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Observed and Predicted Trends in Icelandic Snow Conditions for the period 1930-2100

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Abstract. This study presents an estimate of historical snow conditions in Iceland and a projection of these conditions, given different emission scenarios. Historical snow conditions were estimated using in situ observations from manned meteorological stations over the period 1930-2021 and by remote sensing observations from the MODIS instruments over the period 2001-2021. Historical and future climate conditions, as described by each of the 21 Global Circulation Models (GCM's) from the 5th iteration of the Coupled Model Intercomparison Project (CMIP5) as contained in the NASA Earth Exchange (NEX) Global Daily Downscaled Projections (GDDP) dataset, were used to simulate snow conditions in Iceland over the period 1950-2100 under the Representative Concentration Pathways (RCP) RCP45 and RCP85 with the Snow17 model. The results show an increase in the average annual Snow Cover Frequency (SCF) over the historical record detected both in the in-situ (1930-2021) and remotely sensed data (2001-2021). Average annual snow depth measurements also revealed an increasing trend over the historical record. Simulated snow conditions show a substantial decrease in both Snow Water Equivalent (SWE) and SCF over the period 1950-2100, a trend more pronounced under RCP85 as compared to RCP45.

1. Introduction

Icelandic climate is categorized as maritime, with mild winters, cold summers, strong winds, frequent precipitation and large spatio-temporal variations in weather and climate (Bjornsson et al., 2007; Ólafsson et al., 2007). It is significantly influenced by ocean conditions in the Northern Atlantic (e.g. Massé et al., 2008) and mass balance trends of Icelandic glaciers correlate to changes in large-scale ocean circulations (Eythorsson, 2018). Since the last glacial maximum the average annual air temperature in Iceland has increased about 4°C (Geirsdóttir et al., 2013; Knudsen et al., 2008; Langdon et al., 2011; Larsen et al., 2011; Sicre et al., 2011). The average air temperature in Iceland has risen by 0.8°C/century since the 1850's, comparable to the global average, and by 5.0 °C/century over the period 1980-2016 (Bjornsson et al., 2018). Since 1890 the Icelandic glaciers have lost about 16% of their mass and 18% of their surface area, contributing about 1.5 mm of global sea level rise (Aðalgeirsdóttir et al., 2020; Bjornsson et al., 2013) and are expected to lose most of their remaining mass over the next two centuries at current pace (Adalgeirsdottir et al., 2006; Bjornsson & Palsson, 2008; Jóhannesson et al., 2004; Schmidt et al., 2020). Runoff in Iceland is generally expected to increase in winter as less water is stored in snowpack and runoff from glaciers

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is expected to increase until at least mid-21st century (Blöschl et al., 2017; Jónsdóttir, 2008), the rate of which is expected to vary depending on ocean conditions in the North Atlantic, where recent cooling has led to a slowdown in mass loss of Icelandic glaciers (Noël et al., 2021). Spring melt is generally predicted to begin earlier and autumn snow cover to occur later (Johannesson et al., 2007). Analysis of a recently developed gap filled MODIS snow cover product suggests that the duration of snow cover has increased during the period 2000-2018 for all months expect October and November (Gunnarsson et al., 2019).

Snow cover monitoring by satellite remote sensing has been studied since the 1960s and several global snow cover products have been produced based on these observations. (Dong, 2018; Frei et al., 2012; Robinson et al., 1993). Among the best satellite derived snow products are from the MODIS instruments on the Terra and Aqua satellites (Dietz et al., 2012). An imporant variable for snow remote sensing is the Snow Cover Frequency (SCF), the number of days with snow cover divided by the number of valid observations per year (e.g. Nolin et al., 2021) and is related to e.g. growing season length and habitability (e.g. Callaghan et al., 2011). SCF is a key parameter in the earths energy balance (Cohen, 1994) and can be used to analyze the impacts of climate change on the cryosphere (Brown & Mote, 2009). The prediction of future snow conditions requires the simulation of snow processes based on some or all of the meteorologial forcings thatasc affect the accumulation and energy balance of the snowpack. Many such models have been developed and described in the literature (e.g. Krinner et al., 2018; Magnusson et al., 2015). The Snow17 model was developed for the US national Water Service where it has been used for operational snow forecasting for the past several decades (Anderson, 2006). The Snow17 model has been applied to several regional climate change studies (Miller et al., 2011; Notaro et al., 2014) and has shown good correlation to MODIS Snow Covered Area (SCA) observations (Franz & Karsten, 2013). A key advantage of the Snow17 model is computational efficiency compared to full energy balance models.

The objective of this study was to analyze observed trends and predict the development of snow conditions in Iceland under different plausible climate scenarios and it presents an analysis of historical and future trends in Icelandic climate and snow conditions. Improved understanding of how local snow resources are likely to respond to changing climate conditions is important as these changes are expected to impact local communities and ecosystems as well as changing the challenges and opportunities for exploiting natural resources in cold areas (Eliasson et al., 2017). In this study changes to historical snow cover properties were estimated based on both in-situ and remote sensing observations. Future snow conditions were projected by modelling based on a globally downscaled and bias corrected ensemble of Global Circulation Models (GCM) from the 5th iteration of the Coupled Model Intercomparison Project (CMIP5).

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2. Methods

2.1 Tools and Datasets

2.1.1 Climate Data

The NASA Earth Exchange (NEX) Global Daily Downscaled Projections (GDDP) dataset (Thrasher et al., 2012; Thrasher et al., 2006) was used as an estimate of historical and future climate. The dataset contains global minimum and maximum near surface air temperatures and surface precipitation rates, as estimated by 21 globally downscaled and bias-corrected CMIP5 GCM's, in 0.2-degree horizontal resolution for the period 1950-2100. Daily average temperature was calculated as the mean of daily minimum and maximum temperatures and the ensemble mean was used to represent future climate.

2.1.2 Remote Sensing and Geospatial Data

The MOD10A1.006 and MYD10A1.006 daily snow cover products from the MODIS instruments on NASA's Aqua and Terra satellites (Hall et al., 2016) were used to estimate spatial changes in snow cover over the period of the 2001-2021 water years. The 'NDSI_Snow_Cover' band was used to estimate the presence of snow in each pixel. The band values are given in a range of 0-100% where a value of NDSI_Snow_Cover > 0 indicates the presence of some snow in the pixel and a value of 100 that the pixel is fully snow covered. The 'NDSI_Snow_Cover_Basic_QA' band was used to select observations by quality estimate. A 10 x 10m DEM was used for topographical information (National Land Survey of Iceland, 2016). Glacier outlines for the year 2019 obtained from the Randolph Glacier Inventory, version 6 (RGI Consortium, 2019).

2.1.3 In Situ Snow Observations

Data on in situ snow measurements at manned monitoring stations were acquired from the Icelandic Meteorological Office (IMO) (Icelandic Meterologocial Office, 2021). The data contains all observations and manual measurements of local snow depth (*SND)*, Snow Cover (*SNC*), precipitation (*R*), precipitation class (*RTEG*), and a visual estimate of surrounding mountain snow cover (*SNCM*) for total 266 manned observation stations that have recorded snow data in the period 1930-2021. The number of stations reporting snow data is below 10 until 1950 and rapidly increases thereafter. Figure 1 shows the locations of the monitoring stations that have recorded *SNC* continuously for at least 20 years.
SND is recorded for all days with snow cover, in cm. SNC and SNCM are classified by visual observation as: 0 = no snow, 2 = patchy snow cover, 4 = fully covered ground. (Icelandic Meterologocial Office, 2008).

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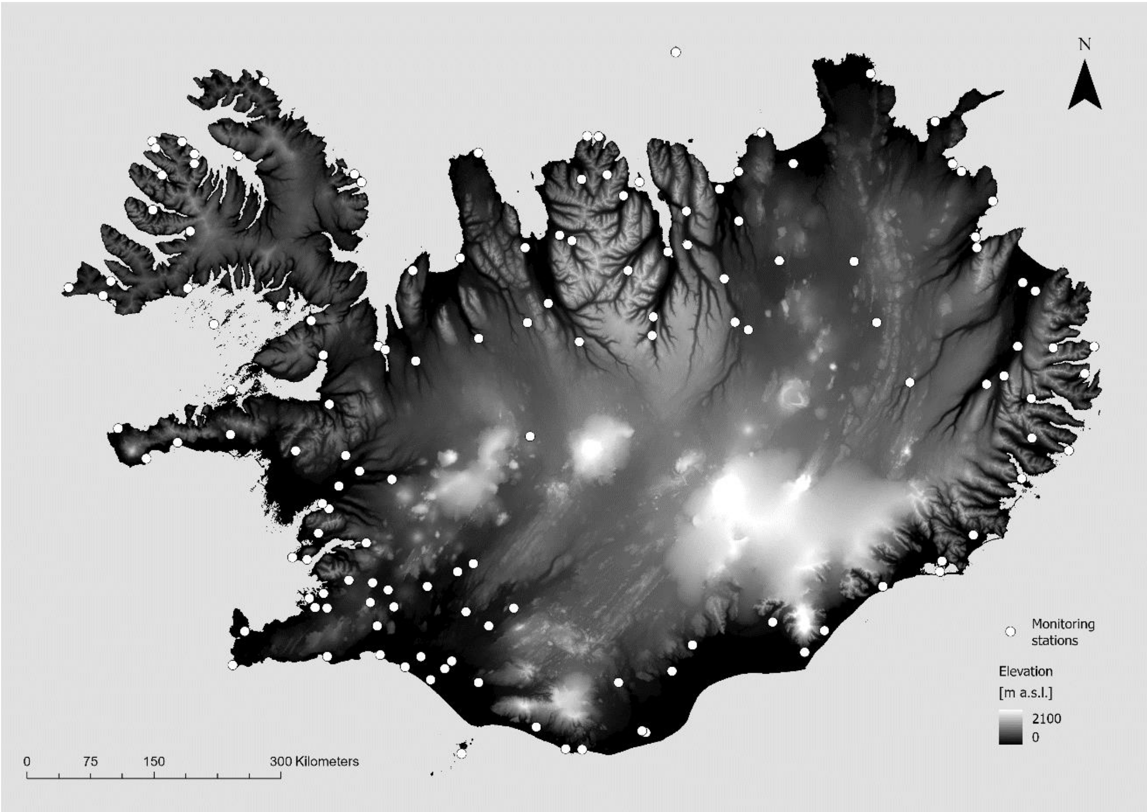

Figure 1 Topography of Iceland *(National Land Survey of Iceland, 2016)* and the location of IMO monitoring stations where snow has been measured continuously for at least 20 years in the period 1930-2021 *(Icelandic Meterologocial Office, 2021)*.

2.2 Data Processing

2.2.1 In Situ Observations

The 1st of April *SND* was calculated for all stations with more than 20 years of continuous snow depth measurements within the period 1930-2021 (n = 89). The annual Snow Cover Frequency (*SCF*) was calculated for all stations with more than 20 years of continuous snow cover observations within the period 1930-2021 (n = 93). *SCF* was calculated as number of days with snow covered ground divided by the number of days in the year, for both only fully snow-covered ground (*SNC or SNCM* = 4) and also including patchy snow cover (*SNC or SNCM* > 2). SCF was calculated both for observations on the immediate surroundings of the observation site (*SFC)* and on surrounding mountains (*SFCM).*

2.2.2 Remote Sensing Observations

Binary snow cover classification was derived from the MOD10A1.006 and MYD10A1.006 snow cover products (Hall et al., 2016). Data from the 'NDSI_Snow_Cover' band was selected for observations with the highest quality estimate ('NDSI_Snow_Cover_Basic_QA' = 0). The daily mean of 'NDSI_Snow_Cover' band was calculated from both snow cover

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products. Pixels with 'NDSI_Snow_Cover' > 0 were classified as snow cover (1), and other as no snow (0). The average annual SCF was calculated by counting the number of snow-covered days and dividing by the number of days with valid observations in each pixel, per hydrological year. SCF was calculated based on the highest quality observations, thus excluding lower quality observations as well as missing data due to cloud cover and polar night, which limits the capability of the MODIS instruments to observe the land surface in Iceland from the end of November to the end of January.

2.2.3 Snow Modelling

Seasonal snowpack in Iceland was simulated using the Snow17 model forced with daily average precipitation and temperature data from NASA NEX GDDP dataset for all hydrological years (October to September) in the period 1950-2100. Code was developed in Google Earth Engine (GEE) for the Snow17 model algorithm described in Anderson (2006). The model was applied to all 21 GCM's in the dataset and was initialized at the start of each year in the study period.

Snow17 uses 10 model parameters which were determined in a distributed grid across Iceland based on local topology, ecology and hydrology, following the methods presented by Anderson (2006) and Mizukami & Koren (2008). Table 1 summarizes the Snow17 model parameters, their description, the values used in this study and the source methodology for each parameter.

Table 1 Snow17 model parameters, description, value ranges and estimation source methods (from Eythorsson et al. 2021)

Parameter	Description	Range	Units	Methodology
GCF	Gauge under-catch factor	1.0	-	Andersson, (2006)
MFMAX	Maximum Melt Factor	0.7 – 2.4	mm/°C*6h	Mizukami & Koren, (2008)
MFMIN	Minimum Melt Factor	0.001 – 1.5	mm/°C*6h	Mizukami & Koren, (2008)
UADJ	Average wind during rain on snow	0.02 – 0.4	mm/mb	Andersson, (2006)
PXTEMP	Temperature determining rain/snow	-1 – 3	°C	Andersson, (2006)
MBASE	Base temp. where melt occurs	0	°C	Andersson, (2006)
NMF	Maximum negative melt factor	0.05 – 0.3	mm/°C*6h	Andersson, (2002)
TIPM	Antecedent temperature index	0.05 – 0.2	-	Andersson, (2002)
PLWHC	Liquid water holding capacity	0.02 – 0.3	%	Andersson, (2002)
DAYGM	Constant basal melt rate	0 – 0.3	mm/day	Andersson, (2006)

The annual SCF and the 1st of April SWE were calculated for each of the models in the ensemble. A pixel was estimated to be snow covered on a particular day if SWE > 0.

2.2.3 Data Analysis

The statistical significance of trend in calculated time series was estimated using the Mann-Kendall trend test and the significance of trends in distributed observations was estimated using Sens's estimator of slope method. Both of these tests are often used to assess the significance of the trends in hydro-meteorological time series (e.g. Drapela & Drapelova, 2011; Gocic & Trajkovic, 2013). The null hypothesis was that there is no monotonic trend present in the data, while the alternative hypothesis is that the data has a monotonic trend. Google Earth Engine (GEE) (Gorelick et al., 2016) was used to access data

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and for spatial analysis. Statistical analysis was performed using GEE and the SciPy toolbox (Oliphant, 2007). ArcMap 10.7.1 was used to produce maps showing the results.

3. Results

3.1 Historical Snow Cover Trends

Figure 2a shows the average temperature and precipitation in Iceland over the period 1950-2021 as estimated from the ensemble average of the GDDP dataset. Figure 2b shows the annual average SCF for all IMO monitoring stations for the period 1930-2021, calculated for local (circles) and mountain (triangles) snow cover based both on just observations of fully snow-covered ground (SNC or SNCM = 4) and including patchy snow cover (SNC or SNCM ≥ 2), the in-situ data is shown with a 10-year rolling average and a linear trendline. The figure shows the average annual SCF estimated from the MODIS Terra/Aqua snow cover products (black markers) for observations above (stars) and below (crosses) 500 m a.s.l. Figure 2c shows the average annual snow depth (*SND*) of all IMO monitoring stations for the period 1930-2021.

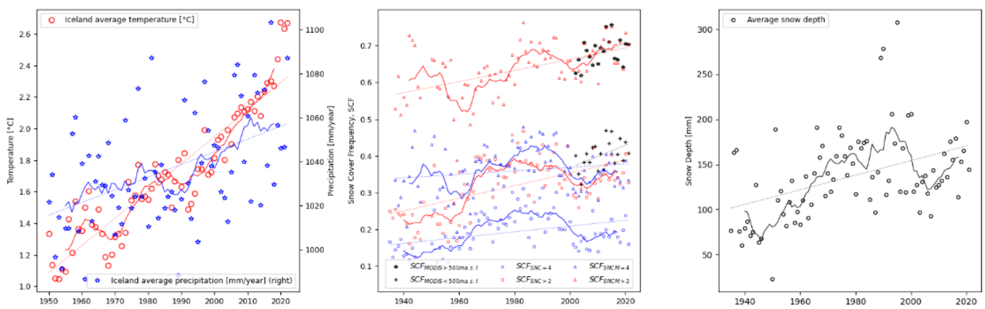

Figure 2 Left panel (Fig. 2a): Average annual temperature and precipitation in Iceland over the period 1950-2021 as estimated by the ensemble average of the 21 GCM's in the NASA NEX-GDDP dataset. Center panel (Fig. 2b): Annual average SCF for all IMO monitoring stations for the period 1930-2021, calculated for local (circles) and mountain (triangles) snow cover for observations of fully snow-covered ground, SNC or SNCM = 4 (blue) and including patchy snow cover, SNC or SNCM ≥ 2 (red), the average annual SCF estimated from the MODIS Terra/Aqua snow cover products (black markers) is shown for observations above (stars) and below (crosses) 500 m a.s.l. Right panel (Fig. 2c): average annual snow depth of all IMO monitoring stations. The in-situ data is shown with both a 10-year rolling average and a linear trendline.

The results in Figure 2 show that on average both *SND* and SCF in Iceland have trended upwards over the period 1930-2021. The trend is more apparent when considering both fully and patchy snow cover, (SNC or SNCM> 2) and the data reveal considerable natural climate variability. The MODIS estimates of SCF below and above 500 m a.s.l. are comparable to the in-situ estimates of local and mountain SCF, respectively. The trendline over the MODIS period 2001-2021 is positive for all SCF estimates. The results show that over the period 1950-2021 both average temperature and precipitation have trended upwards. This increase in precipitation could have resulted in more snow accumulation which would have offset the increased melt rates associated with temperature rise, especially at lower elevations, leading to a thicker snowpack overall.

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Table 2 shows the statistical significance of the linear SCF trendline, estimated using the Mann-Kendall trend test, for both the period of historical records (1930-2021) and the MODIS period (2001-2021), of p values. Statistically significant trendlines at the α = 0.05 level are shown in bold.

Table 2 Statistical significance of the linear SCF trendlines, estimated using the Mann-Kendall (MK) trend test, for both the period of historical records (1930-2021) and the MODIS period (2001-2021), of p values Statistically significant trendlines at the α = 0.05 level shown in bold.

	Trend [% per year]		p-value	
	1930-2021	**2001-2021**	**1930-2021**	**2001-2021**
SCFM (SNCM > 2)	**0.15**	**0.43**	**$1.2 * 10^{-6}$**	**0.02**
SCFM (SNCM = 4)	0.038	0.21	0.2	0.07
SCF (SNC > 2)	**0.15**	**0.37**	**$1.8 * 10^{-6}$**	**0.01**
SCF (SNC = 4)	**0.076**	0.19	**$0.7 * 10^{-3}$**	0.06
SND	**0.081**	**0.30**	**$1.54 * 10^{-5}$**	**0.002**
MODIS below 500 m a.s.l.	-	**0.29**	-	**0.04**
MODIS above 500 m a.s.l.	-	0.24	-	0.11
MODIS all elevations	-	**0.26**	-	**0.04**

The results in Table 2 show that the increasing SCF and *SND* trend observed in Figure 2 is statistically significant over the period 1930-2021 for all SCF estimates except for observations of SNCM = 4, fully snow-covered mountains. Over the MODIS period 2001-2021 the trend is significant for all metrics except for observations of fully snow-covered mountains and for MODIS observations above 500 m a.s.l.

Figure 3a shows the trend in annual SCF over Iceland as estimated from MODIS observations Figure 3b shows areas where the trendline is statistically significant (α = 0.05) for both MODIS and in situ observations (SNC = 4). Blue regions and markers show areas where the SCF had increased significantly, and the red areas with decreasing SCF.

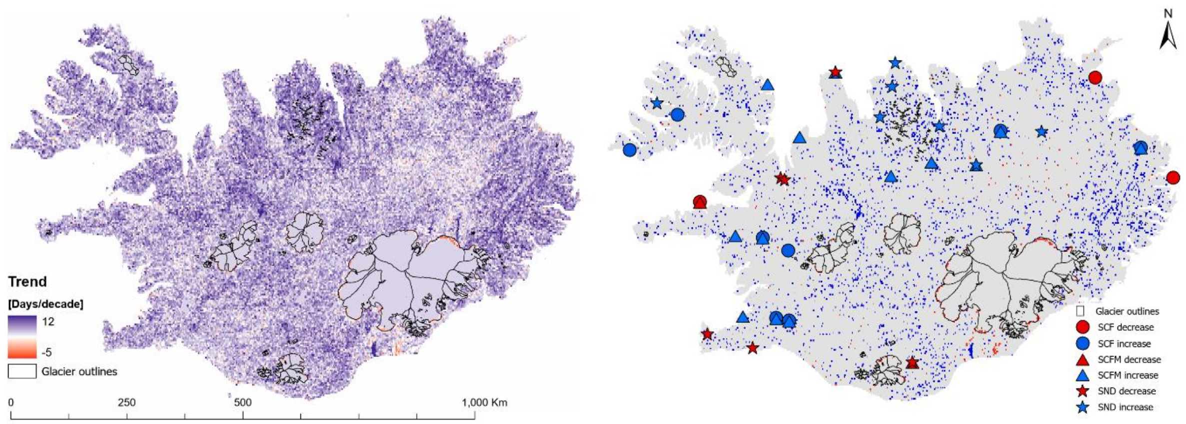

Figure 3 Left panel (Fig 3a): trend in annual SCF over Iceland as estimated from MODIS. Right panel (Fig 3b): areas where the trendline is statistically significant (α = 0.05) for both MODIS and in situ observations (SNC = 4). 2019 outlines of glaciers and the ice divides of their major outlet glaciers are shown with black lines *(RGI Consortium, 2019)*.

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The results presented in Figure 3 show that many areas in Iceland have experienced a significant change in the local SCF, both as estimated from MODIS data and from manned snow cover observations over the period 2001-2021. Most of these areas have experienced an increase in SCF, especially the eastern highlands and the mountainous regions of Northern and Northwestern Iceland. A few areas showed significant decreases in the SCF and most of those were located at the termini of the country's major outlet glaciers, whose retreat has been well documented (Aðalgeirsdóttir et al., 2020; Hannesdóttir et al., 2019; Hauser & Schmitt, 2021) or in coastal areas. All manned observations sites where a decrease in SCF or *SND* had occurred over the period were all located at low elevation in coastal areas except for one.

3.2 Projected Seasonal Snow Conditions

Daily snow conditions in Iceland were simulated in 0.2-degree resolution for the period 1950-2100 for both Representative Concentration Pathways (RCP) RCP45 and RCP85 emission scenarios using the Snow17 model for each of the 21 GCMs in the NASA NEX-GDDP ensemble. Figure 4a shows the simulated average winter SWE across Iceland for both RCP45 (green) and RCP85 (red). Figure 4b shows the simulated average annual SCF across for RCP45 (green) and RCP85 (red). Observations from monitoring stations of mountain (crosses) and local (stars) snow cover and MODIS observations (triangles) are shown in black. The shaded area represents the upper and lower quantiles of the ensemble simulations, and the solid line represents a 10-year moving average of the ensemble

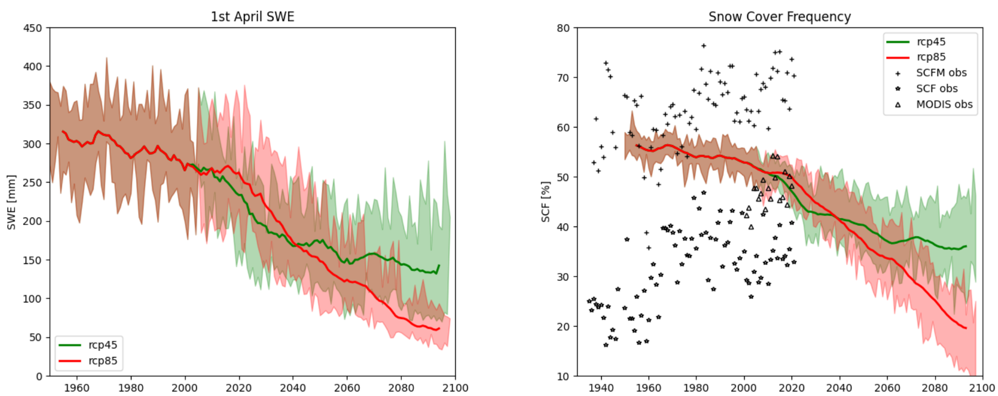

Figure 4 Left panel (Fig. 4a): simulated average winter SWE across Iceland for both RCP45 (green) and RCP85 (red). Right panel (Fig. 4b): simulated average annual SCF across Iceland as projected by RCP45 (green) and RCP85 (red). Observations from monitoring stations of mountain (crosses) and local (stars) snow cover and MODIS observations (triangles) are shown in black. The shaded area represents the upper and lower quantiles of the ensemble simulations, and the solid line shows a 10-year moving average of the ensemble.

Figure 4 shows that both SWE and SCF are expected to decrease in Iceland over the course of the 21st century. The decrease is more severe given the RCP85 emission scenario as compared to RCP45. The simulated estimates of average annual SCF fig shown in Fig. 4b are in line with MODIS observations over the period 2001-2021. In situ observations of local and mountain snow cover (SNC or SNCM > 2) fall below and above the simulated averages, respectively, as expected. The simulated SWE estimates show a decrease in SWE over the period 1950-2100 a trend which grows faster after the 2020s, whereas the observed snow depth measurements (shown in Figure 2) show a significant increase ($p = 1.54 * 10^{-5}$) over the period 1930-2021. The results presented in Figures 2 and 5 reveal an increasing trend in SCF and *SND* over a period where both of these metrics are projected to trend downward. The results also illustrate the substantial natural climate variability in Icelandic snow conditions. The results in Figure 2 show a positive trend for temperature and precipitation in Iceland over the period 1950-2021. Increasing temperatures result in enhanced snow melt, which is apparent in a flat or decreasing SCF in coastal regions (shown in Figure 3), whereas at higher elevation the increased precipitation enhances winter snow accumulation leading to higher SCF despite the enhanced melt rates during summer. With further climate change less precipitation will fall as snow at higher elevations and both *SND* and SCF are expected to have decrease across the country by the end of the 21st century, as illustrated in Figure 4.

4. Discussion and Conclusion

The analysis of snow observations showed a significant increase in snow cover, both as estimated from in situ observations over the period 1930-2021 and from observations from the MODIS instruments on NASA's Terra and Aqua satellites. The MODIS observations were comparable with in-situ observations of both local and mountain snow cover. The results also revealed a large natural variability in snow conditions, which was expected due to the sensitivity of the Icelandic climate to fluctuations in large scale atmospheric and ocean circulations in the north Atlantic region (e.g. Hanna et al., 2004; Massé et al., 2008). The results showed a significant increase in average annual snow depth over all stations for the period 1930-2021. Simulated Snow Cover Frequency, SCF, was comparable with SCF estimates from both MODIS and in situ observations for the historical period. The simulations show that SCF is expected to decrease significantly over the projected period, 2006-2100 especially below 500 m a.s.l. where snow cover is expected to become a rare occurrence by the end of the period, given the RCP85 emission scenario. The simulated Snow Water Equivalent, SWE, is higher than the in-situ measured snow depth over the historical period, which may be due to due to blowing wind or an effect of a large model grid and IMO stations disproportionately being located at lower elevations which receive less precipitation than the country average. The simulated SWE shows a significant decrease in SWE over the period where the average amount of stored water in snow over the winter is expected to decrease by about half or 3/4 under the RCP45 and RCP85 emission scenarios, respectively.

The results of this study suggest that the increase in snow cover in Iceland, observed both from remotely sensed and in situ data, is associated with increased precipitation causing a more frequent and thicker snowpack which persist longer, despite enhanced melt rates. This is consistent with Bjornsson et al. (2018) who found annual precipitation to have increased by about 10% during the period 1980-2015. This increasing trend was also observed by Gunnarsson et al. (2019) which used multi-source satellite remote sensing data to show that there had been an increase in snow cover in Iceland for all months except

October and November over the period (2000-2017). The simulated snow conditions are also in agreement with previous predictions which forecast a decrease in snow cover and snow mass in across a Iceland, as rising average temperature causes spring melts to begin earlier and autumn snow cover to occur later (e.g. Johannesson et al., 2007).

The results presented in this study deserve further investigation. Observations of snow conditions reveal a large natural variability which may be affected by large scale circulations in atmospheric and ocean circulations in the northern Atlantic as well as global temperature changes. The observations of both snow cover and snow depth indicate an increasing trend in these parameters over the historical period whereas simulated snow conditions predict a decrease in both over the course of the present century, the extent of which is dependent on future GHG emissions. The observed increases in SCF and SWE could be part of natural climate variability induced by low frequency cyclical climate patterns, or by a small amount of extreme weather events. The causes and the impacts of these changes to Icelandic ecology and society should be better understood as future changes to snow conditions will impact the hydrological cycle, which will further affect the local ecology, hazard assessments, water resources management, and hydropower production in the country.

5. Author Contribution

DE and SMG designed the experiments. DE developed the code and performed the analysis and prepared the manuscript. DE and AG gathered, assessed, and prepared the data. SMG, AG and OGBS reviewed the manuscripts provided significant consultation and contributions throughout the work.

6. Competing Interests

The authors declare that they have no competing interests.

7. Code/Data Availability

All data used for the analysis in this study are freely available. The code for the snow model and/or the remote sensing analysis can be made available upon request.

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