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Warmer and wetter: Outlining climate services for snow-dependent tourism in Norway – The case of Lofoten

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ABSTRACT

Human-induced climate change potentially impacts nature-based activities in Lofoten and may limit the attractiveness of the destination for tourists seeking recreation and adventure in the mountains. As a climate service, we calculated climate indicators relevant to the tourism sector based on the representative concentration pathways RCP4.5 and RCP8.5 until 2060. We used high-resolution gridded climate data and projections to calculate indicators such as changes in the frequency and intensity of consecutive wet days, changes in precipitation type (snow, sleet, rain), changes in the number of skiing days on ungroomed, natural snow, and changes of the monthly 0 °C-isoline. We found a minor, but non-robust increase in the number of consecutive wet days with a precipitation intensity > 8 mm/day, and a clear change in the precipitation regime depending on altitude that leads to more precipitation falling as rain instead of snow. Also, a strong decrease in the number of skiing days is projected by the climate models as the monthly near-surface 0 °C-isoline increases. These are important findings for long-term planning and investments in the tourism sector in Lofoten, especially as tourism growth is considered an important tool for regional economic development. The analytical methods used in this study are transferable to analyses on a regional to national scale. National maps and data material for 11 regions were recently published on https://klimaservicesenter.no/kss/framskr/sno-sludd-regn.

Practical Implications

Tourism has become an important factor for regional economic development in Norway. However, human-induced climate change has an impact on the conditions upon which the tourism business is built, e.g., geography and weather conditions are important factors for the attractiveness of a destination. This study is a contribution to providing relevant climate information to policymakers and practitioners in the tourism business sector in Lofoten, Nordland County. We assess climate change impacts which are critical to the nature-based tourism industry with a focus on snow-dependent activities during winter and spring as the tourism business sector identified these seasons to have the biggest potential to attract more tourists. Our analysis of climate projections is based upon two climate change scenarios representing the intermediate concentration pathway RCP4.5 in which greenhouse gas emissions (such as CO_2) peak around 2040 and decline thereafter with a mean global temperature increase of 2–3 °C by 2100, and a scenario with continuously rising emissions, RCP8.5, corresponding to an approximately 4–5 °C warmer global climate by 2100.

Our study is motivated by the outcome of a dialogue with practitioners from the local tourism business sector (Antonsen et al., 2022) which led to the calculation of climate indicators such as changes in the frequency and intensity of consecutive wet days, changes in precipitation type (snow, sleet, rain), changes in the number of skiing days on ungroomed, natural snow, and changes in the altitude of the monthly 0 °C-isoline.

The climate projections reveal a general shift in the precipitation regime leading to an increased frequency of days with rain instead

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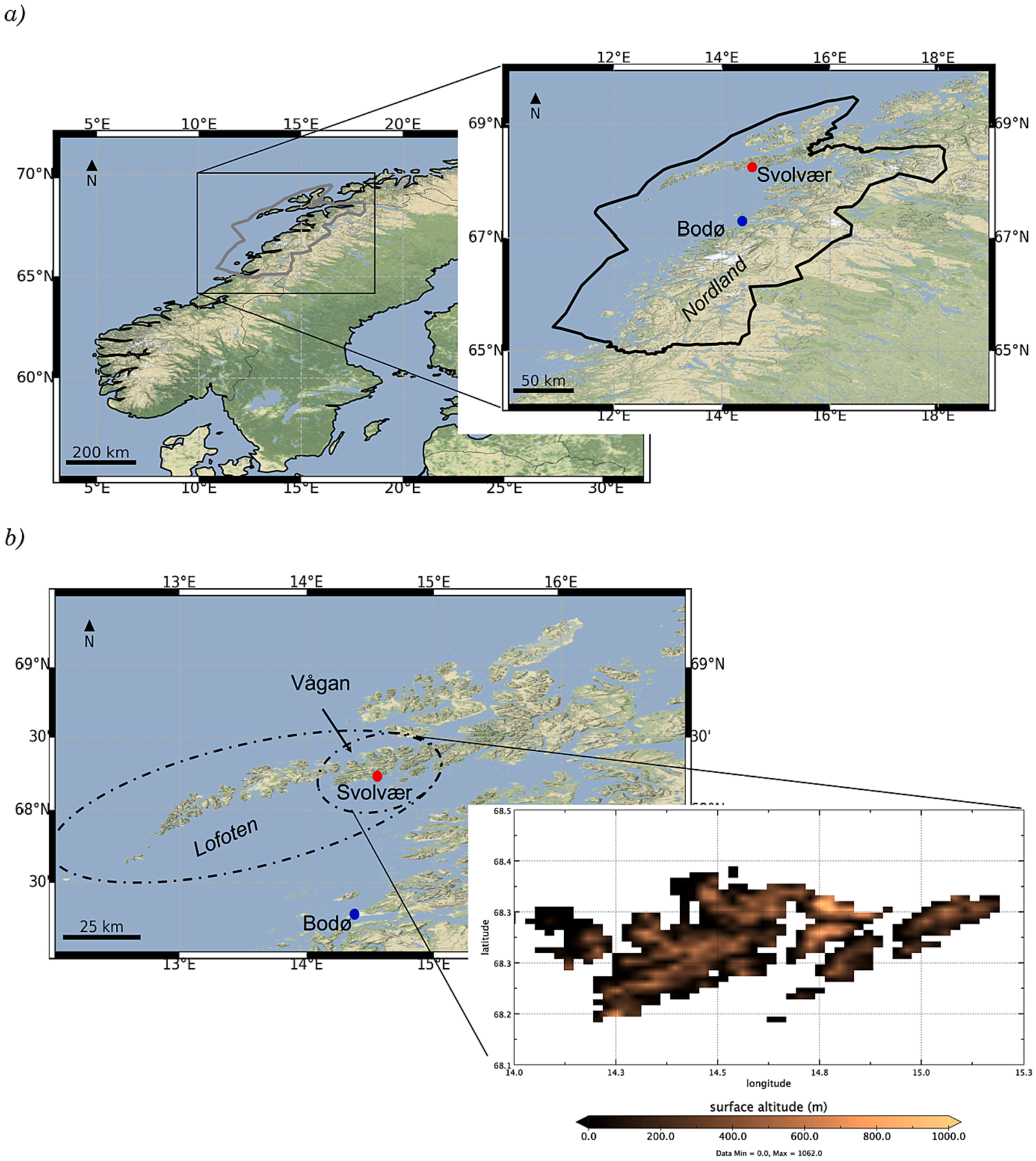

Fig. 1. a) Map with most parts of Scandinavia. The grey line delineates Nordland County. b) The region of Lofoten and the municipality of Vågan are indicated with a black ellipse. Svolvær, the administrational centre of Vågan, is indicated with a red dot. The inlet shows the elevations data for the municipality of Vågan. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of snow, i.e., days with snowfall or sleet will be mainly replaced by days with rainfall. As the precipitation amount increases, but not the occurrence of precipitation days, we conclude that when it rains, it will be more intense. This signal is most pronounced for the winter months under the RCP8.5 scenario. Importantly, this can have impacts on safety related to more frequent rain on snow events, more wet snow avalanches by the middle of the century and more intense rainfall triggering landslides that can lead to access disruptions as shown e.g., for Troms by Dyrrdal et al., 2020. Ski touring days will become rare by the middle of this century under the RCP4.5 scenario, even earlier under the RCP8.5 scenario. This poses a potential risk leading to a decrease in the general interest in snow-dependent activities in the region. Thus, Lofoten may lose its attractiveness to tourists interested in mainly snow-dependent activities, such as skiing on ungroomed, natural snow. Finally, we find no significant increase in days with (persistent) 'bad weather' and conclude therefore that short-notice overnight cancellations caused by bad weather will probably not be a major challenge for the local tourism sector until 2060.

As a further outcome, this work has led to an extension of the climate indicators available as maps on the website of the Norwegian Centre for Climate Services https://www.klimaservicesenter.no. Results from this study will also be implemented in an interactive game designed for practitioners in the tourism sector to reflect on and discuss climate change impacts, mitigation, and adaptation options.

On a final note, although tourism has become an important factor for regional economic development, it should be stressed that this industry is (still) carbon intense and, thus also has a responsibility to reduce greenhouse gas emissions substantially. This is a dilemma, but ideally the motivation to reduce greenhouse gas emissions should be high as this sector is affected by climate change.

Data availability

Data will be made available on request.

1. Introduction

Snow-dependent tourism businesses have been repeatedly identified as particularly susceptible to climate change. The existing literature, however, is highly concentrated on alpine or downhill skiing (e.g., Fang et al., 2018; Steiger et al., 2019). Compared to the European Alps, Norway, irrespective of its long-standing skiing tradition, has been considered under-researched for quite some time (Scott et al., 2020). At the publication date of Steiger et al.'s review article (online in 2017, print in 2019), for instance, there were only a few studies on Norwegian skiing and winter tourism. Examples include a climate change assessment of the former Olympic Winter Games host cities Oslo and Lillehammer (Scott et al., 2015), and a study investigating the potential impacts of a 2 °C warming on skiing and winter tourism demands in several European countries, including southern but not northern Norway (Damm et al., 2017). Meanwhile, additional studies have been published including an article investigating climate change perceptions and responses of summer skiers (Demiroglu et al., 2018), a climate change risk assessment of 110 Norwegian ski areas (Scott et al., 2020) and a study focusing on the adaptive capacity of seven ski resorts in Western Norway (Dannevig et al., 2021). Further information is freely available from the "Mountain" component of the "European Tourism" Sectoral Information Service (SIS), Copernicus Climate Change Services.[1] The data set includes 39 indicators (e.g., number of days with at least 30 cm of natural, groomed, or managed snow) and covers different time periods (i.e., recent past, near future, mid-century and end of the century) and representative concentration pathways, such as RCP2.6, RCP4.5, and RCP8.5 (see Morin et al., 2021 for further details). While the respective data is provided for 100 m elevation bands, spatial resolution remains coarse (NUTS-3 regions). For example, there is only one value for each indicator configuration (e.g., monthly mean air temperature) representing the whole of Nordland County (Norway) which comprises an area of more than 38,000 km^2.

Regarding climate change and ski tourism, Norway may no longer be considered under-researched. What is (mostly) missing, though, are investigations focusing on snow-dependent activities other than alpine downhill skiing. There are a few studies focusing on the perception, vulnerability and/or adaptive capacity of winter tourism stakeholders in the Nordic countries (e.g., Saarinen and Tervo, 2006; Brouder and Lundmark, 2011; Antonsen et al., 2022) clearly showing the broad range of nature-based winter activities in these countries.

Based on interviews with local stakeholders in the region of Lofoten in Nordland County, Antonsen et al., 2022 have systematically categorised nature-based activities as so-called ecosystem services depending on perceived climate indicators resulting in perceived effects due to climate change (see Table 3 in Antonsen et al., 2022). As we consider nature-based activities to play a major (and still growing) socio-economic role as a pulling factor for most tourists in Norway, we here build on Antonsen's study and thus focus on the same region. We argue that nature-based activities strongly depend on suitable weather and climate conditions that i) allow to conduct the activity, e.g., enough snow to go skiing, and ii) to conduct the activity in a safe way.

Given the fact that Norway's climate has become and is further getting warmer and wetter in the future due to human-induced climate change (Hanssen-Bauer et al., 2017), our original motivation for this piece of work is to contribute with climate information to the question if climate conditions will still be favourable for snow-based activities in Lofoten.

To address this question, we analyse meteorological data in two steps: i) We show the recently observed climate change and ii) retrieve data from climate projections and compute future changes in temperature, precipitation, and snow water equivalent. Motivated by the findings in Antonsen et al., 2022, we define climate indicators that are based on these three hydro-meteorological variables. We base our analysis on data retrieved from a set of available high-resolution (12x12 km bias-adjusted and re-gridded to 1x1 km) climate models for the period 1971–2060 based on two representative concentration pathways, RCP4.5 and RCP8.5, which represent a middle and a high greenhouse gas emission scenario. As we focus on winter tourism and snow-dependent activities, we compute seasonal changes that occur from December until May.

2. Study area, data, and methods

2.1. The Lofoten region

Today, Lofoten is one of the most popular destinations in Norway. The region is a group of islands located in the northern part of Norway at 67-68° North in the county of Nordland (see Fig. 1). The region consists of the six municipalities (island groups) Vågan, Vestvågøy, Flakstad, Moskenes, Værøy and Røst. The attractiveness is closely related to the spectacular nature with its combination of alpine landscapes, white sand beaches, fjords, and the open sea. During the last two decades, Lofoten has experienced an increase in registered commercial overnight stays from 250,000 to almost 560,000 in 2019. In 2019, Airbnb facilities accounted for an addition of over 200,000 stays, and cruise and the coastal steamer for over 150,000 (Antonsen et al., 2022). Because the tourism sector was not fully recovered from the pandemic situation during the 2022 winter season, we use data from the latest year before the outbreak of Covid-19. From January to April 2019 Lofoten had 110,000 commercial stays, more than twice as many as in the same period in 2010. So far, Lofoten has mainly been a summer destination, and over 60 % of the total visits take place from June to August. However, according to the *Strategic business plan for Lofoten (2016)*,[2] winter season has the greatest potential to increase the number of tourists visiting Lofoten. Consequently, this will increase the possibility to offer more full-time jobs in the gastronomy and accommodation sector, for instance. In addition, the willingness of tourists to pay for wintertime nature-based activities is usually higher compared to tourists visiting Lofoten during summertime. Besides watching northern lights, going on sea safari, bird watching, and landscape photography, ski touring, winter hiking, and snowshoeing are popular outdoor activities during winter and spring. These activities depend strongly on local weather conditions either for safety reasons or simply for the tourists' positive experience such as enough snow to be able to conduct the activity.

The climate on Lofoten is characterised by its vicinity to the North-Atlantic Ocean and the steep topography which causes high spatial variability in weather conditions. For instance, the spatial variability in the mean annual precipitation amount exceeds 1500 mm with, according to the 1991–2000 climatology (MET Norway, 2021a) 2400 mm at Reine (located at the almost most western edge of Lofoten) and 809 mm at Skrova fyr (located further east close to Svolvær). At Leknes which is located approximately in the middle between Reine and Skrova fyr, the mean annual precipitation amount is 1329 mm. Most precipitation falls in autumn and winter in this area, least in summer. During the past decades, the winter precipitation increased by 15 %-25 % in the area from the period 1961–1990 to 1991–2020, while the summer precipitation decreased by 10 %-15 %. The observed mean annual 2 m-temperature at Skrova fyr is, according to the 1991–2020 climatology, +6.0 °C (see MET Norway, 2021b). July is normally the warmest month (+13.6 °C), while February is the coldest (+0.2 °C). The average winter temperature increased from −0.3 °C during 1961–1990 to 1.1 °C during

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[1] https://cds.climate.copernicus.eu/cdsapp#!/software/app-tourism-mountain-indicators-projections?tab=overview.

[2] https://lofotradet.no/prosjekter accessed on March 16th, 2022.

Table 1
Model combinations retrieved from the high-resolution (12x12 km) Euro-CORDEX data set. The bias-adjusted data set for Norway is available on https://nedlasting.nve.no/klimadata/kss.

global climate model and realisation	regional climate model	institution who performed the simulation
CNRM-CERFACS-CM5_r1i1p1	CCLM4-8-17	Climate Limited-area Modelling Community (CLM-Community)
CNRM-CERFACS-CM5_r1i1p1	RCA4	Swedish Meteorological and Hydrological Institute (SMHI), Rossby Centre
ICHEC-EC-EARTH_r12i1p1	CCLM4-8-17	CLM-Community
ICHEC-EC-EARTH_r3i1p1	HIRHAM5	Danish Meteorological Institute (DMI)
ICHEC-EC-EARTH_r1i1p1	RACMO22E	Royal Netherlands Meteorological Institute (KNMI)
ICHEC-EC-EARTH_r12i1p1	RCA4	SMHI
MOHC-HadGEM2-ES_r1i1p1	RCA4	SMHI
IPSL-CM5A-MR_r1i1p1	RCA4	SMHI
MPI-ESM-LR_r1i1p1	CCLM4-8-17	CLM-Community
MPI-ESM-LR_r1i1p1	RCA4	SMHI

1991–2020 which is an increase of 1.4 °C during the recent past. Note that this temperature climatology is representative only for coastal areas. Temperatures decrease with altitude, and winter temperatures also with distance from the coast.

2.2. Data

In this study, we analyse two gridded meteorological data sets on current and future changes to assess i) observed changes in the very recent climate conditions in Norway and ii) possible changes in climatic conditions in Lofoten until the middle of the century. Both data sets are available on a 1x1 km horizontal grid. For i) we used the seNorge_2018 data set version 21_09 (Lussana, 2021) which comprises observed daily mean temperature and daily total precipitation on a terrain-following grid for the whole of mainland Norway. For ii) we analysed a sub-sample of the high-resolution (12x12 km) regional climate projections originating from the Euro-CORDEX initiative (Jacob et al., 2014) which have been re-gridded, and then bias-adjusted for Norwegian climate conditions (Wong et al., 2016). The Euro-CORDEX initiative provides a multi-model ensemble combining Earth System Models (ESMs) and Regional Climate Models (RCMs) for Europe on a horizontal grid of 50x50 km and 12x12 km. The data set is publicly available at several Earth System Grid Federation nodes, for example on: https://esg-dn1.nsc.liu.se/search/esgf-liu. For this study, we use a sub-sample of ten ESM-RCM model combinations (see Table 1) which was corrected for a cold and wet bias over Norway, i.e., the temperature for the Norwegian mainland in the models is underestimated compared with observations which leads, for example, to an unrealistically long duration of the snow cover. Such biases are problematic when assessing changes in climate indicators that depend on certain thresholds (e.g., temperature lower than 0 °C). Therefore, simulated temperature and precipitation fields were first re-gridded to the 1x1 km grid used in the seNorge datasets by applying the nearest neighbour method (Wong et al., 2016). Then, for every grid point, both temperature and precipitation in the period 1971–2000 were corrected independently by applying the empirical quantile mapping method with the observationally based seNorge1.1 (Mohr, 2008) as the 'ground truth'. Both seNorge datasets are based on daily observations of temperature and precipitation from all official meteorological stations in Norway, interpolated to a 1x1 km grid, considering geographical information like elevation and latitude. The datasets are thus highly correlated, though the altitude dependence of precipitation applied in seNorge1.1 was later reduced. Estimated precipitation is thus somewhat higher in seNorge1.1 than in seNorge2018 at high elevations, but relative changes are not very affected by this. Wong et al. (2016) reported that the adjusted dataset successfully reproduces the climatology for the period 1971–2000, not only for temperature and precipitation, but also for run-off when using them as input in the HBV-model (Bergström, 1995). The data set, including hydrological results such as snow water equivalent (SWE) calculated by the HBV-model, is openly available at https://nedlasting.nve.no/klimadata/kss for two greenhouse gas emission scenarios based on the representative concentration pathways RCP4.5 and RCP8.5 comprising a 130-year long period from 1971 until 2100. Nilsen et al. (2021) showed that – compared to the raw Euro-CORDEX data – this data set significantly reduces biases, e.g., in the number of days when the temperature passes 0 °C, both on an annual basis and in each season. In accordance with the naming in Nilsen et al., 2021, we call this data set "COR-BA" (bias-adjusted RCM data for Norway from the Euro-CORDEX initiative) hereafter.

2.3. Climate indicators

We conduct the data analysis based on available high-resolution gridded meteorological data set for observed recent past (1971–2000) from seNorge_2018 data set version 21_09 (Lussana, 2021) and projected near-future (2031–2060) climate conditions from the COR-BA data set. We constrain the data analysis on the municipality of Vågan which hosts most of the tourist business stakeholders and offers the best possibilities for ski touring[3] in the region of Lofoten. The definitions of the climate indicators are motivated by a dialogue (workshop, interviews, and follow-up conversations) with stakeholders sharing their expertise and experience from the tourism sector. For instance, according to Antonsen et al., 2022, overnight stays and outdoor activity cancellations increase with 'bad weather' (i.e., days with precipitation > 8 mm/day). Thus, an increase/decrease in the number of days with heavy precipitation may have a potentially negative/positive impact for the hotel business sector. We address this by introducing a 'bad weather indicator' depending on precipitation amount and duration.

To assess future snow-dependent activities we combine gridded temperature and precipitation fields, and partition the precipitation fields in rain, sleet, and snow depending on temperature thresholds. Jennings et al. (2018) found that the average air temperature at which rain and snow falls in equal frequency is +1.0 °C, but with considerable spatial variation from -0.4 °C to +2.4 °C at 95 % of almost 12,000 stations in the Northern Hemisphere. The lower values were found for maritime stations. Thus, as Lofoten has a maritime climate, we assume a temperature threshold near 0 °C to be realistic for our study. Therefore, we apply a simple temperature-based climate indicator alluding if precipitation falls as snow (mean daily $T \leq -1$ °C), sleet (1 °C $< T < 1$ °C) or rain ($T \geq +1$ °C). Importantly, as COR-BA also provides gridded information on elevation, we can cluster the precipitation fields depending on altitude levels from 0–300 m to 900–1200 m asl. The highest mountain in Vågan is Higravtindan with 1146 m asl. To our knowledge, this clustering according to the elevation of the grid points has not been performed on the COR-BA data set before. However, the MTMSI dataset is produced by applying such a clustering. In the MTMSI dataset the underlying data used to generate it, is based on a reanalysis which has been clustered by elevation prior to applying the bias correction (Morin et al., 2021), though with less horizontal detail for the NUTS-3 regions.

According to Fauve et al., 2002 and Olefs et al., 2010, a skiable snow area consists of snow layer which is at least 30 cm deep. Besides daily temperature and precipitation COR-BA also provides snow water equivalent (SWE) as a variable. Assuming a constant snow density of 300 kg/m^3, we use a threshold of at least 90 kg/m^2 (mm) which corresponds to a snow depth of 30 cm. Note, we assume a lower density compared to Olefs et al., 2010 as we consider ski touring and

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[3] https://topptursentralen.no/kart/ accessed on March 16th, 2022.

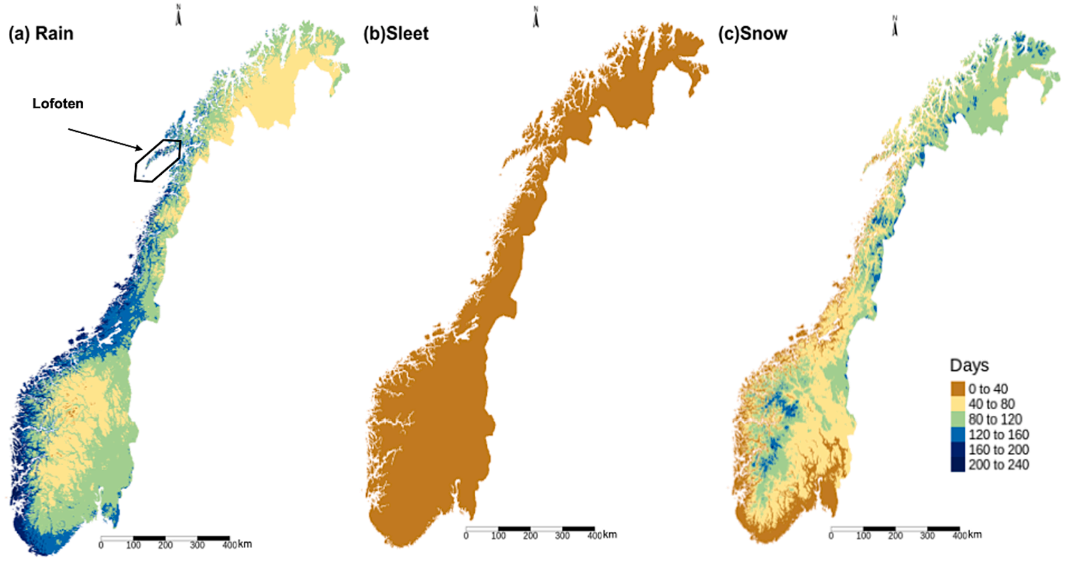

Fig. 2. Map with numbers of days/year with observed a) rain, b) sleet and c) snow for Norway from 1971 to 2000. The region of Lofoten is indicated with a black hexagon in panel a).

snowshoeing on ungroomed snow only. In this context, we define days when SWE ≥ 90 mm as skiing days and count them for the winter and spring seasons. We have chosen to calculate this climate indicator for grid boxes above 200 m asl, as this is the approximate altitude where ski touring is usually conducted under the present climatic conditions. Further, we calculate the annual evolution of the near-surface 0 °C-isoline as this is an indicator of whether snow lasts or melts.

The data aggregation from the COR-BA data set was performed in four steps:

i. Download the elevation and the daily variables mean temperature, precipitation for the periods 1971–2000 and 2031–2060, and snow water equivalent for the period 1971–2060 for the municipality Vågan (528 grid boxes) from the available bias-adjusted model projections (see Table 1) for RCP4.5 and RCP8.5 at https://nedlasting.nve.no/klimadata/kss.
ii. Extract the data for winter (December-February) and spring (March-May).
iii. Calculate the climate indicators for each projection with the Climate Data Operator (CDO) software (Schulzweida, 2022), and
iv. calculate the 10th, 50th and 90th percentiles for each indicator across the model ensemble for a selected RCP, period, and season.

We define the range from the 10th-90th percentile as the model uncertainty to be conform with Hanssen-Bauer et al., 2017.

3. Results

Observed recent precipitation frequencies distinguished into rain, sleet and snow for mainland Norway are shown in Fig. 2 as annual averages for the period 1971–2000. In general, rainy days are dominating over snowy days in the lowlands in southern Norway, including coastal areas to approximately 70°N, while snowy days are dominating in the mountains and most northern regions (parts of Nordland, Troms and Finnmark). The average for Norway is roughly 100 days with rainfall, 19 days with sleet and 72 days with snowfall per year. As the climate in Norway has been warming, the domination of rainy days has increased by ten days throughout the 30-years period (linear trend analysis, not shown), while the number of days with snowfall has decreased by two days throughout the period. The number of days with sleet increased similarly by two days.

Table 2
Projected mean seasonal temperature changes (in °C) for the county of Nordland by the middle of the century (2031–2060 compared to 1971–2000) under a middle (RCP4.5) and high (RCP8.5) representative concentration pathway. Values are given as the 10th, 50th (median) and 90th percentiles (10th p, 50th p, 90th p) of the multi-model COR-BA ensemble.

	RCP4.5			RCP8.5		
	10th p	*50th p*	*90th p*	*10th p*	*50th p*	*90th p*
Winter DJF	1.1	2.2	3.0	2.3	2.7	3.3
Spring MAM	1.3	1.9	3.1	1.8	2.4	3.1

Table 3
As Table 2 for relative precipitation changes (in %).

	RCP4.5			RCP8.5		
	10th p	*50th p*	*90th p*	*10th p*	*50th p*	*90th p*
Winter DJF	−12	1	12	−4	5	14
Spring MAM	−14	0	10	−9	7	11

Table 4
Change in number of precipitation days (rain + sleet + snow) in Vågan for four altitude levels.

Altitude [m asl]	number of data values	RCP4.5 DJF	RCP4.5 MAM	RCP8.5DJF	RCP8.5 MAM
0–300	364	−2	2	−1	2
300–600	142	−7	−2	−6	−2
600–900	19	−11	−7	−12	−7
900–1200	3	−14	−12	−16	−14
Area weighted average		**−1**	**0**	**−1**	**0**

Assuming the high emission scenario RCP8.5, the climate in Lofoten will be approximately 2 °C warmer compared to the reference period 1971–2000 by the middle of the century 2031–2060 (Table 2). However, there will be no change in precipitation frequency (Table 3) but an overall moderate increase (<10 mm) in the mean seasonal precipitation amount (Table 4).

As local practitioners raised the concern of short-term cancellations due to persistent precipitation ('bad weather'), we calculated changes in

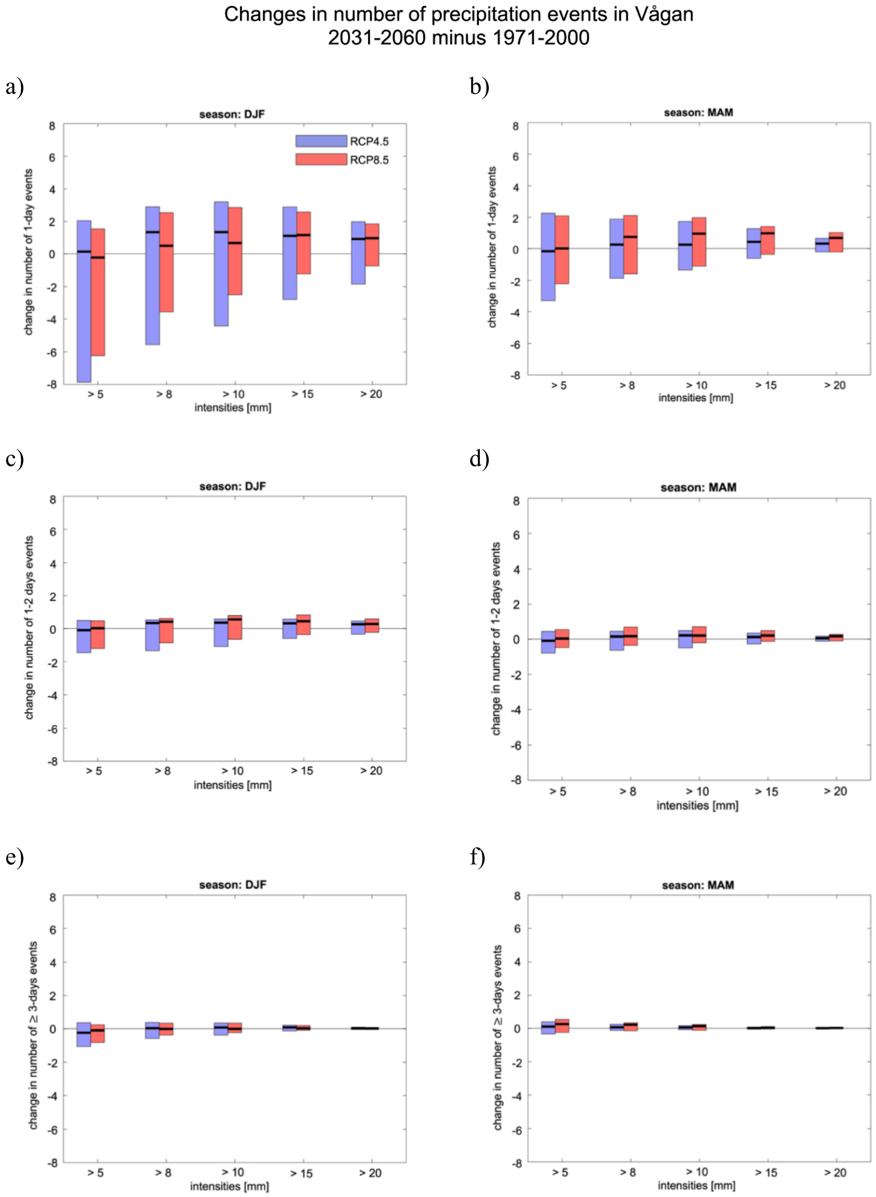

Fig. 3. Changes in the number of precipitation events for the municipality of Vågan depending on intensities (>5, 8, 10, 15, 20 mm) and durations a)-b) 1 day, c)-d) 1–2 days, and e)-f) longer than 3 days by the middle of the century (2031–2060 versus 1971–2000) for RCP4.5 (blue) and RCP8.5 (red). Coloured boxes indicate the range of model uncertainty (10th to 90th percentile). Bold black horizontal lines within the coloured boxes represent the model median (50th percentile). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

precipitation events for different intensities and duration for the municipality of Vågan. Events lasting one day (Fig. 3a)), longer than one day (Fig. 3b)) and longer than 3 days (Fig. 3c)) are shown for intensities ranging between 5 and 20 mm/day. Interestingly, there are marginal to no changes in this climate indicator for events lasting longer than 1 or 3 days. However, for events with a duration of one day (Fig. 3a)), the data displays a small (shown as the model median), but non-robust (models do not agree in the sign of the signal) increase by one day for intensities exceeding 8 mm/day. At the same time, the impact of applying the scenarios RCP4.5 and RCP8.5 is similar, which is not surprising, as emissions in both scenarios are very similar until the middle of this century. The model uncertainty (10th to 90th percentile) is biggest ranging from −8 to + 3 days during wintertime meaning that this signal is not robust as the models do not agree in the sign of the change.

In Fig. 4 and Fig. 5 we partition precipitation into three types consisting of snow, sleet, and rain based on the temperature thresholds described in Section 2 for four altitude levels (0–300 to 900–1200 m asl). The number of rainy days increases by at least one week for both scenarios and seasons (Fig. 4). The increase is strongest with more than 10 days during winter at medium to high altitudes (300–900 m asl). This increase is almost entirely compensated by the decrease in the number of days with snowfall and sleet which leads – in total – to no change in the number of days with precipitation (Table 4). This is an important finding as it highlights a climate change signal which can have a great impact in mountainous regions which would be masked if we would not distinguish between the three precipitation types. More rainy days due to higher temperatures are slightly stronger in the RCP8.5 scenario which is as expected.

The changes in the precipitation amounts are shown in Fig. 5. Here, the rainfall amount increases linearly with altitude and is strongest during winter (Fig. 5a and 5c). As this climate indicator depends on temperature thresholds, the projected changes are more pronounced in the RCP8.5 scenario, e.g., during winter the median climate projection (50th percentile in the model ensemble) shows an increase by 380 mm in

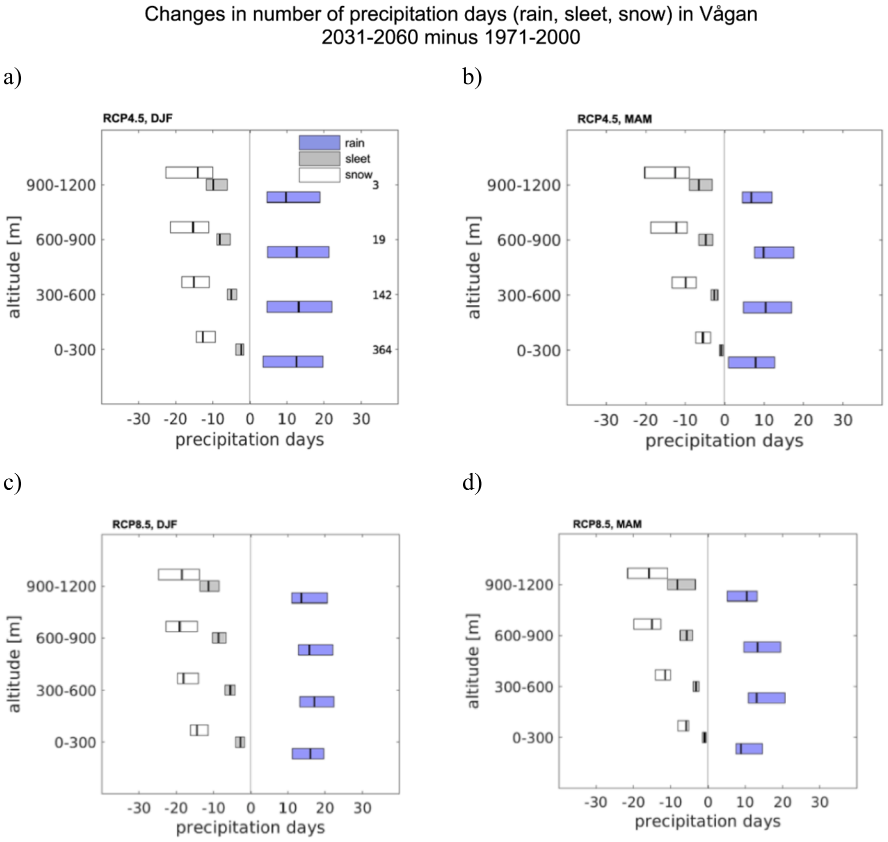

Fig. 4. Projected changes in the number of precipitation days (blue: rain; grey: sleet; white: snow) for the municipality of Vågan at altitudes from 0 to 300 m to 900–1200 m above sea level by the middle of century (2031–2060 versus 1971–2000) for a)-b) RCP4.5 and c)-d) RCP8.5. Model uncertainty is indicated with coloured boxes which span from the 10th to 90th percentiles. The model median is indicated with a black vertical line within the coloured boxes. The number of data values for each altitude level is shown in black on the right side in panel a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

rainfall at 900–1200 m asl (Fig. 5c)).

Overall, the general shift in the precipitation type leads to precipitation falling more frequently as rain instead of snow, i.e., days with snowfall (or sleet) will be often replaced by days with rainfall. Regardless of the scenario, the total number of days with precipitation will not change (Fig. 4 and Table 4), while the precipitation amount will mostly increase at altitudes below 900 m asl (Fig. 5 and Table 5). The model uncertainty, which is indicated as horizontal bars comprising the span between the 10th to the 90th percentile of the model projections, is sometimes larger than the climate signal shown as the model median. This means that the signal-to-noise ratio can be < 0, or in other words, the internal model variability is sometimes larger than the climate change signal as also shown by Willibald et al., 2021. However, the direction of change is robust (all models agree in sign, with one exception at 0–300 in Fig. 5a). This is not surprising since we analyse data from a small number of grid boxes covering the municipality of Vågan. The number of grid boxes are listed in Table 4 (second column) and Fig. 4a) (right y-axis). For example, for values retrieved from altitudes higher than 600 m asl, there are less than 20 data values.

Ski touring and snowshoeing require a snow cover of at least 30 cm. This is a climate indicator that was explicitly mentioned by practitioners (see Table 3 in Antonsen et al., 2022). Thus, we have calculated the number of days fulfilling this criterion (see Section 2). As ski touring and snowshoeing activities are performed in the mountains, we calculated the area average for grid points above 200 m asl. In Fig. 6 the number of ski touring days are shown for the scenarios RCP4.5 and RCP8.5 as seasonal means (winter and spring) for the years 1971 until 2060. As temperature increases and precipitation falls more often as rain instead of snow, we also see a strong decline in the number of days with a snow cover > 30 cm. Under recent climate conditions (1971–2000) and into the first decade of the 21st century the climate projections (model median) show 30 to 50 days with a snow depth > 30 cm during winter and approximately 30 to 70 days during spring. Unfortunately, the observational evidence of the past strong decline is rather poor due to the lack of local snow measurements. But snow measurements at Børnupvatn at 380 m asl (Bodø municipality, Nordland County) indicate that the snow depth has declined since 1995 and that the snow cover is even not persistent anymore during winter since 2002, i.e., there are short episodes when the snow completely melts away (see Fig. 1 in Supplementary Materials). According to the climate model projections for RCP4.5, the number of ski touring days will be reduced by 60–70 % by the 2020–2030s compared to the reference period 1971–2000. By 2050, there will be only 5–10 ski touring days left during spring, and the reduction in ski touring days is even larger for the scenario RCP8.5. However, as SWE is influenced by the bias-adjustment method (Meyer et al., 2019), these results should be interpreted with care. According to Meyer et al., 2019, the univariate quantile mapping method leads to an overestimation of precipitation for temperature above 0 °C which again influences the snow accumulation and melting processes in the hydrological model. This may affect SWE and thus the simulated numbers of ski touring days, as a strong decline is apparent during spring within the first decade of this century (Fig. 6b) and 6d)).

For both scenarios, the near-surface 0 °C-isoline will increase by a few hundred metres. This is exemplified by a time series for April (Easter season) in Fig. 7 which shows an apparent increase from approximately 450 m in the historical period (1971–2000) to 700 m (RCP4.5) and to 800 m (RCP8.5) in the future period (2031–2060). However, year to year variations can be quite large. The change in 30-year median values

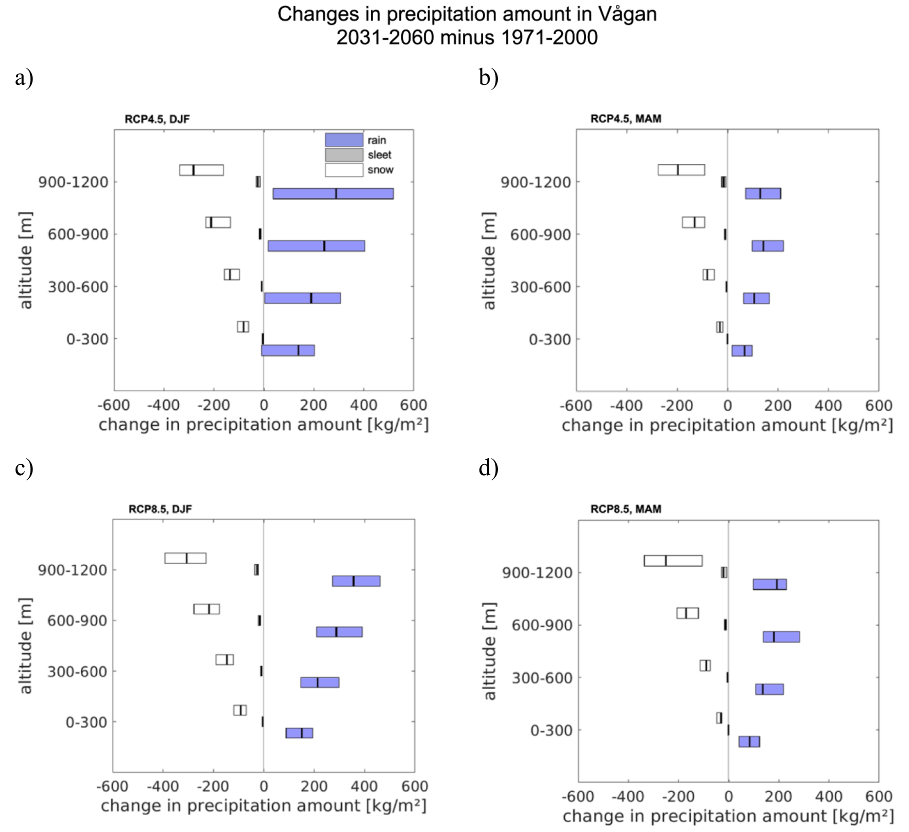

Fig. 5. As Fig. 4 for projected changes in precipitation amount in kg/m^2.

Table 5
Changes in precipitation amount [kg/m^2] (rain + sleet + snow) in Vågan.

Altitude [m asl]	RCP4.5 DJF	RCP4.5 MAM	RCP8.5 DJF	RCP8.5 MAM
0–300	52	35	56	51
300–600	45	20	59	42
600–900	14	0	53	−2
900–1200	−18	−83	24	−79
Area weighted average	**12**	**7**	**14**	**12**

for the future period (2031–2060) are shown in Table 6 for December until May for both scenarios.

4. Conclusions and discussion

In this study, we have investigated how climate change may impact snow-based activities in Lofoten, Norway. The study is motivated by the work of Antonsen et al., 2022 who systematically categorised nature-based activities as so-called ecosystem services depending on indicators quantifying their relationship to meteorological conditions. In Abegg et al., 2021 a thorough revision on snow indicators is given including a conceptual base for the application of indicators. Here, we focus on natural snow-dependent activities as they play a major socio-economic role as pulling factors for tourism in the region during winter and spring.

We used the seNorge gridded observational data set and the bias-adjusted sub-ensemble of Euro-CORDEX projections (COR-BA dataset) which are both high-resolution data sets on a 1x1 km horizontal grid for mainland Norway. Based on these data sets we have calculated climate indicators relevant for snow-based activities in Lofoten to address the question: Will snow conditions still be good enough to attract tourists to the region who want to experience snow-dependent activities in the future?

The partitioning of precipitation into snow, sleet, and rain depending on temperature thresholds for defined altitude levels is not novel (e.g., Frei et al., 2018, Su et al., 2022). However, to our knowledge, it is the first time that it is applied to the COR-BA data for Norway. By doing so, we could identify a general shift in the precipitation regime leading to more precipitation falling as rain instead of snow, i.e., days with snowfall or sleet will be mainly replaced by days with rainfall. This result agrees with the findings in global analysis by e.g., Krasting et al., 2013, Berghuijs et al., 2014, IPCC, 2021, and by Kotlarski et al., 2023 showing a future decrease in snow cover in the European Alps. As the precipitation amount is increasing but not the occurrence of precipitation days, we conclude that when it will be raining it can be raining more intensely. This change is most pronounced for the winter months under the RCP8.5 scenario. Importantly, this can have impacts on safety related issues, e.g., more frequent rain on snow events, more wet snow avalanches by the middle of the century and more intense rainfall triggering landslides that can lead to access disruptions as shown e.g., for Troms by Dyrrdal et al., 2020, and slippery hiking trails. As of today, the COR-BA dataset does not allow for a quantitative assessment of the potential change in snow quality, but it is reasonable to assume that in a warmer climate the snow will be wetter, especially at lower altitudes.

One should be aware of that the simulated SWE is affected by an additional uncertainty introduced by the choice of a univariate bias-adjustment method which impacts the quantitative result of the simulated number of ski touring days. However, we can summarize that the number of ski touring days will become rare by the middle of this century under the RCP4.5 scenario, even earlier under the RCP8.5 scenario. This may display a potential risk of decrease in the general interest in snow-dependent activities in the region and therefor Lofoten may lose its attractiveness for tourists interested in conducting mainly snow-dependent activities.

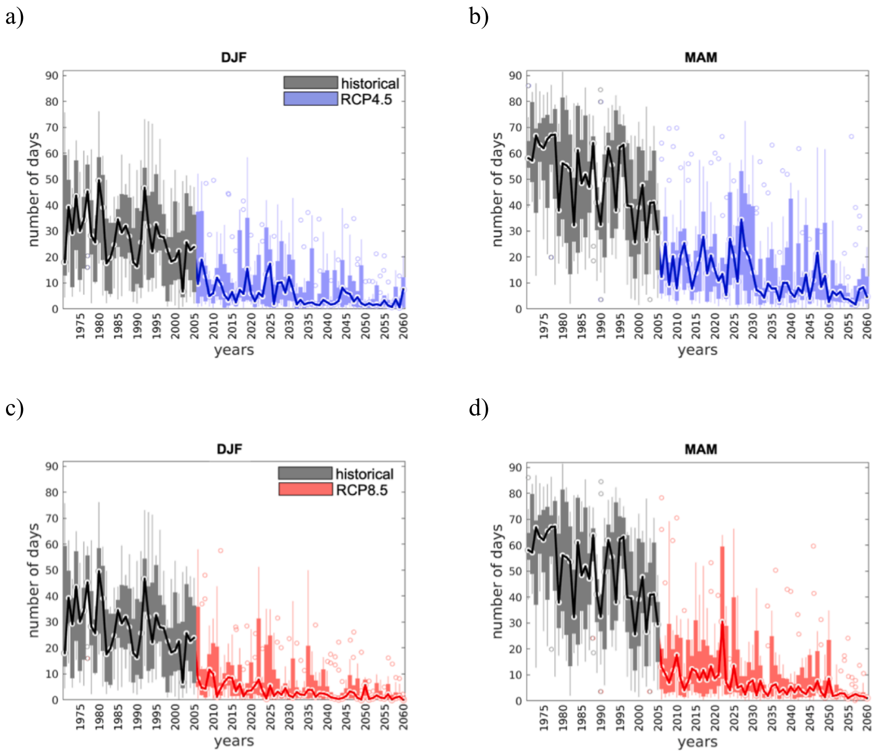

Fig. 6. Simulated number of days with snow depth > 30 cm for areas above 200 m asl for a)-b) RCP4.5 and c)-d) RCP8.5. Bold lines indicate the model median, the bottom and top edges of the bars indicate the model spread between the 25th to 75th percentiles. Thin vertical lines and circles indicate the most extreme values.

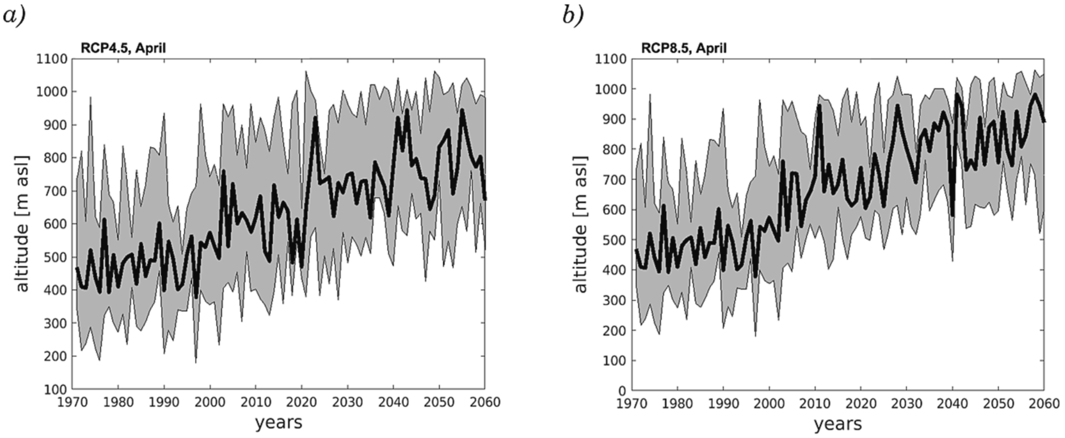

Fig. 7. Time series of the near-surface 0 °C-isoline altitude for April a) RCP4.5 and b) RCP8.5. The grey band indicates the model uncertainty from 10th to 90th percentile. The bold black line indicates the model median (50th percentile).

Table 6
Increase of the near-surface 0 °C-isoline [m] for the period 2031–2060 vs. 1971–2000. Values represent the model median retrieved from the COR-BA data set.

month	RCP4.5	RCP8.5
December	224	358
January	173	213
February	290	356
March	277	410
April	290	360
May	64	65

We find no significant increase in days with (persistent) ‘bad weather’ and thus conclude that short-notice overnight cancellations caused by persistent bad weather will probably not pose the most important risk for the local tourism sector in the future.

The direction of change in the precipitation form (snow, sleet, rain) and snow cover (>30 cm) is robust (all models agree in sign), but the magnitude of change is less certain (large model spread). This is because we analyse a data set consisting of only 528 grid boxes covering Vågan municipality which is a relatively small geographical area. It is important to note that the bias-adjustment of temperature and precipitation were performed independently (Wong et al., 2016), thus the relation between temperature and precipitation in the COR-BA data set may be affected. Recently, Kuya et al. (2023) validated the COR-BA data set for mainland Norway for reference period 1971–2000. While the geographical distribution of rain, sleet and snow was found to be realistically represented, COR-BA overestimates rainfall by 10 % and underestimates snowfall by 12 % on average. Although this can have a quantitative impact on the results, the projected changes may still give qualitatively useful information.

In future work, this issue can be mitigated by, e.g., either applying a multivariate bias-adjustment as shown by Meyer et al., 2019 for alpine catchments or by an adjustment in two steps for rainfall and snowfall separately as described by Verfaillie et al. (2017).

The analysis is extended for the whole country by the Norwegian Centre for Climate Services. Annual maps showing the change in the number of days with a snow depth > 30 cm ski touring days are also made available for Norway.[4] In addition, future changes in precipitation days partitioned in rain, sleet and snow for several altitudes are published on https://klimaservicesenter.no which is maintained by MET Norway. This climate information is based on both scenarios RCP4.5 and RCP8.5.

We are aware that we underestimate model uncertainty by using a sub-sample of (only) ten model combinations (GCM/RCM pairs). As of today, there is data from more Euro-CORDEX simulations available, however, these data are neither bias-adjusted for Norway nor downscaled on a 1x1 km grid, yet. Having local-scale data available on such a high-resolution grid is essential when calculating climate indicators relevant to a specific sector (e.g., tourism). Currently, the NCCS is working on extending the data set for RCP4.5 and RCP2.6, and the socio-economic pathway SSP3-7.0 as soon as new Euro-CORDEX data become available. Additionally, the influence of two different bias-adjustment methods is tested.

Finally, we emphasise that a systematic dialogue (e.g., facilitated by social scientists as in Antonsen et al., 2022) with practitioners from the tourism sector was crucial to develop sector-relevant climate indicators. As a result, this work has led to a further extension of the climate indicators available as maps on the NCCS' website. However, it is a fine balance of what kind of practitioners' expectations and wishes can be met by climate model outputs given that climate projections are bound to certain representative concentration pathways, computational resources, model data availability, horizontal and temporal resolution, and output variable availability and quality.

CRediT authorship contribution statement

Stephanie Mayer: Conceptualization, Writing – original draft, Methodology, Formal analysis, Visualization, Funding acquisition, Writing – review & editing. **Elinah Khasandi Kuya:** Methodology, Formal analysis, Visualization, Writing – review & editing. **Karin Antonsen:** Conceptualization, Writing – review & editing. **Bruno Abegg:** Conceptualization, Writing – review & editing, Supervision. **Inger Hanssen-Bauer:** Conceptualization, Methodology, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cliser.2023.100405.

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