

Dynamical downscaling of precipitation in Iceland 1961–2006

Ólafur Rögnvaldsson, Jóna Finndís Jónsdóttir and Haraldur Ólafsson

ABSTRACT

Atmospheric flow over Iceland has been simulated for the period January 1961 to July 2006, using the mesoscale MM5 model driven by initial and boundary data from the European Centre for Medium Range Weather Forecasts (ECMWF). Firstly, the simulated precipitation is compared to estimates derived from mass balance measurements on the Icelandic ice caps. It is found that the simulated precipitation compares favourably with the observed winter balance, in particular for Hofsjökull, where corrections to take liquid precipitation and/or winter ablation into account have been made, and for the outlet glaciers Dyngjufjökull and Brúarjökull. Secondly, the model output is used as input to the WaSiM hydrological model to calculate and compare the runoff with observed runoff from six watersheds in Iceland. It is found that model results compare favourably with observations. Overall, the MM5 V3–7 is somewhat better than the MM5 V3–5. The V3–7 is drier than V3–5 on upstream slopes.

Key words | dynamical downscaling, glaciological data, hydrological data, MM5, precipitation, WaSiM

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INTRODUCTION

The geographical distribution of precipitation in Iceland is poorly known but very important for hydrological applications, both in general and particularly in the context of climate change. Therefore, an extensive task carried out in the recent VO/CE project (Jóhannesson *et al.* 2007; further information on the Veður og orka – Climate and Energy (VO/CE) project can be found on the web: <http://www.os.is/ce>) was concerned with modelling of precipitation and a compilation of precipitation datasets on a regular grid covering the whole country. These datasets provide the opportunity to model river runoff and glacier mass balance both in the current climate and also in a hypothetical future climate based on climate change scenarios. Thus, climatological downscaling of precipitation is of great use for hydrological purposes. Furthermore, the MM5 model, using a similar set-up as used in this study, is in

operational use in Iceland for the production of short to medium range weather forecasts. Improvements in the numerical tools do therefore benefit both the hydrology community as well as weather forecasting, although the interests of these two communities lie in different timescales.

The climate of Iceland is largely governed by the interaction of orography and extra-tropical cyclones, both of which can be described quite accurately by present-day atmospheric models. As a result, dynamical downscaling of the climate, using physical models, can be expected to give reliable information about precipitation distribution, especially in the data-sparse highlands.

In this paper we compare dynamical downscaling of large-scale meteorological fields provided by the ERA40 reanalysis (Uppala *et al.* 2005) to precipitation estimates derived from mass balance measurements on the Icelandic

ice caps. The dynamical downscaling is done by using the mesoscale MM5 model (Grell *et al.* 1995). We also use output from the MM5 model as input to the WaSiM hydrological model (Jasper *et al.* 2002) for the same six watersheds as used for validation purposes of a 15-year time series described by Rögnvaldsson *et al.* (2007, hereafter referred to as RJO07) and compare the simulated discharge with the observed discharge.

Previous studies (Rögnvaldsson *et al.* 2004, 2007; Bromwich *et al.* 2005) have shown the combination of the Grell cumulus scheme, the Reisner2 microphysics scheme and the MRF PBL scheme to be a reliable set-up for simulating precipitation over Iceland at 8 km resolution. Rögnvaldsson & Ólafsson (2002) also tested the sensitivity of simulated precipitation to the number of vertical levels (23 vs. 40) and to the size of the simulation domain. They found that the simulated precipitation is neither sensitive to domain size nor vertical resolution.

This paper begins with a description of the model approach, followed by comparison of the model results to glaciological data and a comparison of modelled discharge to observed discharge. The results are discussed in brief, followed by concluding remarks.

MODELLING WITH THE MM5 MODEL

Atmospheric flow over Iceland was simulated for the period January 1961 through June 2006 using V3–7 of the PSU/NCAR MM5 mesoscale model (Grell *et al.* 1995). The domain used is 123×95 points, centered at 64°N and 19.5°W , with a horizontal resolution of 8 km. There are 23 vertical levels with the model top at 100 hPa and model output is every 6 h. The domain set-up is shown in Figure 1.

The MM5 model was used with initial and lateral boundaries from the ERA40 re-analysis project to 1999. After that date, operational analyses from the ECMWF were used. The ERA40 data were interpolated from a horizontal grid of 1.125° to 0.5° prior to being applied to the MM5 modelling system. The modelling approach differs from that used by Bromwich *et al.* (2005). Instead of applying many short term (i.e. of the order of days) simulations and frequently updating the initial conditions, the model was run over a period of approximately six months with

only lateral boundary conditions updated every six hours. This was made possible by taking advantage of the NOAA land surface model (Koren *et al.* 1999; Ek *et al.* 2003).

For discussions regarding the use of limited-area models for regional climate studies and the use of run-off measurements for validation of precipitation simulated by atmospheric models we refer to RJO07 and references therein.

PREVIOUS VERIFICATION OF SIMULATED PRECIPITATION

RJO07 simulated atmospheric flow over Iceland for the period September 1987 through June 2003 using V3–5 of MM5 driven by initial and boundary data from the ECMWF. The simulated precipitation was compared with two types of indirect precipitation observations. Firstly, winter balance on two large outlet glaciers in SE Iceland and on two large ice caps in central Iceland. Secondly, model output was used as input to the WaSiM hydrological model to calculate and compare the simulated run-off with observed run-off from six watersheds in Iceland for the water years 1987–2002. Model precipitation compared favourably with both types of validation data.

In this paper we extend the RJO07 study to a 45-year period using a new version of the MM5 model and more glaciological and hydrological data.

COMPARISON WITH GLACIOLOGICAL DATA

The spatial variability of the mass balance on large ice masses, such as Vatnajökull and Langjökull ice caps, can be mapped given data along several profiles extending over the elevation range of the ice caps. Mass balance has been observed on parts of Vatnajökull ice cap in SE Iceland since 1991 (Björnsson *et al.* 1998) and from 1996 on Langjökull ice cap, central Iceland (Björnsson *et al.* 2002) (see location on Figure 2). Here, we use measurements of accumulated winter mass balance, expressed in terms of liquid water equivalents. Björnsson *et al.* (1998) estimated the uncertainty of the areal integrals of the mass balance to be a minimum of 15%. Due to surging of the Dyngjufjökull glacier in 1998–2000, the uncertainty is considerably greater for this period and the following winter (Pálsson *et al.* 2002b).

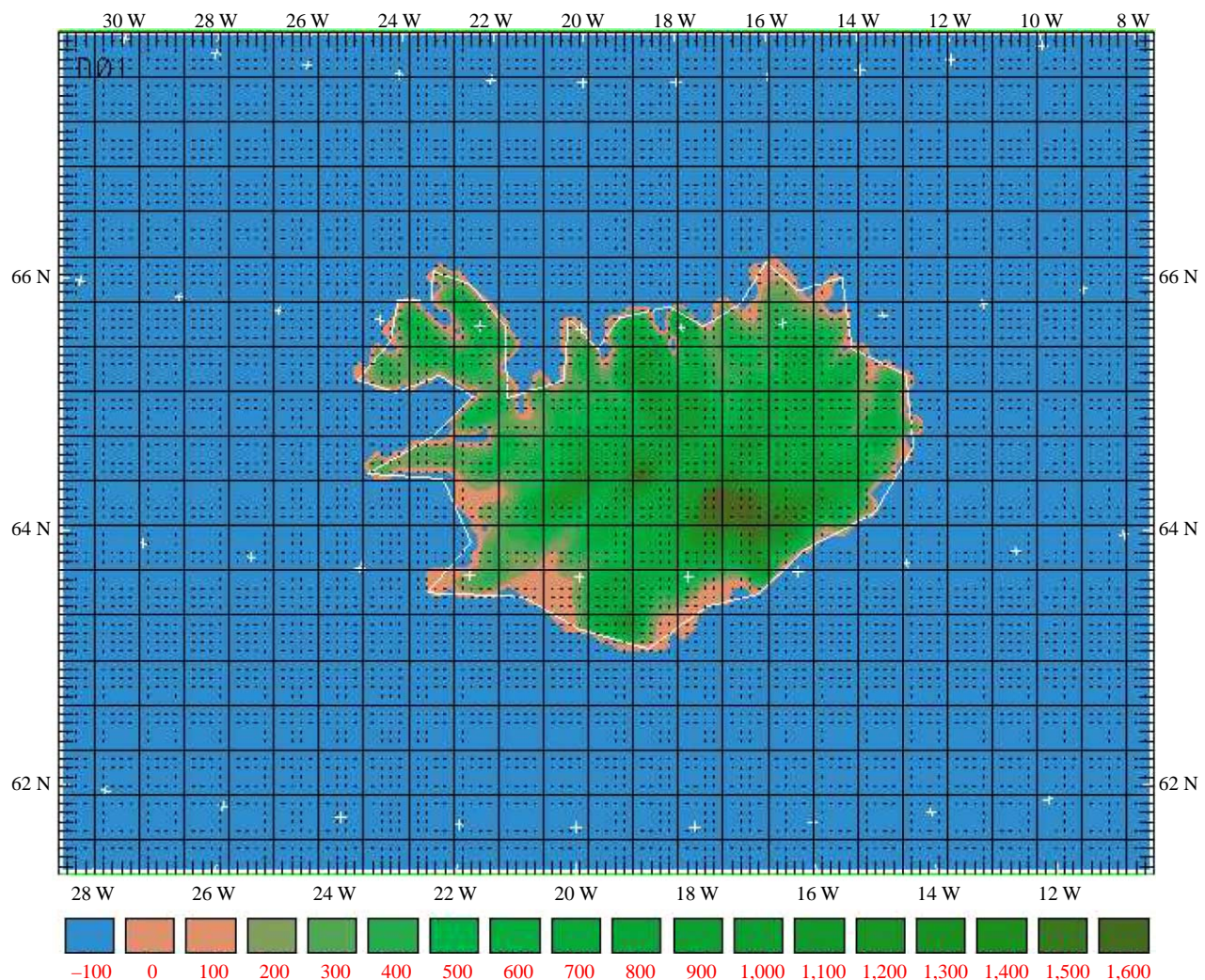


Figure 1 | Domain set-up of the MM5 model: horizontal grid size is 8 km and the number of grid points is 123×95 with 23 vertical levels.

As yet unpublished data for the past few winters are from Björnsson & Pálsson (Helgi Björnsson and Finnur Pálsson, Institute of Earth Sciences and Science Institute, University of Iceland, personal communication). The ice caps and typical locations of the mass balance stakes are depicted in Figure 2.

Mass balance on Hofsjökull ice cap has been observed at sites along the profile HN (cf. Figure 2) since 1987 and along profiles HSV and HSA since 1988 (Sigurðsson *et al.* 2004). Due to the relatively coarse horizontal resolution in our model configuration the maximum elevation of the Hofsjökull ice cap is approximately 1,540 m, i.e. more than 250 m lower than in reality. Hence, we use area-integrated data from an elevation range of approximately

1,450–1,650 m along the three profiles HN, HSV and HSA (Jóhannesson *et al.* 2006b). The number of observational data points ranges from 3 (1987–1988) to 10 (2000–2001), the most common number being 7 or 8 (16 winters out of the 19 studied here). The winter balance on Hofsjökull has been modelled to estimate the amount of precipitation that falls as rain and ablation that may take place during the winter season. These estimates have been added to the measured winter balance to produce estimates of total precipitation at the measurement sites. The methodology behind this procedure is described in detail in Jóhannesson *et al.* (1995, 2006a, pp 31–37). This correction has not been carried out for Vatnajökull and Langjökull ice caps as a whole.

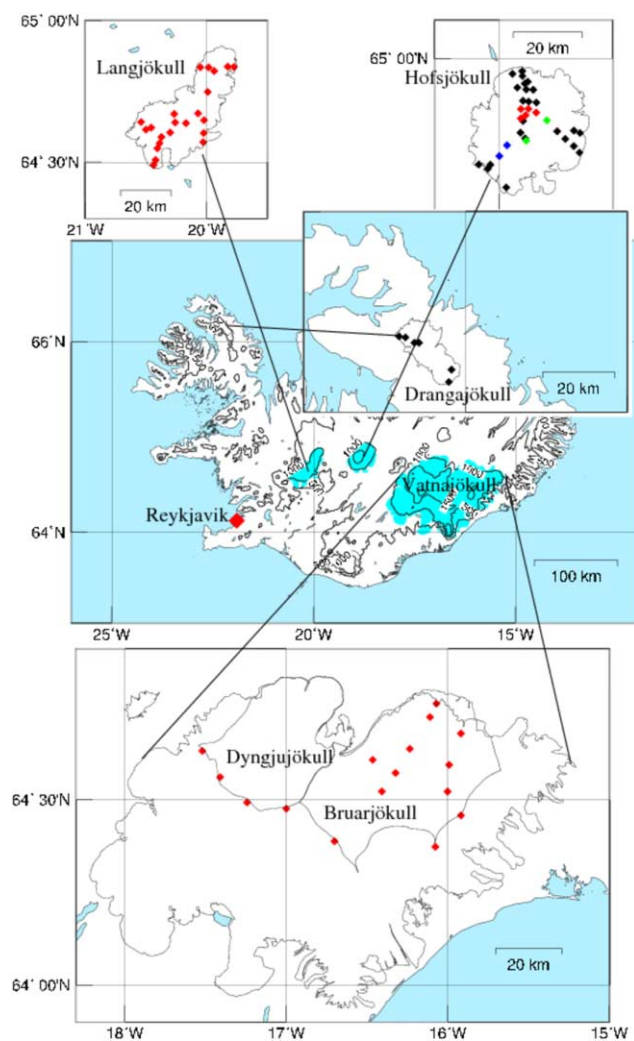


Figure 2 | Overview of the six ice caps and glaciers used for validation purposes, where dots indicate a typical location of an observation site. Red dots on Hofsjökull glacier are along profiles HN (N part), blue dots along profile HSV (SW part) and green dots along profile HSA (SE part). Observations at locations shown in black at Hofsjökull have not been used in this study. Drangajökull is split up in two regions, NW and SE parts (cf. Table 2). See Figure 1 in RJO07 for comparison.

The simulated winter precipitation at Hofsjökull ice cap is in good agreement with observations (cf. Figure 3) over the northern part of the ice cap (HN, red dots, cf. Figure 2), the SE part (HSA, green dots, cf. Figure 2) and the SW part (HSV, blue dots, cf. Figure 2). The solid line in Figure 3 shows the average of the observed winter precipitation, corrected to take liquid precipitation and/or winter ablation into account, at altitudes between 1,450 and 1,650 m at locations HN, HSA and HSV. The dashed line represents precipitation simulated by MM5 (nine-point average) at the

location of the ice cap. The simulated precipitation is within one standard deviation of the average observed winter precipitation within this altitude range for 16 out of the 19 winters during the period (1987–2006). The Spearman's rank correlation, ρ , is 0.63 with a significance value of 0.004 and the RMS error is 300 mm.

Areal integrals of winter balance over the Vatnajökull ice cap as a whole (8,100 km²), the Dyngjujökull (1,040 km²) and Brúarjökull (1,695 km²) outlet glaciers on the north side of the ice cap, and the Langjökull ice cap (925 km²) are compared with simulated wintertime precipitation by the MM5 model in Figure 4. The winter balance is not corrected to take liquid precipitation and/or winter ablation into account. The model shows least skill on Langjökull ice cap ($\rho = 0.50$; 0.14) where it has an RMS error equal to 372, and the greatest skill on Brúarjökull ($\rho = 0.83$; 0.0002) where the RMS error is equal to 171. The correlation for Dyngjujökull is 0.61 with a significance value of 0.06 and the RMS error is equal to 286. The simulated precipitation is within estimated observational error margins for 10 out of 12 winters for Dyngjujökull, 13 out of 14 for Brúarjökull and 5 out of 10 for Langjökull ice cap. The correlation for Vatnajökull ice cap

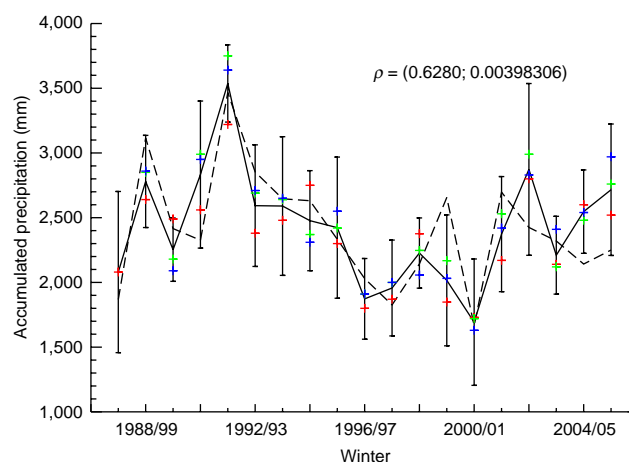


Figure 3 | Estimated mean accumulated winter precipitation (mm) along profiles HN (N part), HSA (SE part) and HSV (SW part) at altitudes between 1,450 and 1,650 m (solid line, Jóhannesson *et al.* 2006a). Dashed line represents simulated precipitation by MM5 (nine-point average) at Hofsjökull ice cap. Red, green and blue crosses represent mean winter balance values at stakes along profiles HN, HSA and HSV, respectively, within the altitude interval 1,450–1,650 m (cf. Figure 2). Error bars indicate the standard deviation of the observations. Observed values from individual snow stakes are from Sigurðsson & Sigurðsson (1998) and Sigurðsson *et al.* (2004) Sigurðsson & Thorsteinsson (personal communication). See Figure 3 in RJO07 for comparison.

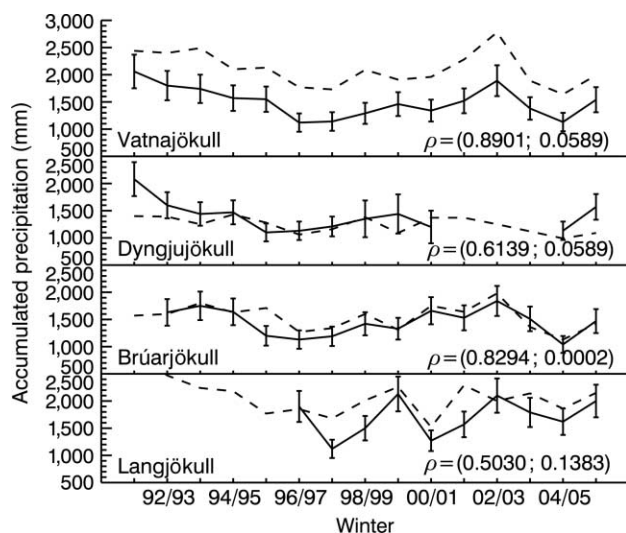


Figure 4 | Observed accumulated winter balance (solid) and precipitation simulated by MM5 (dashed) for Vatnajökull ice cap as a whole (top), Dyngjufjökull (second from top) and Brúarjökull (second from bottom) outlet glaciers and Langjökull ice cap (bottom). Error bars indicate 15% uncertainty of the observations, except for 1998–2001 at Dyngjufjökull where it is 25%. Glaciological data for Vatnajökull, Dyngjufjökull and Brúarjökull are from Björnsson et al. (1998, 2002) and Pálsson et al. (2002a,b; 2004b,c,d). Data for Langjökull ice cap are from Björnsson et al. (2002) and Pálsson et al. (2004a). As-yet unpublished data for the past few winters are from Björnsson & Pálsson. See Figure 4 in RJO07 for comparison.

is 0.89, with a significance value of 0.06 and the RMS error is equal to 634. The relative importance of liquid precipitation and/or winter ablation is greatest for Vatnajökull as a whole because the southern margin of the ice cap reaches near sea level where rain may fall and ablation may take place at any time of the year. The north flowing outlet glaciers from Vatnajökull and Langjökull ice cap do not reach to such low altitudes so this problem is less important there. This is presumably the reason why the simulated winter precipitation is consistently about 500 mm greater than the observed winter balance for the Vatnajökull ice cap as a whole. When this constant value is added to

the observations, the RMS error for Vatnajökull drops to 177 from 634.

Table 1 shows the comparison between observed accumulated precipitation and simulated precipitation using V3–5 and V3–7 of the MM5 model. The periods shown are the same as in RJO07, as well as including data from three additional winters (“starred” values in Table 1). V3–7 performs better over Dyngjufjökull and Brúarjökull outlet glaciers, but worse over the Langjökull and Hofsjökull ice caps.

Mass-balance measurements at Drangajökull ice cap in NW Iceland have only been carried out since 2004. Table 2 shows a comparison between simulated and observed winter balance for the mass-balance years 2004–2005 and 2005–2006 (Oddur Sigurdsson, Hydrological Service, National Energy Authority, personal communication). The model does not appear to capture the strong observed NW–SE precipitation gradient. The single grid cell values for the SE part are very close to the observed values but they are too high for the NW part. The area-averaged values from MM5 are, however, close to the mean observed values for the NW region of the ice cap but too low for the SE part.

COMPARISON WITH HYDROLOGICAL DATA

Jónsdóttir (2008) used the latest output from V3–7 of the MM5 model as input to the WaSiM model, run at a 1×1 km resolution, for the period 1961–1990 to create a run-off map of Iceland. The difference between measured and modelled discharge was in general found to be less than 5%, although larger discrepancies were observed (see Figure 5). For a full list of stations we refer to Table 2

Table 1 | Comparison of observed accumulated winter balance (mm) and simulated wintertime precipitation at Langjökull and Hofsjökull ice caps and Dyngjufjökull and Brúarjökull outlet glaciers (cf. Figure 2) using data from V3–5 and 3–7 of the MM5 model. “Starred” values include data for the 2003–2004, 2004–2005 and 2005–2006 winters in addition to the period shown in column 2

Glacier	Period	RMS (mm)			Spearman's ρ			Dev. from 0		
		V3–5	V3–7	V3–7*	V3–5	V3–7	V3–7*	V3–5	V3–7	V3–7*
Langjökull	1996–2003	264	411	372	0.893	0.571	0.503	0.007	0.180	0.138
Hofsjökull	1987–2003	278	286	300	0.918	0.688	0.628	5.5×10^{-7}	0.003	0.004
Dyngjufjökull	1991–2001	405	271	286	0.365	0.614	0.610	0.300	0.059	0.060
Brúarjökull	1992–2003	194	185	171	0.691	0.811	0.830	0.019	0.003	0.0002

Table 2 | Accumulated winter balance (mm) and simulated wintertime precipitation at Drangajökull, NW Iceland (cf. Figure 2). Observed winter balance is taken as the mean of stakes above 400 m altitude in the northwestern (NW) part of the ice cap and in the southeastern (SE) part. Simulated precipitation is both taken as a nine-point mean value (lower values) for the nearest grid cells as well as the nearest grid cell value (higher values)

Winter	NW _{Obs} (mm)	NW _{MM5} (mm)	SE _{Obs} (mm)	SE _{MM5} (mm)
2004/2005	1,797 (3 pts)	2,090/2,554	2,675 (2 pts)	2,072/2,603
2005/2006	1,833 (3 pts)	2,105/2,524	2,815 (2 pts)	2,127/2,604

in Jónsdóttir (2008, pp 105–106). The WaSiM model was not run with a groundwater module. Instead, precipitation simulated by MM5 was scaled in order to make the simulated water balance fit the measured water balance for individual watersheds. A detailed description of this method can be found in Section 6 in Jóhannesson *et al.* (2007, pp 50–53) and Jónsdóttir (2008, pp. 103–106). Therefore, comparison of measured and simulated water balance cannot be directly used for validation of the model-generated precipitation. According to the non-scaled MM5 output for the period 1961–1990, mean precipitation for the whole of Iceland was $1,790 \text{ mm yr}^{-1}$. After scaling the precipitation, this value was reduced to $1,750 \text{ mm yr}^{-1}$, i.e. by approximately 2%. This difference can, to some extent, be explained by the fact that precipitation falls on porous post-glacial lava in some areas and flows through groundwater aquifers to the ocean without participating in surface run-off. Earlier research (Tómasson 1982) has estimated this flow to be of the order of $33\text{--}62 \text{ mm yr}^{-1}$. This comparison of total accumulated scaled and

non-scaled precipitation indicates that MM5 produces comparatively unbiased precipitation estimates when integrated over the whole of Iceland.

Table 3 compares observed and modelled discharge from six watersheds (cf. Figure 6) that are not much affected by groundwater flow. These discharge stations are the same as used for validation of an earlier MM5 model version (V3–5) by RJO07. The periods shown are the same (1987–2002), for comparison purposes, as well as longer periods where available (“starred” values in Table 3). Here, non-scaled precipitation is used in the hydrological modelling in order to obtain an independent validation of the precipitation generated by MM5. For the 15-year period, the difference between modelled and observed discharge (denoted by Q_{meas} in Table 3) is reduced, or remains the same, for four out of six watersheds when the newer version of the MM5 model (V3–7) is used compared with the results obtained with the earlier model version. The relative difference between the simulated and observed water balance is in the range -24.5 to 10.8% , with four of the six values in the range -5 to 9% . The relative difference between observed (denoted by Q_{meas}^* in Table 3) and simulated run-off for the longer simulation periods ranges between -3.0 and 5.0% .

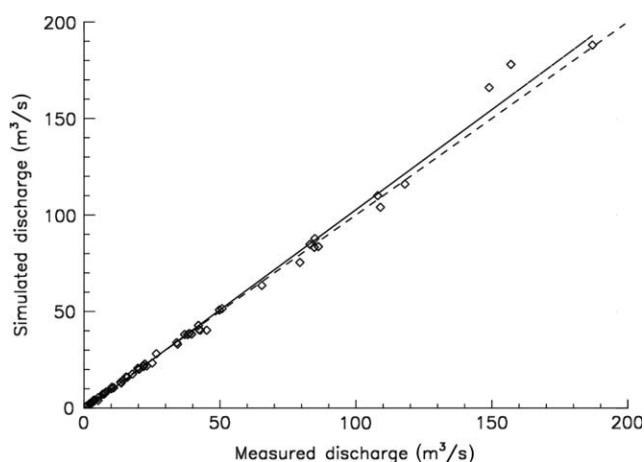


Figure 5 | Measured and simulated (WaSiM/MM5) mean discharge ($\text{m}^3 \text{s}^{-1}$) at the watershed gauges. Dashed line indicates a perfect fit, while the solid line represents the linear best fit between the measured and simulated discharge. Same as Figure 3 and 4 in Jóhannesson *et al.* (2007, p 51).

DISCUSSIONS

In this study, numerically simulated precipitation has been compared with non-conventional observations of precipitation, i.e. snow accumulation and run-off. This type of data only provides validation on a much longer timescale than conventional rain-gauge data, and the daily error in the precipitation downscaling remains unclear. However, the comparison with the observational data shows that the climatological values of the simulated precipitation are of good quality.

Table 3 | Comparison of observed and simulated discharge (m^3s^{-1}) at six discharge stations and Nash–Sutcliffe coefficients of model fit, using unscaled modelled precipitation from V3–5 and 3–7 of the MM5 model for the 15-year period 1987–2002 and for longer periods (“starred” values) for V3–7 where available (cf. Table 2 in Jónsdóttir (2008)). The longer simulation periods are, respectively, 1963–2001, 1971–2001, 1963–2001, 1976–2001, 1976–2001 and 1991–2004. The discharge stations are, respectively; Vatnsdalsá River, Norðurá River, Fossá í Berufirði River, Hvalá River, Fnjóská River and Hamarsá River. The location of the discharge areas is shown in (Figure 6)

Station no.	Q_{meas}	Q_{meas}^*	Q_{calc}			Difference (%)			R2			R2 log		
			V3–5	V3–7	V3–7*	V3–5	V3–7	V3–7*	V3–5	V3–7	V3–7*	V3–5	V3–7	V3–7*
45	12.3	10.3	13.4	13.4	10.8	8.9	8.9	5.0	0.69	0.62	0.54	0.60	0.57	0.46
128	26.8	22.4	29.1	29.7	22.8	8.5	10.8	2.0	0.61	0.53	0.58	0.64	0.63	0.56
148	9.1	8.2	10.4	8.64	8.4	14.3	–4.6	1.0	0.64	0.57	0.59	0.71	0.56	0.6
198	26.8	15.5	25.4	20.2	16.1	–5.2	–24.5	4.0	0.62	0.45	0.51	0.60	0.39	0.53
200	48.4	39.6	53.9	51.3	38.3	11.4	6.2	–3.0	0.53	0.50	0.51	0.53	0.53	0.55
265	19.6	19.9	20.8	18.6	20.2	6.1	–4.9	2.0	0.70	0.64	0.66	0.74	0.71	0.71

The present study is based on a horizontal resolution of 8 km. In areas where there is substantial subgrid orography, changes in the horizontal resolution will inevitably lead to locally different simulated precipitation. Such a difference may, however, not give a proportionally large signal in tests of the kind that are presented in this paper. This is because the glacier observations (apart from Drangajökull, NW Iceland) are not in the vicinity of substantial subgrid variability in orography, and because the run-off calculations are all based on averaging over a substantial area.

The discharge stations, and accompanying watersheds (cf. Figure 6) are the same as used for validation of an earlier MM5 model version (V3–5) by RJO07. As the WaSiM model was not run with a groundwater module it was necessary to compare the non-scaled simulated precipitation from the MM5 model with simulated discharge from watersheds that are not affected by groundwater flow. Looking at a geological map of Iceland (cf. Figure 7) it is clear that these watersheds are in areas where the geological formations are relatively old, i.e. from the Tertiary or late Tertiary periods. As a result the bedrock is dense with a low

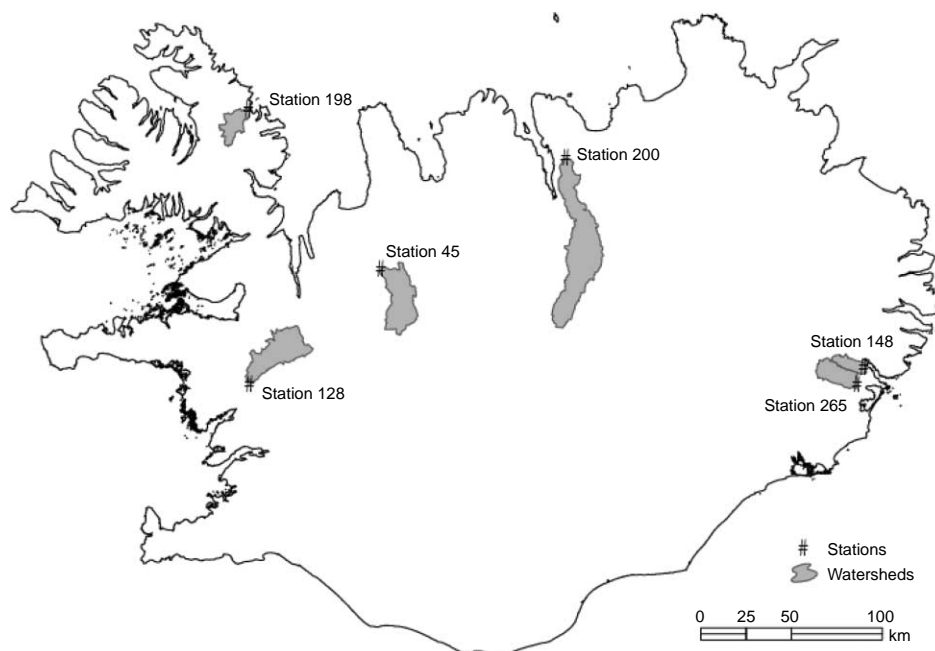


Figure 6 | The location of the six watersheds and corresponding gauging stations used for validation of the MM5 precipitation data. Same as Figure 2 in RJO07.

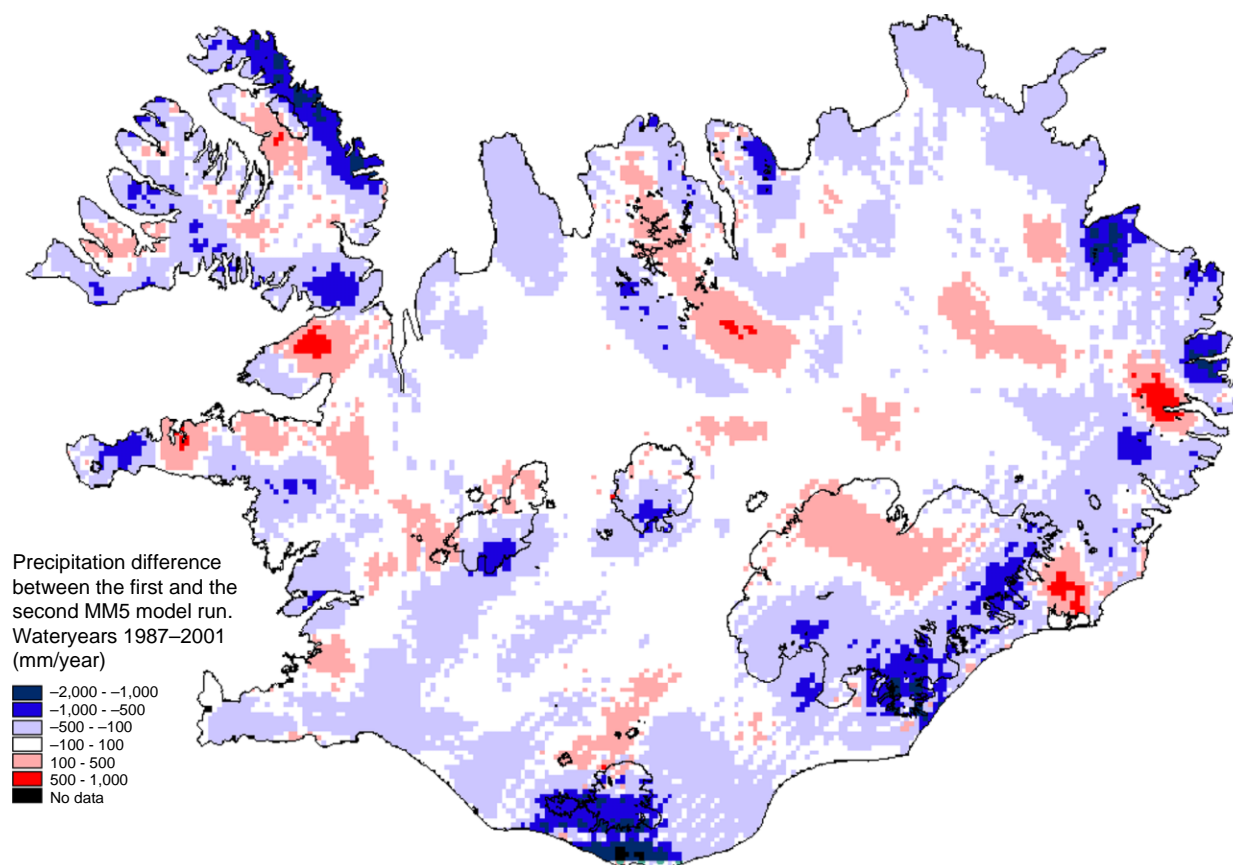


Figure 8 | Difference (MM5 V3–7 minus MM5 V3–5) in simulated mean annual precipitation for the water years 1987–2002.

in the model. However, as the ratio of simulated convective precipitation to explicitly simulated precipitation by the microphysical scheme is low (less than 5% of the total precipitation), this difference is not believed to play an important role in the difference is simulated precipitation between V3–5 and V3–7 of MM5. Other model components used in this study and the RJO07 study, such as the planetary boundary layer scheme, radiation schemes (both short and long wave) and the cumulus scheme, only experienced minor modification or bug fixes between V3–5 and 3–7.

Simulated run-off based on model data from V3–5 and V3–7 is, in general, in good agreement with observed run-off (cf. Table 3). For the 15-year period 1987–2002, the relative difference between observed and simulated run-off is reduced for three out of six watersheds when using data from V3–7 of the MM5 model. The difference remains the same for one watershed (station no. 45) and increases

for two out of six watersheds. Notably, V3–7 seems to underestimate precipitation at gauging station no. 198, located in NW Iceland. However, this underestimation in run-off is not present when run-off is simulated over a longer time period (1976–2002 vs. 1987–2002). The relative difference drops from –24.5% to 4.0%. The reason for this sensitivity is unclear. The Nash–Sutcliffe coefficients of model fit remain similar for both V3–5 and V3–7, with V3–5 showing slightly greater skill. The exception being station no. 198, where the older model shows considerably greater skill, regardless of the time period in question.

When looking at long term means (weeks and/or months) of observed and simulated precipitation, as is done here, there is always the risk of compensation of errors on a shorter timescale (hours and/or days). Arason *et al.* (2010) use the same simulated data series as is done in this paper and compared the results in a systematic

way to observed liquid precipitation. This was done in order to minimize the effects of undercatchment of solid precipitation in observations. They conclude that there are indeed systematic errors in the simulated precipitation, even in areas of resolved orography. Most noticeable, the risk of false alarms (i.e. the model simulates precipitation, but none is observed) is highest in N Iceland, particularly during winter. The probability of missing precipitation events (i.e. precipitation is observed, but none is simulated by the model) is greatest in the summer and on the lee side of Iceland in southerly flows. This sensitivity to flow regimes could, to some extent, explain the large differences between simulated discharge (cf. Table 3, –24.5% for the period 1987–2002 vs. 4.0% difference for the period 1976–2001) at station no. 198 in NW Iceland. Subgrid orographic effects could also play an important role. Figure 1 in Arason *et al.* (2010) shows, for example, great variability in the relative error (MM5-Obs/Obs) for the two stations located in the vicinity of discharge station no. 198 in NW Iceland. The relative error of the simulated summer (i.e. June, July and August) precipitation is 4.5% and 73.6% for two stations, which are located within 15 km of each other (stations Litla Ávík and Gjögur, respectively).

Although there are some biases in the simulated precipitation, important statistical properties can still be gained from the dataset. Elíasson *et al.* (2009) have extracted statistical parameters of extreme precipitation from the simulated time series. They find the average difference between observed and simulated precipitation (Obs-MM5) at 70 out of 73 observation stations to be around -5 mm d^{-1} , with a standard error of 17 mm. As observations at the interior of Iceland are very sparse, the simulated time series gives important information about plausible return periods of extreme precipitation in these regions.

CONCLUSIONS

In general, the MM5 V3–7 model results compare favourably with the observed winter balance, in particular for Hofsjökull, where corrections to take liquid precipitation and/or winter ablation into account have been made, and for the outlet glaciers Dyngjufjökull and Brúarfjökull. More extensive comparison of simulated precipitation with glaciological observations needs to be made with

corrected mass balance data from all the ice caps. Simulated discharge compares favourably with observed discharge for the majority of observation sites, indicating a satisfactory performance of the model.

There is an overall improvement of the simulated precipitation when going from MM5 V3–5 to MM5 V3–7. However, this improvement is both period- and site-dependent and, at some locations, the study shows a degradation in model performance. In general, V3–7 gives less precipitation on the upstream slopes.

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