https://doi.org/10.5194/hess-2019-564
Preprint. Discussion started: 19 November 2019

Hydrology and Earth System Sciences
Open Access
Discussions

Climate change and snow cover trends in Iceland

Darri Eythorsson[a], Sigurdur M. Gardarsson[a], Shahryar K. Ahmad[b] and Oli Gretar Blondal Sveinsson[c]

[a] Faculty of Civil and Environmental Engineering, University of Iceland
[b] Faculty of Civil and Environmental Engineering, University of Washington
[c] Research and Development Division, Landsvirkjun

Abstract

We studied the trends in climate change and snow cover in Iceland. Climate was classified based on the Köppen-Geiger (KG) classification system for 1950-2100 using the ensemble average of + NASA-NEX downscaled CMIP5 projections for RCP 4.5. Snow Cover Frequency (SCF) was calculated based on in MODIS10A1 snow product in days/year and SCF trends were calculated for 2001-2016. Trends in climate and snow cover changes were evaluated in 4 different elevation bands: Coastline (0-100 m.a.s.l.), Lowland (100-500 m.a.s.l.), Highland (500-1000 m.a.s.l.) and Mountains/Glaciers (1000+ m.a.s.l.). The results showed that in all elevations zones warmer climate classes have been replacing colder climates and polar tundra since 1950's, based on climate projections we expect these trends to continue throughout the present century. We observed that in large areas of the country a significant increase in SCF had occurred during the period 2001-2016. These changes were most pronounced in the highlands where SCF had increased by 3.5 days/year on average. The only locations where we observed decreasing SCF was around the termini of the country's outlet glaciers. The results suggest that by the end of the present century polar tundra climate (ET) will have decreased from 20% to 5% coverage and cold climate with warm summers (Dfb), will extend around the island and spread into the highlands.

https://doi.org/10.5194/hess-2019-564
Preprint. Discussion started: 19 November 2019

Hydrology and Earth System Sciences
Open Access
EGU
Discussions

1 Introduction

We studied recent climate change in Iceland and compared these changes to changes in snow cover in the country. Past and predicted future climate characteristics were assessed according to the Köppen-Geiger (KG) classification method using Global Circulation Model (GCM) projections. The climate trends were combined with MODIS satellite observations of snow cover to investigate the impact of climate change on snow cover in Iceland. Understanding the past and future impacts of climate change on snow resources is essential for water management in cold regions, not least in Iceland. The specific research questions were: Has the Icelandic climate been undergoing recent changes, and if so, have these changes coincided with changes in local snow resources? Furthermore, what changes can be expected to these regimes in the future?

Icelandic climate is highly controlled by the sea conditions in the surrounding North Atlantic ocean (e.g. Massé et al., 2008) and seasonal mass balance trends of Icelandic glaciers have been shown to correlate with large-scale oceanic circulations in the North Atlantic (e.g. Eythorsson, 2018). Air temperatures in Iceland have been increasing over all long-term records. However, a marked cooling trend was observed between the 1940-1980, this cooling trend has been ascribed to changes in large scale atmospheric circulation (Hanna et al., 2004). Since 1980 air temperatures in Iceland have increased on average by 0.5 °C per decade and annual precipitation has increased by 200-300 mm/year (Bjornsson et al., 2018). As a result of this warming, Icelandic glaciers have been retreating in recent decades, and are expected to mostly disappear completely over the next two centuries if current climate trends persist (Adalgeirsdottir et al., 2006; Helgi Bjornsson & Palsson, 2008; Jóhannesson et al., 2004). Since the end of the 19th century glacial melt in Iceland has been estimated to have contributed about 3 mm to global sea level rise (Bjornsson et al., 2013). The observed climate trends have been predicted to impact local snow resources with spring thaws beginning earlier and autumn snow cover to occur later (Johannesson et al., 2007), however new research has suggested that the duration of snow cover has increased during the period 2000-2018 (Gunnarsson et al., 2019).

Future climate conditions can be estimated using GCM projections (Stocker et al., 2013). To represent future climate we used the ensemble average of the 21 GCM projections in the CMIP5 collection for the Representative Concentration Pathway (rcp) 4.5 (Taylor et al., 2012). GCM results have been used to quantify climate change by classifying regional climate and analyzing changes in classifications over time (Chen & Chen, 2013). We used the Köppen-Geiger classification system (Köppen, 1918) which has often been used to study climate change (e.g. Engelbrecht & Engelbrecht, 2016; Rube et al., 2017) and to validate GCM results (Lohmann et al., 1993).

When estimating the availability of snow resources from remote sensing an important indicator is Snow Cover Frequency (SCF), the number of snow-covered days per year. SCF has been related to growing season length and species habitability (e.g. Callaghan et al., 2011) and is an important parameter in surface energy balance (Cohen, 1994). SCF is an important variable to include in geophysical simulations, like hydrological modelling in cold regions (e.g. Guan et al., 2013; Nahaet al., 2016). Historical changes in the SCF have been used to assess the progression and impacts of climate change on the snow regime (Brown & Mote, 2009). Remote sensing by satellite sensors is a commonly applied way of measuring snow cover (Frei et al., 2003). The launch of the MODIS instruments on board the TERRA and AQUA satellites has improved snow cover information for hydrological model validation (Dietz et al., 2012). Improved understanding and modelling of future changes in snow conditions in cold areas is important, as these are changes that are expected to impact local communities and ecosystems as well as changing the challenges and opportunities for exploiting natural resources in the region (Eliasson et al., 2017).

Our hypothesis in this study is that recent warming in Iceland has resulted in decreasing snow cover. We expected the trend to be most apparent at lower altitudes around the coastline but also persistent at higher altitudes. Our results, however, showed that the SCF had increased across the entire country. We observed that the frequency of snow-covered ground has increased and the increase is more prominent at high elevation than at lower elevated areas. The only locations where

https://doi.org/10.5194/hess-2019-564
Preprint. Discussion started: 19 November 2019

Hydrology and Earth System Sciences
Discussions

we consistently observed a significant decreasing SCF trend was at the terminus of the country's glaciers.

2 Methods

2.1 Tools and Datasets

Google Earth Engine (GEE) (Gorelick et al., 2016) was used to access data and for spatial analysis. Statistical analysis was performed using GEE and the SciPy toolbox (Oliphant, 2007). ArcGis 10.6.1 was used to produce maps showing the results. The MODIS10A1 MODIS/TERRA daily snow cover product (Hall et al. 2006) was used to estimate changes in snow cover. The NASA NEX GDDP dataset (Thrasher et al., 2006) was used to estimate historical and predict future climate conditions. For calculations involving elevation a 20x20m DEM from the National Land Survey of Iceland was used.

2.2 Elevation Zones

Icelandic climate and ecology vary significantly depending on elevation. Lower elevations are characterized by milder climates and denser vegetation, whereas the central highlands experience much harsher climate and are very sparsely vegetated, the highest elevations are glacierized. We analyzed the climate and snow regimes in various elevation bands. Iceland was divided into four elevation bands: *Coastline* (0-100 m a.s.l.), *Lowland* (100-500 m a.s.l.), *Highland* (500-1000 m. a.s.l.) *and Glaciers/Mountains* (1000 + m a.s.l.). A high resolution (20x20m) digital elevation model (DEM) from the National Land Survey of Iceland was uploaded to GEE and used to calculate the elevation bands. Figure 1 shows the areas of each of the defined elevation zones in Iceland.

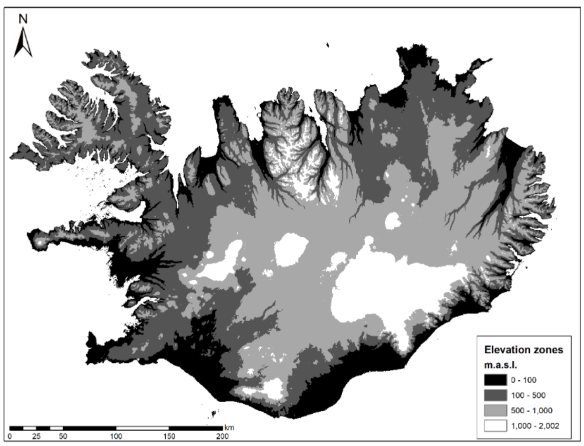

Figure 1. Elevation zones in Iceland used for analysis of climate and snow changes.

2.3 SCF trend

Annual Snow Cover Frequency (SCF) was calculated with 500m x 500m resolution for Iceland based on the MOD10A1.005 MODIS/TERRA snow cover daily product (Hall et al., 2006). The annual SCF was estimated using the methods described in Eythorsson et al., (2019). The MOD10A1.005 dataset was remapped to provide a binary classification for valid observations. Observations with zenith angles > 25° were excluded to decrease the *panoramic bow tie effect* which is a panoramic distortion known to cause systematic errors in snow mapping (Souri & Azizi, 2013). Invalid observations due to cloud

https://doi.org/10.5194/hess-2019-564
Preprint. Discussion started: 19 November 2019

cover or polar night, for example, were masked by giving them a null value. The number of days a pixel is covered with snow was counted and divided by the number of valid observations of that pixel, per year. On average we observed an average of 60 valid observations/year per pixel. We did not perform gap-filling of the MODIS snow cover product to avoid introducing another source of uncertainty. The annual SCF was calculated for the period where MODIS observations are available (water years 2001-2016). The trend of annual SCF values in each pixel over the period was estimated by linear regression and Sen's estimator of slope methods. The statistical significance of the observed trend was assessed using both the non-parametric Mann-Kendall trend test and Sen's estimator of slope methods. Maps were produced showing the areas where significant changes in the SCF had occurred at the $\alpha = 0.01$ and $\alpha = 0.05$ confidence level.

2.3.1 SCF in areas of recent land surface changes.

The annual SCF values were extracted for three locations in Iceland where land surface changes had physically impacted the local SCF during the MODIS period. The locations selected were: (a) Holuhraun volcano, which erupted in the winter of 2014, where the SCF was expected to decrease following the eruption; (b) the Hálslón area, where a major storage reservoir was commissioned in 2007 and an ice-covered lake replaced a deep canyon leading to an expected increase in SCF; and (c) Eystri Hagafellsjökull, where the glacier terminus has receded in recent years, leading us to expect a sudden decrease in the SCF as perennial glacier coverage has given way to reveal the subsurface beneath during the snow-free months of the year.

To determine whether the change that has occurred over the historical period (2001-2016) is statistically significant a hypothesis test was developed. As the SCF data was not expected to be normally distributed a Mann-Whitney-Wilcoxon (MWW) test on two sample means was performed. To determine the time of occurrence of the change, historical time series were analyzed by selecting a split in the time series and performing the hypothesis test on the resulting two time series, before and after the split. The null hypothesis was that the means of the two series are the same: H_0: $\mu_1 = \mu_2$ and the alternative hypothesis was that the means are not the same: H_1: $\mu 1 \neq \mu 2$. Code was written in python that tests the hypothesis for all possible splits in the historical time series and returns the split with the lowest p-value. We argue that the data are reliable if the tests return the same period of change in the SCF as the known land surface changes.

2.4 Köppen-Geiger climate classifications

Köppen-Geiger climate classifications were calculated for Iceland in a 0.2-degree horizontal resolution using the methods described in Eythorsson et al., 2019. Climate classifications were assigned to each pixel based on the classification criteria outlined by Kottek et al. (2006) and Peel et al. (2007), as summarized in Appendix 1. The classification scheme contains five main classes, each with two levels of subclasses, in total 30 climate classes. As example, an area that has the main class *D – Cold*, second subclass *w – dry winter* and the third subclass a – *hot summer* would have the code *Dwa.*

We classified Icelandic climate for each year in the period 1950-2100. We used the ensemble average of the NASA NEX dataset for both historical and predicted future climate conditions (Thrasher et al., 2006). The dataset contains an ensemble of 21 Global Circulation Models (GCM's) used in the CMIP5 model intercomparison project of the International Panel on Climate Change (IPCC) (Taylor et al., 2012).

The dataset includes model runs for two Representative Concentration Pathways (RCP) - RCP 4.5 and RCP 8.5. We selected RCP 4.5 as a more conservative prediction of future climate change. RCP 4.5 is a stabilization scenario where total radiative forcing is stabilized before 2100 by employment of a range of technologies and strategies for reducing greenhouse gas emissions, whereas RCP 8.5 is characterized by increasing greenhouse gas emissions over time and is representative for scenarios in the literature leading to high greenhouse gas concentration levels (van Vuuren et al., 2011). We

https://doi.org/10.5194/hess-2019-564
Preprint. Discussion started: 19 November 2019

calculated the proportion of each climate class within each study area for each year and estimated climate change as the change in KG classification in each grid cell.

2.5 Comparison of SCF and Climate trends

The evidence for statistical significance of the changes in the snow and climate regimes was estimated by performing the non-parametric Mann-Kendall and Sen's estimator of slope methods on the timeseries of the SCF and the proportional KG class coverage. Both of these tests have been used often to assess the significance of the trends in hydro-meteorological time series (Drapela & Drapelova, 2011; Gocic & Trajkovic, 2013). In the significance tests the null hypothesis is that there is no monotonic trend present in the data H_0: s = 0, while the alternative hypothesis is that the data has a monotonic trend H_1: $|s| > 0$. Both tests were performed at $\alpha = 0.01$ and $\alpha = 0.05$ significance levels.

The significance of the trend calculated by linear regression was assed using the Mann-Kendall trend test. We applied the test using the *stats.kendalltau()* function in SciPy and the *ee.Reducer.kendallsCorrelation()* function in GEE. We applied Sen's slope test on the significance of the trend using the *stats.mstats.theilslopes()* function in SciPy and the *ee.Reducer.sensSlope()* function in GEE. We developed maps of areas showing evidence for significant changes in the SCF during the period 2001-2016. We then calculated the ratio of area with significant SCF changes during the period within each study area. We extracted the time series of KG climate class coverage within each study area and assessed the significance of the trend of the two most common climate classes, using both the Mann-Kendall and Sens's slope tests.

3 Results

3.1 SCF Trend Analysis

The statistical significance of the SCF trend in Iceland over the period 2001-2016 was analyzed with both the non-parametric Mann-Kendall trend test and Sen's estimator of slope methods as described in Section 2.5. Figure 3 shows the results from these analyses at two confidence levels ($\alpha = 0.05$ and $\alpha = 0.01$). Black areas indicate a significant positive SCF trend and white areas a significant negative SCF trend, while gray areas do not support rejection of the null hypothesis.

https://doi.org/10.5194/hess-2019-564
Preprint. Discussion started: 19 November 2019

Hydrology and Earth System Sciences
Open Access
Discussions

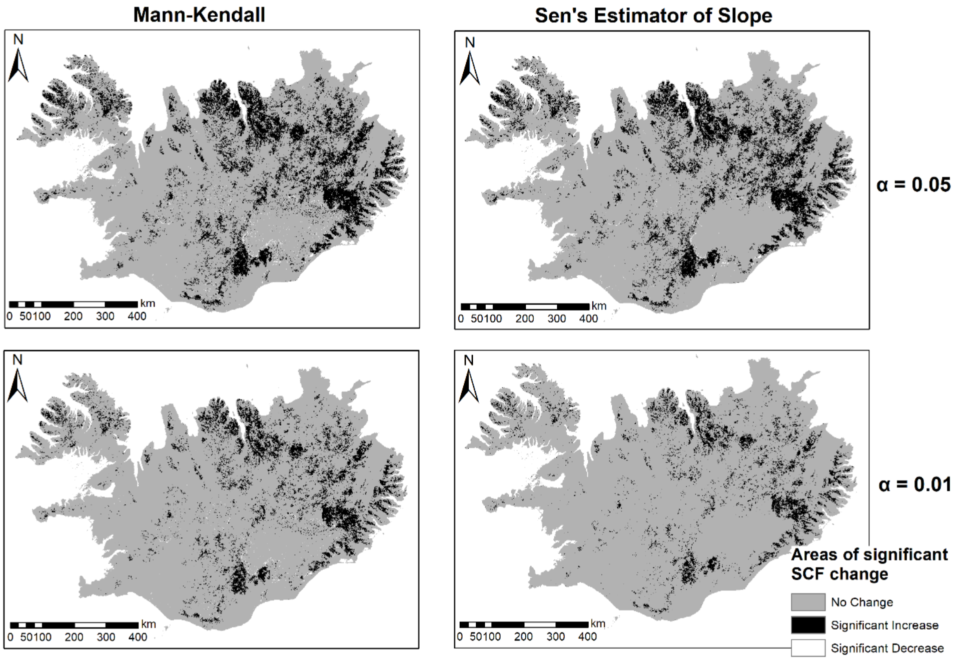

Figure 2. Areas of significant change in the SCF identified using Mann-Kendall and Sen's Slope hypothesis tests at confidence levels α = 0.05 and α = 0.01

Figure 2 shows that large areas of Iceland experienced a significant change in the SCF during the period 2001-2016. The figure clearly shows that the SCF increased specifically in the eastern and northeastern parts of the country. This is an interesting result as these are relatively arid areas as they are in the rain shadow of the Vatnajökull Glacier. Increasing SCF trends were also observed on the north-facing peninsulas, e.g. the Trollaskagi and Gjögraskagi peninsulas. A clear increase in SCF was also observed southwest of the Vatnajökull Glacier. Few areas of decreasing SCF trends were e observed, mostly at the terminus of outlet glaciers which have receded in recent years. This is especially evident for example at the terminus of outlet glaciers along the south- western edge of the Vatnajökull Glacier, Tungnárjökull, Síðujökull and Skeiðarárjökull.

3.2 Verification of SCF trends

The SCF data were analyzed in areas where recent land surface changes were expected to have had an impact on the snow regime during the MODIS record. Three locations were analyzed: Holuhraun volcano, which erupted in 2014 and the hot lava has melted snow for two consecutive years; Karahnjukar canyon, where a hydropower reservoir was formed in 2006 by inundation of a deep canyon and now has ice cover for most of the year; and Eystri Hagafellsjökull, an outlet glacier that receded during the study period. One 500x500m pixel at each location was selected for analysis. Figure 1 shows the time series of the SCF in the three ground truth locations as well as mean values for the periods before and after the expected SCF change.

https://doi.org/10.5194/hess-2019-564
Preprint. Discussion started: 19 November 2019

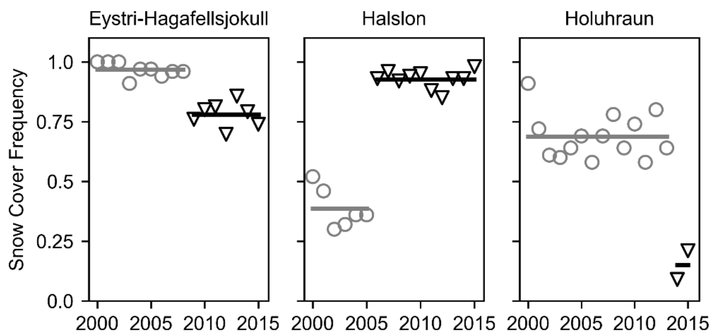

Figure 3. SCF data from verification locations of recent land surface changes (horizontal bars show mean values)

The time series for the SCF at each location was analyzed for evidence of statistically significant change during the MODIS record (2001-2016) by an MWW hypothesis test, as described in Section 2.3.1.

Table 1 shows the results of the hypothesis tests. The results show that for all three locations the null hypothesis was rejected. Hence, the SCF record captures physical land surface changes that occurred during the period and that the timing of these changes can be identified by the MWW test. We also note that, like the Hálslón reservoir, all other hydropower reservoirs constructed during the MODIS era, Sporðöldulón, Ufsarlón and Kelduárlón, could be clearly identified from the SCF maps.

Table 1. Results of SCF verification experiment in Iceland

Location:	Time of change	MWW p-value	SCF trend
Holuhraun	2014	0.017	Significant decrease
Hálslón	2007	0.00025	Significant increase
Eystri Hagafellsjökull	2008	0.00031	Significant decrease

3.3 Köppen-Geiger classifications

Köppen-Geiger (KG) classifications were calculated for Iceland in 0.2x0.2-degree resolution. The four most common KG classes in Iceland in this period were: *ET* – Polar Tundra, *Dfc* – Cold climate with cold summers and no dry season, *Dfb* – Cold climate with warm summer and no dry season, and *Dsc* – Cold climate with cold summers and dry summers. Figure 4 shows the KG classification for Iceland for the years 1950 (upper) and 2099 (lower).

https://doi.org/10.5194/hess-2019-564
Preprint. Discussion started: 19 November 2019

Hydrology and Earth System Sciences
Discussions

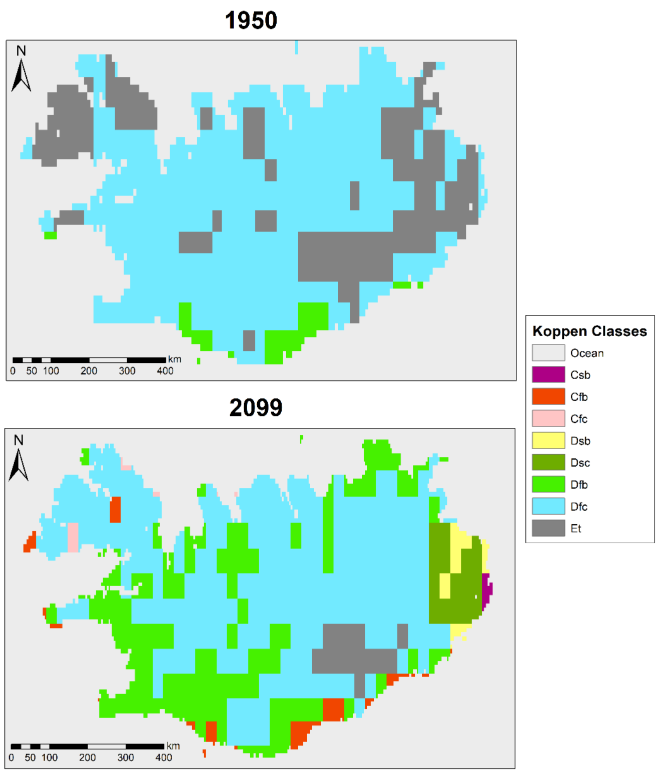

Figure 4. Annual Köppen-Geiger (KG) classification maps calculated for Iceland in the study for the years 1950 (upper) and 2099 (lower). (*Dfc* – Cold climate with cold summers and no dry season and *Dfb* – Cold climate with warm summer and no dry season)

The results show that between 1950 and 2099 the polar tundra climate that initially covered a large portion of the highlands will mostly disappear, except on the Vatnajökull Glacier. Here *ET* is replaced by a cold climate with the cold summer classes *Dfc* and *Dsc*. A warm summer climate (*Dfb*), that in the beginning of the period was mostly limited to small areas in the southern lowlands on each side of the Mýrdalsjökull Glacier, will by the end of the period have spread almost around the entire country and stretched far into the highlands. At the middle of the current century temperate climate classes (*Cfb, Cfc* and *Csb*) start appearing consistently in coastal areas. This would be the first time that such a climate classification would be experienced in Iceland.

Figure 5 shows the proportional coverage of the top climate classes for the period 1950-2099. The uppermost graph shows the results for the whole of Iceland and the lower graphs show the main climate classes within each elevation zone. The results in Figure 5 show that by the end of the current century the polar tundra climate (Class *ET*) in Iceland will decrease from about 20% coverage in 1950 to about 5%, by the middle of the current century and the ET class will disappear altogether in the coastal and lowland regions. Over the same period, warm summers (class *Dfb*) will increase by about the same amount. The net coverage of the most common climate class, *Dfc*, will not change much over the period. However, as seen in Figures 4 and ~~6,~~ class *Dfc* is replaced by class *Dfb* in coastal areas while it replaces class *ET* in the highlands; thus we expect the spatial distribution of class *Dfc* to change significantly during the period.

https://doi.org/10.5194/hess-2019-564
Preprint. Discussion started: 19 November 2019

Hydrology and Earth System Sciences
Discussions
Open Access

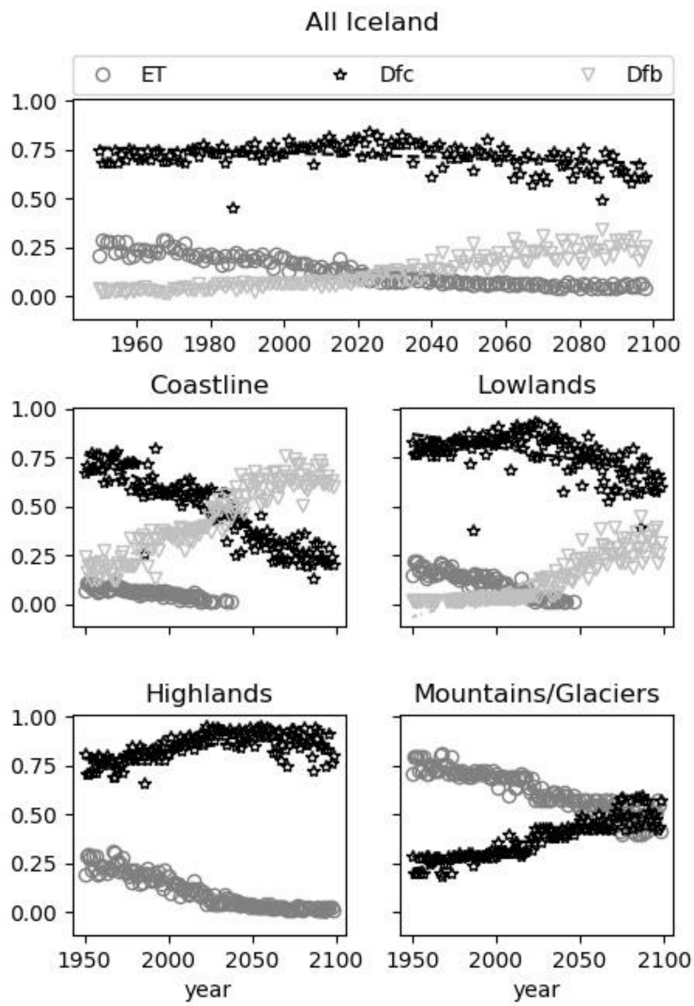

Figure 5. Proportional coverage of the three main KG Classes in each elevation zone in Iceland for the period 1950-2099

3.4 Comparison of SCF and Climate trends

We calculated the ratio of the area where significant SCF changes were observed within each of the elevation zones described in section 2.2 for the MODIS period (2001-2016). We also calculated the proportional annual coverage of the main KG climate classes in each elevation zone for both the MODIS period and for the full historical climate time series (1950-2016). The significance of the trend of the proportional annual KG coverage was assessed using the Mann-Kendall and Sen's estimator of slope hypothesis tests, as described in section 2.5.

Table 3 summarizes the evidence for the statistical significance of these changes. The results in Table 3 show that the biggest SCF changes have occurred in the highlands, where 27.4% of the area has already seen a significant change in the SCF. The smallest SCF changes were observed by the

https://doi.org/10.5194/hess-2019-564
Preprint. Discussion started: 19 November 2019

coastline and at the highest elevations in mountain peaks and on glaciated terrain, where 2.4 and 5.4% of the areas has undergone a significant change in SCF, respectively. Areas with significant SCF changes covered 14.3 % in the lowlands, and 16.3% across Iceland.

The results in Table 2 show that for the MODIS period there have been no significant changes to any of the main climate changes in Iceland nor within any of the elevation zones considered. However, for the full historical period 1950-2016, we observed significant changes in every one of the climate classes within all elevation zones. For the full historical period the changes in climate classes were significant to a confidence level of α = 0.001. These results suggest that climate change is underway in Iceland, but that during the MODIS period, these changes were not identifiable by statistical means.

Table ~~1.~~ Changes in proportional annual KG coverage and percentage of area with significant SCF changes

Area	KG classes 1950-2016				KG classes 2001-2016			SCF Significant Area [%]		Mean SCF change [%/yr]
	Name	Slope [%/yr]	MK p-value	Sens's slope	Slope [%/yr]	MK p-value	Sens's slope	α = 0.05	α = 0.01	
All Iceland	Dfc	0.10	< 0.001	Sig	0.15	> 0.05	InSig	16.3	7.4	0.64
	ET	-0.18	< 0.001	Sig	-0.24	> 0.05	InSig			
	Dfb	0.07	< 0.001	Sig	0.02	> 0.05	InSig			
Coastline	Dfc	-0.27	< 0.001	Sig	-0.06	> 0.05	InSig	2.4	0.7	0.08
	ET	-0.08	< 0.001	Sig	-0.12	> 0.05	InSig			
	Dfb	0.33	< 0.001	Sig	0.1	> 0.05	InSig			
Lowlands	Dfc	0.11	< 0.001	Sig	0.1	> 0.05	InSig	14.3	5.9	0.67
	ET	-0.18	< 0.001	Sig	-0.34	> 0.05	InSig			
	Dfb	0.04	< 0.001	Sig	0.02	> 0.05	InSig			
Highlands	Dfc	0.22	< 0.001	Sig	0.17	> 0.05	InSig	27.4	13.3	0.95
	ET	-0.23	< 0.001	Sig	-0.26	> 0.05	InSig			
Glacier/ Mountain	Dfc	0.1	< 0.001	Sig	0.003	> 0.05	InSig	5.4	2.3	0.23
	ET	-0.1	< 0.001	Sig	0	> 0.05	InSig			

5 Discussion

In this study we assessed the impact of climate change on snow cover in Iceland. Our results showed that warmer climate classes have been replacing colder across the country. In the highlands, cold climate with cold summers, *Dfc,* has been replacing polar tundra, and at lower elevations cold climate with warm summer, *Dfb,* has been replacing class *Dfc*. This warming trend has been progressing since at least the 1950's and is unaffected by the reported midcentury cooling trend (Hanna et al., 2004). However, while the Icelandic climate has been warming, large areas have experienced a significant increase in the SCF in the MODIS period 2001-2016, most notably the inland regions in the highlands and lowlands where SCF has increased by about 2.4 and 3.5 days/year in the study period, respectively. These results are inconsistent with our original hypothesis that the warming trend observed would result in a reduced frequency of snow cover.

The results clearly identify local changes to the snow cover regime during the MODIS era. Land surface changes like reservoir construction, volcanic eruptions and glacial recession are clearly observed in the SCF data and can be related to changes in snow cover. Since 2000 the area of the glaciers in Iceland has been reduced by 600 km^2 (IMO, 2017). This recent recession of the country's main glaciers was clearly observed in our results, as in the areas in front of the retreating termini of all the major outlet glaciers in Iceland areas of significantly decreasing SCF were observed. These

https://doi.org/10.5194/hess-2019-564
Preprint. Discussion started: 19 November 2019

results are somewhat counterintuitive, as most of these areas are in the highlands, where our results showed very large areas of increasing SCF trends.

Several recent studies have analyzed snow cover changes in the Northern Hemisphere (NH), most of whom observed an ~~increase~~ in snow cover in the past few decades. Yunlong et al., 2018 estimated a decrease in NH snow covered days by 5.3 days/decade since 2001, using MODIS, IMS and AMSR-E data. Hori et al., 2017 used MODIS and AVHRR data to estimate changes in Snow Cover Extent (SCE) across the NH and found an average decrease of 10 days/decade in large areas of the NH during the period 1978-2015. Liston & Hiemstra, 2011 used MERRA reanalysis data to model NH snow cover and observed a 2.5 days/decade decrease in the number of snow covered days for the period 1979-2009. Fontrodona et al, 2018 analyzed in situ snow depth data across Europe, including sites in Iceland, and found an average decrease in mean snow depth of – 12.2% per decade. Eythorsson et al., 2019 used MODIS data to estimate a 9.1 days / decade decrease in the Arctic SCF during the period 2001 – 2016, their results however showed large areas in the far north where SCF is increasing during the period. The increasing SCF at high latitudes is consistent with studies that suggest that decreasing sea ice concentrations in the Arctic seas have resulted in increasing precipitation in these areas (e.g. Kopec et al., 2016; Singarayer et al., 2006). The observed pattern of increasing SCF trends in Iceland is consistent with the results of Gunnarsson et al., (2019) which found an increasing snow cover duration in all months except October and November using a gap filled MODIS product.

We suggest that the increasing SCF trends observed in Iceland could be associated with increased precipitation, which would lead to a more frequent and thicker snowpack which would persist longer in the spring. This is consistent with Bjornsson et al., (2018) who found annual precipitation to have increased by about 10% during the period 1980-2015. Figure 6 shows Sen's slope of the average annual precipitation during the period 1950-2100, according to the ensemble mean of the NEX GDDP projections for RCP 4.5. Figure 6 shows that the average annual precipitation is expected to increase during this time across all regions in Iceland, but most in the eastern highlands. The small graph in Figure 6 shows the average annual precipitation across Iceland for the period 1950-2100. The results show that precipitation in Iceland has shown an upward trend since the 1950's which is expected to continue throughout the present century (Thrasher et al., 2006).

https://doi.org/10.5194/hess-2019-564
Preprint. Discussion started: 19 November 2019

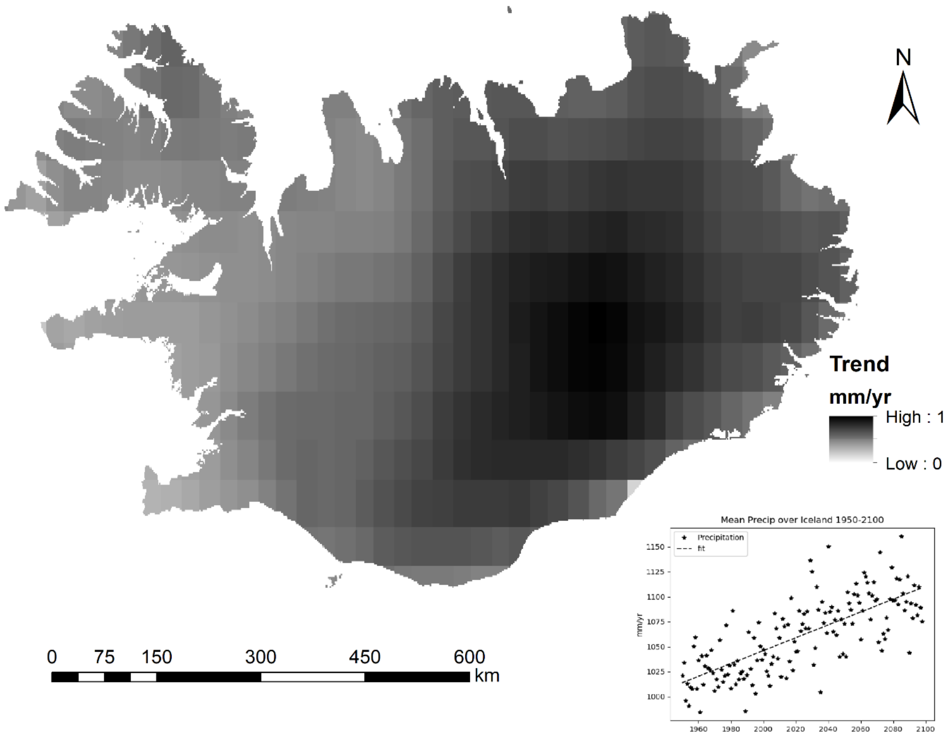

Figure 6 Sens slope of precipitation changes and time series of mean annual precipitation in Iceland, 1950-2100

These results deserve further investigation. We note that the MODIS period, 2001-2016, is rather short and trends during this short period can be induced by low frequency cyclical climate patterns, or by a small amount of extreme weather events. We suggest that the physical reasons for the SCF trends we observed in our study be analyzed further. The impact of increased precipitation on the boundaries of the melt season in spring and autumn should be assessed. Changes in the intensity of the summer melt season as the climate warms should be investigated. Lastly, we note that the changes in the content of water stored in the snowpack cannot be inferred from the SCF data as they only measure the frequency of snow cover. However, it is not unreasonable assume that water storage in snow correlates positively with SCF, but this hypothesis deserves further analysis.

5 Conclusion

All over Iceland we observed a trend of warmer climate classes reaching further inland and into the central highlands, replacing colder climates like polar tundra. Our study showed these changes occurring since the 1950's based on the CMIP5 projections. Our results show that these trends can be expected to continue until at least the end of the current century. We found these changes to be statistically significant during the period 1950-2016, but during the MODIS period (2001-2016) we did not find evidence for any statistically significant changes in climate classifications anywhere in Iceland. However, during the MODIS period, our results showed evidence for changes in the SCF over large areas of the country, especially in the central highlands. In most of these areas the SCF had increased during the period. These results provide clear evidence of ongoing climate change in Iceland.

Projected until the end of the present century our results showed that warmer climate classes that have until now been restricted to small areas in the southern lowlands will continue to spread north and into the highlands. Well into the current century we observed temperate climate classes appearing consistently in coastal areas for the first time in recorded history. If these climate trends continue, we expect that the increasing SCF trends we observed will halt or reverse in the future, especially in the lowland regions. The evolution of the snow regime in the Icelandic highlands deserves further attention as these are the sources of a large portion of the country's water resources.

Acknowledgments: We thank the University of Iceland Research Fund which is supporting the first author through the doctoral grants of the University of Iceland Research fund. We also acknowledge the assistance of the facilitators at a workshop on scientific writing, arranged by Aalto University, Helsinki, Finland, and IWA/YWP Finland in August 2018.

Conflicts of Interest: The authors declare no conflict of interest. The funding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; nor in the decision to publish the results.

https://doi.org/10.5194/hess-2019-564
Preprint. Discussion started: 19 November 2019

References

Adalgeirsdottir, G., Johannesson, T., Bjornsson, H., Palsson, F., & Sigurdsson, O. :. Response of Hofsjokull and southern Vatnajokull, Iceland, to climate change. *Journal of Geophysical Research-Earth Surface*, *111*(F3). https://doi.org/Artn F03001\rDoi 10.1029/2005jf000388, 2006

Bjornsson, Halldor, Sigurdsson, B., Davidsdottir, B., Olafsson, J., Astthorsson, O., Olafsdottir, S., … Jonsson, T.: *Climate Change and it's impact on Iceland - Report of the scientific committee on Climate Change*, 2018

Bjornsson, Helgi, & Palsson, F.:. Icelandic glaciers. *Jökull*, *58*(58), 365–386.

Bjornsson, Helgi, Palsson, F., Gudmundsson, S., Magnusson, E., Adalgeirsdottir, G., Johannesson, T., Berthier, E., Sigurdsson O., Thorsteinsson, T. (2013). Contribution of Icelandic ice caps to sea level rise: Trends and variability since the Little Ice Age. *Geophysical Research Letters*, *40*(8), 1546–1550. https://doi.org/10.1002/grl.50278, 2008

Brown, R. D., & Mote, P. W.: The response of Northern Hemisphere snow cover to a changing climate. *Journal of Climate*, *22*(8), 2124–2145. https://doi.org/10.1175/2008JCLI2665.1, 2009

Callaghan, T. V., Johansson, M., Brown, R. D., Groisman, P. Y., Labba, N., Radionov, V., Bradley R. S., Blangy S., Bulygina O. N., Christensen T. R., Colman J. E., Essery R. L. H., Forbes B. C., Forchhammer M. C., Golubev V. N., Honrath R. E., Juday G. P., Meshcherskaya A. V., Phoenix G. K., Pomeroy J., Rautio A., Robinson D. A., Schmidt N. M., Serreze M. C., Shevchenko V. P., Shiklomanov A. I., Shmakin A. B., Sköld P., Strum M., Woo M., Wood, E. F.: Multiple effects of changes in arctic snow cover. *Ambio*, *40*(SUPPL. 1), 32–45. https://doi.org/10.1007/s13280-011-0213-x, 2011

Chen, D., & Chen, H. W.: Using the Koppen classification to quantify climate variation and change: An example for 1901-2010. *Environmental Development*, *6*(1), 69–79. https://doi.org/10.1016/j.envdev.2013.03.007, 2013

Cohen, J.: Snow cover and climate. *Weather*, *49*(5), 150–156. https://doi.org/10.1002/j.1477-8696.1994.tb05997.x, 1994

Dietz, A. J., Kuenzer, C., Gessner, U., & Dech, S.: Remote sensing of snow – a review of available methods. *International Journal of Remote Sensing*, *33*(13), 4094–4134. https://doi.org/10.1080/01431161.2011.640964, 2012

Drapela, K., & Drapelova, I.: Application of Mann-Kendall test and the Sen's slope estimates for trend detection in deposition data from Bily Kriz (Beskydy Mts., the Czech Republic) 1997--2010. *Beskydy*, *4*(2), 133–146. 2011

Eliasson, K., Ulfarsson, G. F., Valsson, T., & Gardarsson, S. M.: Identification of development areas in a warming Arctic with respect to natural resources, transportation, protected areas, and geography. *Futures*, *85*, 14–29. https://doi.org/10.1016/j.futures.2016.11.005, 2017

Engelbrecht, C. J., & Engelbrecht, F. A.: Shifts in Köppen-Geiger climate zones over southern Africa in relation to key global temperature goals. *Theoretical and Applied Climatology*. https://doi.org/10.1007/s00704-014-1354-1, 2016

Eythorsson, D., Gardarsson, S. M., Ahmad, S. K., Hossain, F., & Nijssen, B.: Arctic climate and snow cover trends - Comparing Global Circulation Models with remote sensing observations. *International Journal of Applied Earth Observation and Geoinformation*, *80*, 71–81. https://doi.org/https://doi.org/10.1016/j.jag.2019.04.003, 2019

Eythorsson, D., Gardarsson, S. M., Gunnarsson, A., & Hrafnkelsson, B.: Statistical summer mass-balance forecast model with application to Brúarjökull glacier, South East Iceland. *Journal of Glaciology*. https://doi.org/10.1017/jog.2018.22, 2018.

Fontrodona Bach, A., van der Schrier, G., Melsen, L. A., Klein Tank, A. M. G., & Teuling, A. J.: Widespread and Accelerated Decrease of Observed Mean and Extreme Snow Depth Over Europe. *Geophysical Research Letters*. https://doi.org/10.1029/2018GL079799, 2018

Frei, A., Miller, J. A., & Robinson, D. A.: Improved simulations of snow extent in the second phase of the Atmospheric Model Intercomparison Project (AMIP-2). *Journal of Geophysical Research*, *108*(D12), 4369. https://doi.org/10.1029/2002JD003030, 2003

Gocic, M., & Trajkovic, S.: Analysis of changes in meteorological variables using Mann-Kendall and Sen's slope estimator statistical tests in Serbia. *Global and Planetary Change*, *100*, 172–182. https://doi.org/10.1016/j.gloplacha.2012.10.014, 2013

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R.: Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*. https://doi.org/10.1016/j.rse.2017.06.031, (2016).

Guan, B., Molotch, N. P., Waliser, D. E., Jepsen, S. M., Painter, T. H., & Dozier, J.: Snow water equivalent in the Sierra Nevada: Blending snow sensor observations with snowmelt model simulations. *Water Resources Research*, *49*(8), 5029–5046. https://doi.org/10.1002/wrcr.20387, 2013

Gunnarsson, A., Garðarsson, S. M., & Sveinsson, Ó. G. B.: Icelandic snow cover characteristics derived from a gap-filled MODIS daily snow cover product. *Hydrol. Earth Syst. Sci.*, *23*(7), 3021–3036. https://doi.org/10.5194/hess-23-3021-2019, 2019

H Souri, A., & Azizi, A.: Removing Bowtie Phenomenon by Correction of Panoramic Effect in MODIS Imagery. *International Journal of Computer Applications,Published by Foundation of Computer Science, New York, USA.*, *68*, 12–16, 2013

Hall, D. K., Riggs, G. A., & Salomonson, V. V. MODIS/Terra Snow Cover Daily L3 Global 500m Grid V005 2000-01-01 to 2016-12-31., 2006

Hanna, E., Jónsson, T., & Box, J. E.: An analysis of Icelandic climate since the nineteenth century. *International Journal of Climatology*, *24*(10), 1193–1210. https://doi.org/10.1002/joc.1051, 2004

Hori, M., Sugiura, K., Kobayashi, K., Aoki, T., Tanikawa, T., Kuchiki, K., Niwano M., Enomoto, H.: A 38-year (1978–2015) Northern Hemisphere daily snow cover extent product derived using consistent objective criteria from satellite-borne optical sensors. *Remote Sensing of Environment*, *191*, 402–418. https://doi.org/10.1016/j.rse.2017.01.023, 2017

IMO.: *Overview of Icelandic Glaciers at the End of 2017*. Retrieved from http://en.vedur.is/media/Eplicanámskeið/VAT_newsletter_2018_06.pdf, 2017

Johannesson, T., Adalgeirsdottir, G., Bjornsson, H., Crochet, P., Eliasson, B. E., Gudmundsson, S., Jonsdottir J. F., Olafsson H., Palsson F., Rognvaldsson O., Sigurdsson O., Snorrason A., Sveinsson O. G. B., Thorsteinsson, T.: *Effect of climate change on hydrology and hydro-resoures in Iceland*. Reykjavik, 2007

Jóhannesson, T., Adalgeirsdottir, G., Björnsson, H., Pálsson, F., & Sigurðsson, O.: *RESPONSE OF GLACIERS AND GLACIER RUNOFF IN ICELAND TO CLIMATE CHANGE*, 2004

Kopec, B. G., Feng, X., Michel, F. A., & Posmentier, E. S.: Influence of sea ice on Arctic precipitation. *Proceedings of the National Academy of Sciences*, *113*(1), 46–51. https://doi.org/10.1073/pnas.1504633113, 2016

Köppen, W.: Klassifikation der Klimate nach Temperatur, Niederschlag und Jahresablauf (Classification of climates according to temperature, precipitation and seasonal cycle). *Petermanns Geographische Mitteilungen*, 1918

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F.: World map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, *15*(3), 259–263. https://doi.org/10.1127/0941-2948/2006/0130., 2006

Liston, G. E., & Hiemstra, C. A.: The changing cryosphere: Pan-Arctic snow trends (1979-2009). *Journal of Climate*, *24*(21), 5691–5712. https://doi.org/10.1175/JCLI-D-11-00081.1, 2011

Lohmann, U., Sausen, R., Bengtsson, L., Cubasch, U., Perlwitz, J., & Roeckner, E.: The Koppen climate classification as a diagnostic tool for general circulation models. *CLIM.RES.*, *3*(3), 177–193. https://doi.org/10.3354/cr003177, 1993

Massé, G., Rowland, S. J., Sicre, M. A., Jacob, J., Jansen, E., & Belt, S. T.: Abrupt climate changes for Iceland during the last millennium: Evidence from high resolution sea ice reconstructions. *Earth* *and Planetary Science Letters*. https://doi.org/10.1016/j.epsl.2008.03.017, 2008

Naha, S., Thakur, P. K., & Aggarwal, S. P.: Hydrological Modelling and data assimilation of Satellite Snow Cover Area using a Land Surface Model, VIC. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLI-B8*(July), 353–360. https://doi.org/10.5194/isprsarchives-XLI-B8-353-2016, 2016

Oliphant, T. E.: Python for scientific computing. *Computing in Science and Engineering*, *9*(3), 10–20. https://doi.org/10.1109/MCSE.2007.58, 2007

Peel, M. C., Finlayson, B. L., & Mcmahon, T. A.: Updated world map of the Koppen-Geiger climate classification. *HESSD Earth Syst. Sci. Discuss*, *4*(4), 439–473. https://doi.org/10.1127/0941-2948/2006/0130. 2007

Rubel, F., Brugger, K., Haslinger, K., & Auer, I.: The climate of the European Alps: Shift of very high resolution Köppen-Geiger climate zones 1800-2100. *Meteorologische Zeitschrift*. https://doi.org/10.1127/metz/2016/0816, 2017

Singarayer, J. S., Bamber, J. L., Valdes, P. J., Singarayer, J. S., Bamber, J. L., & Valdes, P. J.: Twenty-First-Century Climate Impacts from a Declining Arctic Sea Ice Cover. *Journal of Climate*, *19*(7), 1109–1125. https://doi.org/10.1175/JCLI3649.1, 2006

Stocker, T. F., Qin, D., Plattner, G. K., Tignor, M. M. B., Allen, S. K., Boschung, J., Nauels A., Xia Y., Bex V., Midgley, P. M.: *Climate change 2013 the physical science basis: Working Group I contribution to the fifth assessment report of the intergovernmental panel on climate change*. *Climate Change 2013 the Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. https://doi.org/10.1017/CBO9781107415324, 2013

Taylor, K. E., Stouffer, R. J., & Meehl, G. A.: An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*. https://doi.org/10.1175/BAMS-D-11-00094.1, 2012

Thrasher, B., Melton, F., & Weile, W.: NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) | CDS. Retrieved May 1, 2017, from https://cds.nccs.nasa.gov/nex-gddp/, 2006

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., … Rose, S. K.: The representative concentration pathways: An overview. *Climatic Change*, *109*(1), 5–31. https://doi.org/10.1007/s10584-011-0148-z, 2011

Yunlong, W., Huang, X., Hui, L., Sun, Y., Qisheng, F., & Tiangang, L.: Tracking Snow Variations in the Northern Hemisphere Using Multi-Source Remote Sensing Data (2000–2015). *Remote Sensing*, *10(1)*(136). https://doi.org/doi:10.3390/rs10010136, 2018

https://doi.org/10.5194/hess-2019-564
Preprint. Discussion started: 19 November 2019

Appendix 1. Köppen-Geiger climate classification criteria

1st	2nd	3rd	Description	Criteria*
A			Tropical	$T_{cold} \geq 18$
	f		-Rainforrest	$P_{dry} \geq 60$
	m		-Monsoon	Not Af and $P_{dry} \geq 100\text{-}MAP/25$
	w		-Savannah	Not Af and $P_{dry} < 100\text{-}MAP/25$
B			Arid	$MAP < 10{*}P_{threshold}$
	w		-Desert	$MAP < 5{*}P_{threshold}$
	s		-Steppe	$MAP \geq 5{*}P_{threshold}$
		H	-Hot	$MAT \geq 18$
		K	-Cold	$MAT < 18$
C			Temperate	$T_{hot} > 10$ & $0 < T_{cold} < 18$
	s		-Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		-Dry Winter	$P_{wdry} < P_{swet}/10$
	f		-Without dry season	Not Cs or Cw
		A	-Hot Summer	$T_{hot} \geq 22$
		B	-Warm Summer	Not a & $T_{mon}10 \geq 4$
		C	-Cold Summer	Not a or b & $1 \leq T_{mon}10 \leq 4$
D			Cold	$T_{hot} > 10$ and $T_{cold} \leq 0$
	s		-Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		-Dry Winter	$P_{wdry} < P_{swet}/10$
	f		-Without dry season	Not Ds and Not Dw
		A	-Hot Summer	$T_{hot} \geq 22$
		B	-Warm Summer	Not a & $T_{mon}10 \geq 4$
		C	-Cold Summer	Not a, b or d
		D	-Very cold Winter	Not a or b & T_{cold} <-38
E			Polar	$T_{hot} < 10$
	T		-Tundra	$T_{hot} > 0$
	F		-Frost	$T_{hot} \leq 0$

* MAP = Mean annual precipitation, MAT = mean annual temperature, T_{hot} = temperature of the hottest month, T_{cold} = temperature of the coldest month, T_{mon10} = number of months with mean temperatures above 10, P_{dry} = precipitation of the driest month, P_{sdry} = precipitation of the driest month in summer, P_{wdry} = precipitation of the driest month in winter, P_{swet} = precipitation of the wettest month in summer, P_{wwet} = precipitation of the wettest month in winter, $P_{threshold}$ = varies according to: (if 70% of MAP occurs in winter then $P_{threshold}$ = 2*MAT, if 70% of MAP occurs in summer then $P_{threshold}$ = 2*MAT+28, otherwise $P_{threshold}$ = 2*MAT + 14). Summer (winter) is defined as the warmer (cooler) six-month period of ONDJFM and AMJJAS.
From Peel et al., 2007