow increases are most likely driven by rainfall over the mountainous basins, where ROS intensity will decrease.

It is important to note that this work relies on the use of a single model. While convection permitting scales do improve the representation of precipitation in climate models, precipitation remains a challenging variable to simulate (Berthou *et al* 2019). Although the RCM used in this study has been evaluated thoroughly and demonstrated skill in simulating precipitation in Norway, the use of a single RCM is a limitation, due to the prohibitive computational costs of running RCMs at the necessary spatial scales of 3 km. Another potential limitation arises from the PGW approach. This approach accounts for projected thermodynamic changes in the global climate system but it does not account for the projected dynamical changes which are highly uncertain (Shaw *et al* 2016). Thus, a limitation of this method is the assumption that the timing and frequency of weather systems in the future climate is the same as in the historical climate.

In the high-flow analysis, there is a missing groundwater component, since only the surface and subsurface of runoff are considered in the total runoff from the NoahMP land surface model from WRF. Additionally, the hydrological routing processes are not included in the study which will result in the uncertainty of high-flows, when compared with observed discharge from gauge stations.

From a methodology perspective, future studies should take an ensemble approach to simulating future changes in ROS when the computational

power increases and costs become affordable. This would allow for more robust findings on projected changes to ROS events. Additionally, future work should consider longer time periods to enable investigations of the role of low frequency atmospheric variability (i.e. North Atlantic Oscillation and Arctic Oscillation) on future changes in ROS frequency and intensity. Future assessments of the impact and contributions of ROS events on flooding should apply hydrological models that include hydrological routing processes.

From a scientific perspective, future research should explore the relationship between large scale atmospheric processes and ROS in autumn and winter when atmospheric processes i.e. rainfall, strongly influence the frequency and intensity of ROS. Similarly, future studies should also investigate the role of local-scale atmospheric and land surface processes in spring and summer when snowmelt and convective rainfall influence ROS intensity and frequency.

Data availability statement

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

Acknowledgments

Appendix A. Pseudo-global warming CMIP5 models

Table A1. CMIP5 models used for deriving the climate perturbations in the PGW simulation for mid-century warming.

Model name	Names of member realisations
ACCESS1-3	r1i1p1
CanESM2	r1i1p1, r2i1p1, r3i1p1
CCSM4	r1i1p1, r2i1p1, r6i1p1
CESM1-CAM5	r1i1p1, r2i1p1, r3i1p1
CMCC-CM	r1i1p1
CNRM-CM5	r2i1p1, r4i1p1, r6i1p1
CSIRO-Mk3-6-0	r1i1p1, r2i1p1, r3i1p1
GFDL-CM3	r1i1p1
GFDL-ESM2M	r1i1p1
GISS-E2-H	r1i1p1, r2i1p1
HadGEM2-CC	r1i1p1, r2i1p1, r3i1p1
HadGEM2-ES	r3i1p1
INM-CM4	r1i1p1
IPSL-CM5A-MR	r1i1p1
MIROC5	r1i1p1, r2i1p1, r3i1p1
MIROC-ESM	r1i1p1
MPI-ESM-LR	r1i1p1, r2i1p1, r3i1p1
MPI-ESM-MR	r1i1p1
MRI-CGCM3	r1i1p1

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