Relation between meso-scale climate and glacier/snow mass balance on Svalbard

SVALI Deliverable D2.3-11

Report

BJÖRN CLAREMAR
SVALI POSTDOC
DEPARTMENT OF EARTH SCIENCES
UPPSALA UNIVERSITY

JULY/AUGUST 2013

UPPSALA
UNIVERSITET

Abstract
The surface snow mass balance for a glacier can be estimated by point observations or by satellite observations or a combination of the two. The point observations must, however, somehow be horizontally interpolated or extrapolated and the satellite measurements only takes care of the elevation changes not the snow water equivalent changes. The most important processes determining the mass balance are the precipitation and melting that can be related to positive degree days. The horizontal distribution of the precipitation and the temperature can be simulated by an atmospheric model. During the summer the surface snow mass balance is most affected by the melting process. Rain and melt water can accumulate in the snow by retention or refreezing in the snow or at the glacier ice surface but this will mainly affect the firn only deeper down. For the glacier as a whole this is, however, important. In this report the precipitation and temperature outputs from the Polar WRF model are related to accumulation and melting at a number of Svalbard glaciers.

It is found that the terrain affects the precipitation more than what is captured by the model with the horizontal resolution of 8 km. In flat terrain there are indications that the model is more in resemblance to the observed accumulated winter snow. The wind drift of surface snow, however, complicates the interpretation of the observed snow accumulation and lowers the inter-annual correlations between model and observations. The comparison of summer melt and summer temperature, using a positive degree day method, indicates an underestimation of summer temperatures at several glacier sites.

To use atmospheric models to give data of precipitation and temperature patterns over Svalbard glaciers we conclude that the horizontal resolution must be finer than 8 km. Seasonally and geographically dependent lapse rates could increase the reliability of the local temperature for correcting the model elevation to the observation sites. Finally, a wind drift model must be used to calibrate the atmospheric model to point measurements, but may be of less importance when integrating over a glacier.

1. Introduction

Precipitation in cold regions is difficult to measure. This problem is twofold; it regards wind and internal accumulation. The first one is related to the effect of wind causing falling snow to flow around precipitation gauges due to flow distortion. Another way to determine snow deposition is the snow mass balance. However, here wind drift plays an important role for the accuracy of this method. The internal accumulation is melt water that percolates and refreezes in earlier years' layers, i.e. the firn, and cannot be accounted for in observations of the snow mass balance. The internal accumulation is mainly a problem during the summer season.

This report investigates the precipitation output from the WRF (Weather Research and Forecast) model and compares it to observed surface snow mass balance (SMB) or total glacier mass balance (GMB) which includes calving estimations at a number of glaciers on Svalbard. The observed summer melt is related and compared to the modelled positive degree days (PDD).

2. Measurements and model

2.1 Observation sites

We use GMB data from Glacier Mass Balance Bulletin (GMBB) (WGMS 1991–2011) (Austre Brøggerbreen, Kongsvegen and Midtre Lovénbreen) and SMB data from individual research groups (Lomonosovfonna, Vestfonna, and Holtedahlfonna, Amundsenisen and Hansbreen).

Austre Brøggerbreen (78.88°N, 11.83°E) and Midtre Lovénbreen (78.88°N, 12.07°E) are both small glaciers (5 and 4 km long, respectively) very close to Ny-Ålesund and have been monitored since 1967 and 1968, respectively (Norwegian polar institute). Both have very strong negative mass balances, Austre Brøggerbreen by 20 m and Midtre Lovénbreen by 16 m from the start of measurements until 2009.

Kongsvegen (78.80°N 12.98°E) is a glacier about 30 km to the south-east from Ny-Ålesund with outlet together with Kronebreen and Kongsbreen in Kongsfjorden. Monitored since 1987 (Norwegian polar institute). In the beginning Kongvegen had positive mass balance but from 1997 more or less negative mass balance

Hansbreen (77.08°N 15.67°E) is situated in the southern Spitsbergen with an outlet in Hornsund. It starts at about 600 m a.s.l. and is about 16 km long. It has been monitored since 1989 (Polish Academy of Sciences) and have had an negative glacier mass balance. Data are from Szafraniec (2002).

Lomonosovfonna (LF-09, 78°49'N, 17°26'E) is a drilling site maintained by Uppsala University at approximately 1200 m a.s.l. It is drained by several outlet glaciers, for instance Nordenkiöldbreen and Mittag-Lefflerbreen. The annual layers, i.e., net balance, are identified and snow water equivalent (SWE) is estimated since 1989.

The Vestfonna site data consist of snow pit data from spring 2008 to fall 2010 in a transect at the north-western slope 197–500 m a.s.l. (c. 80.0°N, 19.5°E) and at the Ahlmann Summit at 600 m (80°N 20.15°E) (Möller 2011). The lower parts have a negative SMB whereas the higher parts have positive SMB.

Holtedahlfonna lies in the north-western part of Spitsbergen (c. 79°N, 13.5°E) and has outlets in the before mentioned Kongsbreen and Kronebreen. The area is c. 1,375 km^2 and it lies at about 500–1300 m a.s.l. SMB data from the period 2003–2010 were provided by Jack

Kohler (Norwegian Polar Institute). In this period the net SMB was mainly negative except for 2006, 2008 and 2012.

Amundsenisen (77.3°N, 15.5°E) is situated about 30 km to the north from Hansbreen, at approximately 700 m a.s.l. SMB used in this study is from the years1990–1994 (Jania, 1994).

2.1 WRF model

The WRF model (Skamarock et al. 2008) is an open source model (http://www.mmm.ucar.edu/wrf/users/) widely used in research and is useful in ranges 100 of kilometres down to individual cloud scales of 1–5 km. The model output used in this investigation was produced as a data base covering Svalbard and the period 1989–2010 as SVALI deliverable 3.1-4. The horizontal resolution was 8 km and the model set-up was basically that of the study by Claremar et al. (2012) but for the Polar WRF3.2.1 version (e.g. Wilson et al. 2011). In Claremar et al. (2012) some physics schemes were changed in a sensitivity study. We chose for the data base simulations reported here to use the Morrison double-moment microphysics scheme (Morrison et al. 2005) and the MYNN2.5 turbulence schemes (Nakanishi and Niino 2006). Forcing data were from the ERA-Interim re-analysis (Dee et al. 2011). The outer 9 model grid points are omitted to avoid too severe model boundary effects. Figure 1 shows the model grid and terrain and the glaciers investigated.

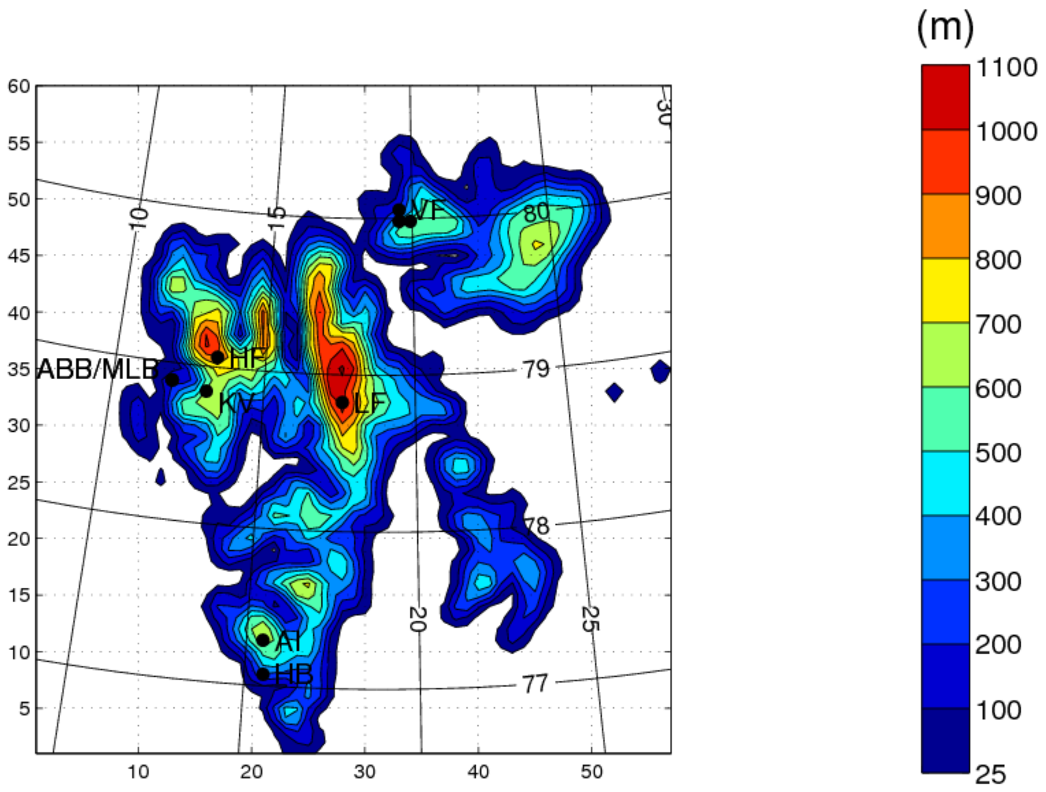

FIGURE 1. Model domain and the positions of the glaciers. Abbreviations are for Austre Brøggerbreen (ABB), Midtre Lovénbreen (MLB), Kongsvegen (KV), Hansbreen (HB), Amundsenisen (AI), Lomonosovfonna (LF) and Vestfonna (VF).

3. Results

The modelled precipitation clearly shows the influence from the terrain and the most common winds from the east or south-east. In figure 2 the mean annual precipitation for the period 1989–2010 is shown. The highest precipitation is found on high elevations but also on the south-eastern slopes. Valleys are in precipitation shadows.

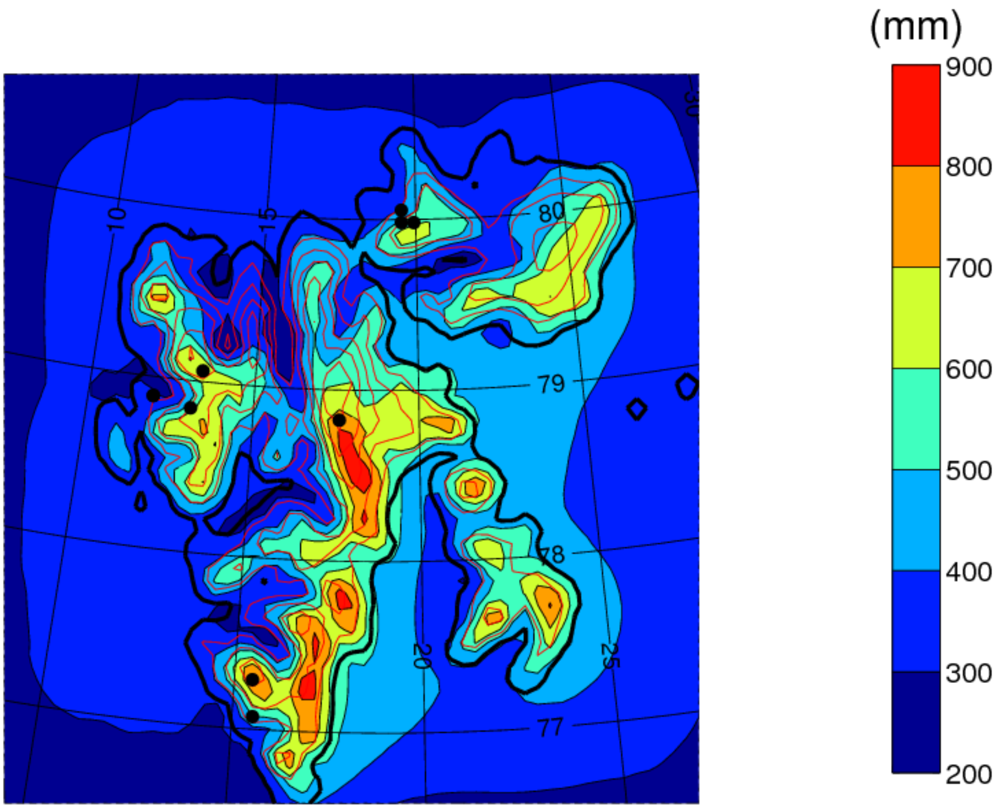

FIGURE 2. Mean annual precipitation. Red contour lines show terrain heights with equidistance of 200 m.

3.1 Winter accumulation

The winter precipitation and winter mass balance are the easiest variables to compare since melting and sublimation are of minor importance. Figure 3 shows the average winter precipitation between 1 Sept and 31 May in the period 1989–2010. Comparing with Figure 2 it is clear that most of the precipitation falls during these 9 winter months.

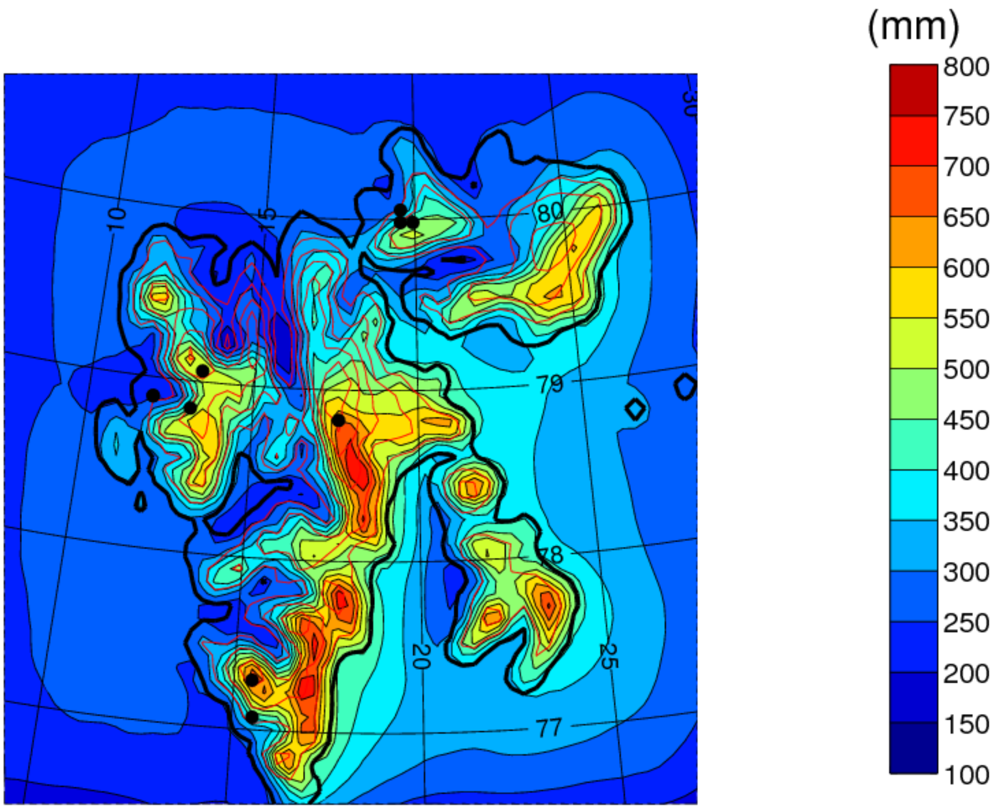

FIGURE 3. Mean winter precipitation (1 September–31 May). Red contour lines show terrain heights with equidistance of 200 m.

There are data of winter SMB only from Holtedahlfonna, Amundsenisen, Hansbreen and Vestfonna. At Holtedahlfonna, 8 years are available covering the WRF period (spring 2003–2010). In Figure 4, the observed and modelled winter accumulation are shown. The average modelled and observed accumulation during this period is 0.55 m and 0.56 m, respectively. Even if it is evident that the inter-annual variations are close to each-other and the correlation coefficient, r, is 0.63, the correlation is not statistically significant due to the small amount of data (Pearson's test gives $r = 0.71$ for $n = 8$).

At Amundsenisen (1990–1994), shown in Figure 5, the observed and modelled accumulations are more different. Observed values are in average 1.50 m, whereas modelled only gives 0.66 m. However, the correlation is very high, $r = 0.96$, which is significant (Pearson's test gives $r = 0.84$ for $n = 5$). This points at the conclusion that the WRF model, with its set-up underestimates the precipitation. But blowing snow from surrounding mountains can also play a large role here.

The neighbouring glacier Hansbreen (Figure 6), shows similar differences (40 % underestimation but very low correlation, $r = 0.11$) but the more isolated position for this glacier points at that the WRF set-up really underestimates the precipitation due to the complex terrain and microphysics scheme.

At Vestfonna, winter mass balance was measured at six sub-sites with different heights in 2008 but only four in 2009. Where several observations were done at a sub-site a mean value is used. Further the observations were grouped into three intervals, the lowest below 350 m, the middle between 350 and 500 m in the transect and the highest on the Ahlmann Summit at 600 m (only 2008). These groups correspond to the three grid point at VF in Figure 1 at the model heights 221, 420 and 532 m. The result is given in table 1. There is a height gradient of the winter accumulation but otherwise poor agreement between model and observations. The negative accumulation in the lower transect, however, indicates that the wind transports away the surface snow. On the other hand, the observed accumulation on Ahlmann Summit is much higher than the modelled accumulation, indicating wind transport to this area. The prevailing winter wind direction is south-easterly so the snow is not transported up the transect. Rather, the curvature and position determines were the transported snow is accumulated. If we take the mean accumulation of the three intervals this gives observed 0.40 m and modelled 0.49 m winter accumulation.

From this we cannot evaluate whether the model underestimate or overestimate the precipitation in general. On the other hand, we can expect that the model does not capture the local topographical effects of the precipitation, which can explain the underestimation at Amundsenisen.

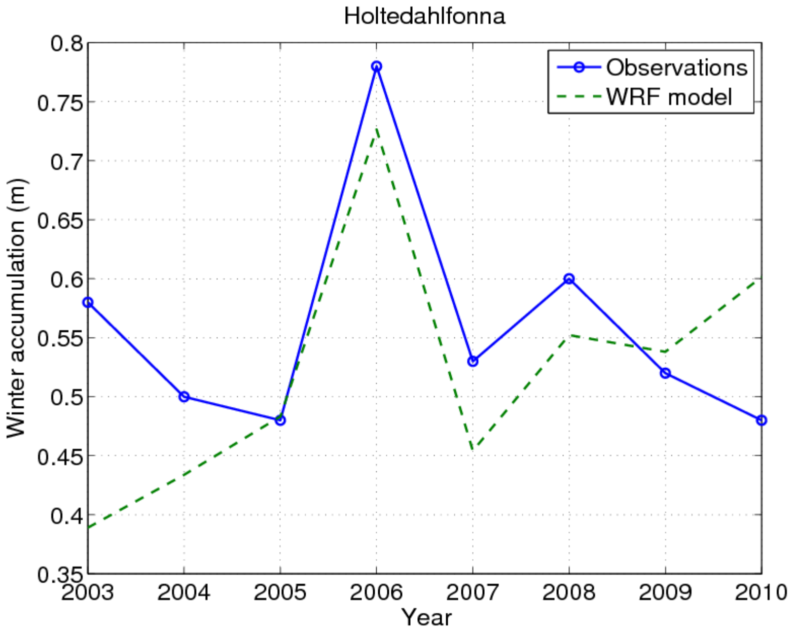

FIGURE 4. Observed and modelled winter accumulation at Holtedahlfonna.

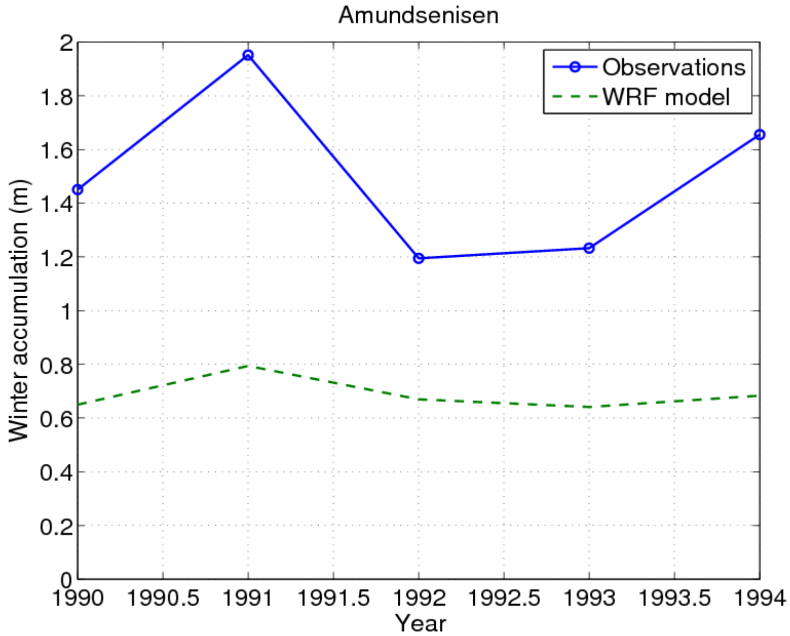

FIGURE 5. Observed and modelled winter accumulation at Amundsenisen.

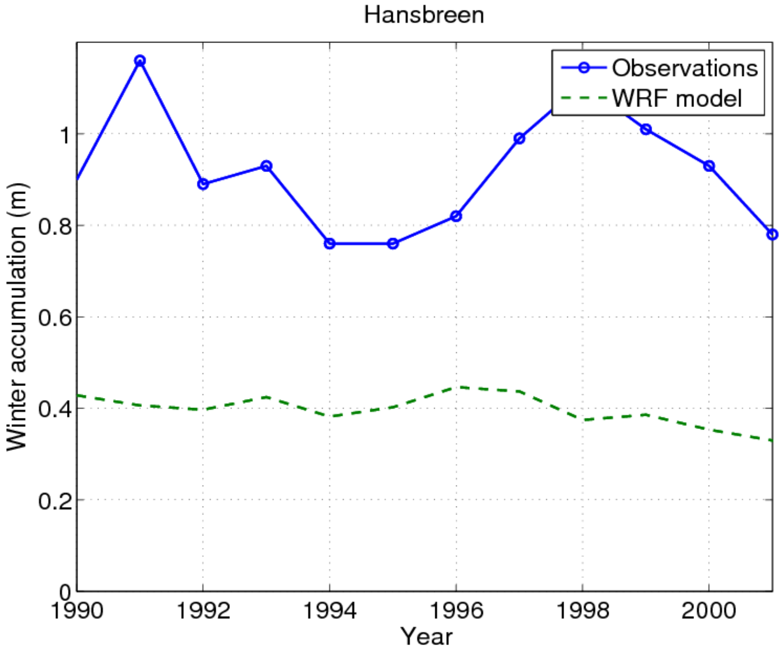

FIGURE 6. Observed and modelled winter accumulation at Hansbreen.

Table 1. Observed and modelled winter accumulation (m) at Vestfonna.

	2008		2009	
	observed	modelled	observed	modelled
Lower transect	–0.09	0.39	–0.12	0.36
Upper transect	0.30	0.51	-	0.46
Ahlmann Summit	0.98	0.58	-	0.51

3.2 Summer balance

The summer precipitation has about the same pattern as in the winter, as seen in Figure 7, but much lower, of the order 100 mm in 3 months. There is, however, a significant shift to the western sides of terrain slopes, indicating more westerly winds. During the summer, the influence from melting is the major factor of summer balance over mostly all Svalbard. The effect of positive temperatures on melting is embedded in Positive Degree Days (PDD) and there have been numerous studies for finding the degree day factor (DDF) for relating the ablation to PDD. DDF varies among different glaciers because of the albedo and whether the sky is clear or cloudy and if the surface is bare ice or snow. The values are of the order 3 mm K^{-1} day^{-1} for ice and 10 mm day^{-1} for snow. In this section the summer precipitation and modelled PPDs at the glaciers (temperature are height corrected using the lapse rate –4 K km^{-1}) are compared to the summer balance and the best suitable DDFs are estimated. Very large estimated DDFs would indicate an underestimation of the summer temperature by the model. It was assumed that the summer precipitation, even in liquid form, was added to the mass of the measured snow layer.

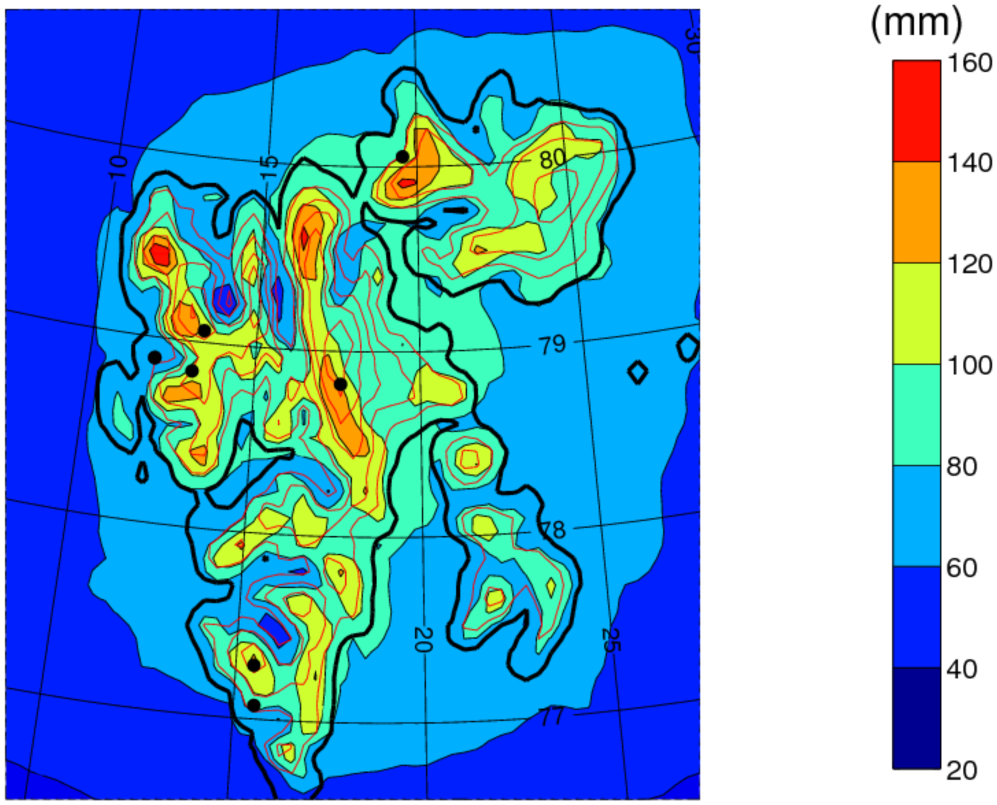

FIGURE 7. Mean summer precipitation (June-August).

At Holtedahlfonna, the summer ablation (Figure 8) was less correlated to the model, compared to the winter accumulation, r = 0.39 (not significant). The best DDF (with regards to the uncertainties in the precipitation) was estimated to 22 mm K^{-1} day^{-1}. This indicates an underestimation of the PDDs at this site and thus the summer temperature.

At Hansbreen (Figure 9), the correlation coefficient is 0.29 (not significant) and the DDF is 13 mm K^{-1} day^{-1}. The neighbouring Amundsenisen only had 3 values but the DDF was estimated to 23 mm K^{-1} day^{-1},. i.e. an underestimation of the temperature.

Vestfonna had observations only along the transect but for 3 years (Table 2). The mean DDF for the sub-sites was estimated to 10 mm K^{-1} day^{-1}, a good value in the light of that there were observed snow on the surface during the summer season The model and observations agreed on higher ablation at the lower part of the transect. Otherwise the correlation was low.

The summer ablation was difficult to model and depends both on the uncertainty of temperature and precipitation and on whether the melt water is stored in the annual snow layer as retained or refreezed water or percolated down to the firn. Remembering now that the summer precipitation is only of order 0.1 m, the PDD model and the temperature is probably the most sensitive parameter for the summer balance, at least for Hansbreen and Holtedahlfonna. At Vestfonna in 2008 and 2009, the observed ablation was of the same order as the modelled precipitation.

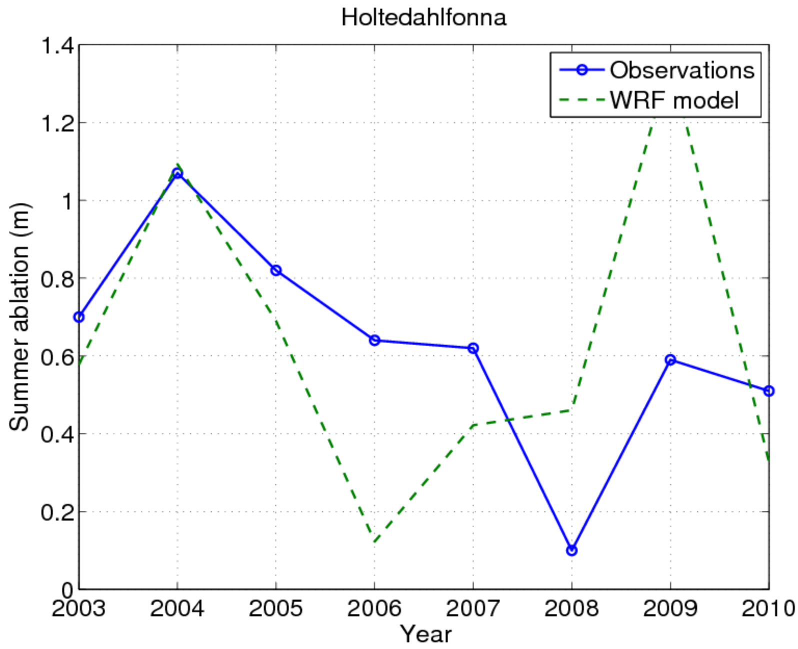

FIGURE 8. Observed and modelled summer ablation at Holtedahlfonna.

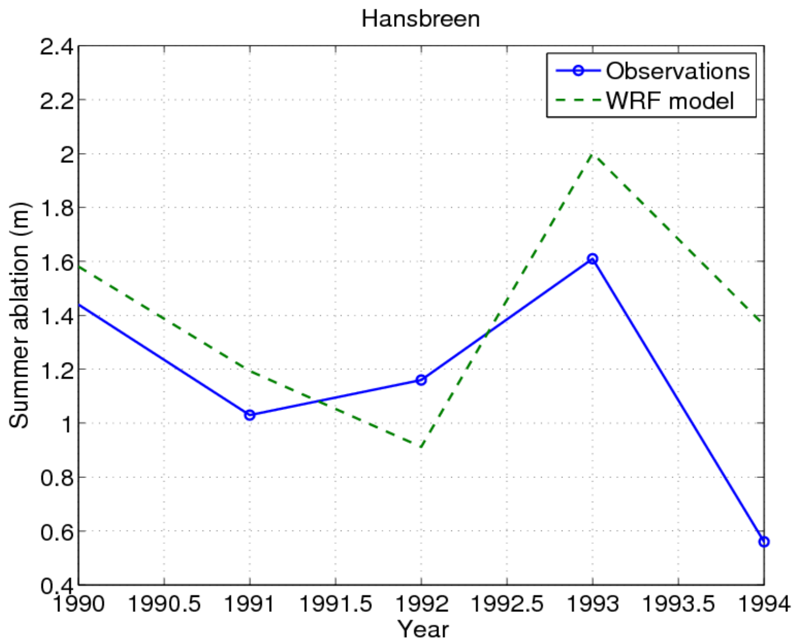

FIGURE 9. Observed and modelled summer ablation at Hansbreen.

Table 2. Observed and modelled summer ablation (m) at Vestfonna.

	2008		2009		2010	
	observed	modelled	observed	modelled	observed	modelled
Lower transect	0.15	0.36	-	0.59	0.67	0.37
Upper transect	0.04	0.07	0.22	0.45	0.55	0.17

3.3 Net mass balance

The above analysis indicates some problems in the WRF simulations and an uncertainty in the observations due to wind drift. However, in this section, the modelled net SMB is estimated for four glaciers with only the net glacier balance available together with calving (for Lomonosovfonna only SMB).

For Lomonosovfonna it is shown that the modelled annual precipitation and PDDs cannot explain the variations in the observations that are lower (Figure 10). Tuning the DDF to 25 mm K^{-1} day^{-1} gives the correct mean value. Thus the summer temperature is underestimated here.

For Austre Brøggerbreen (Figure 11) and Midtre Lovénbreen (Figure 12) the correlation is much higher (r = 0.75 for both). The DDFs are 9 and 8 mm K^{-1} day^{-1}, respectively.

The correlation is also high at Kongsvegen (r = 0.77) and here DDF is estimated to 11 K^{-1} day^{-1} (Figure 13).

Given all the uncertainties, the north-western glaciers are rather well modelled by the WRF model output, although the calving is included in the observations. Also the DDFs are in good agreement with other studies as there were snow on the surface during the whole summer at least on the major parts of the glaciers. However, Lomonosovfonna is very poor modelled, both in too high PDDs and inter-annual variability. This can very likely be due to snow loss from wind transport since it is one of the high-points of the plateau.

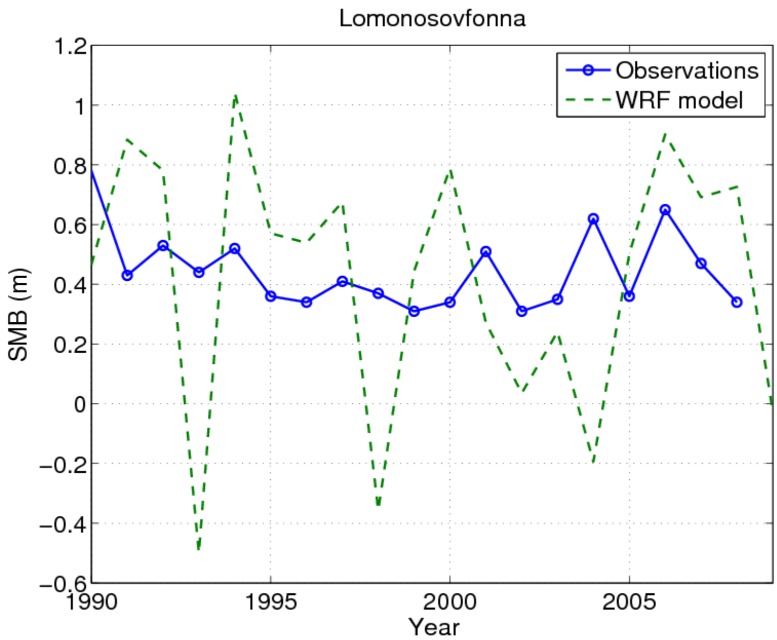

FIGURE 10. Observed and modelled net SMB at Lomonovfonna.

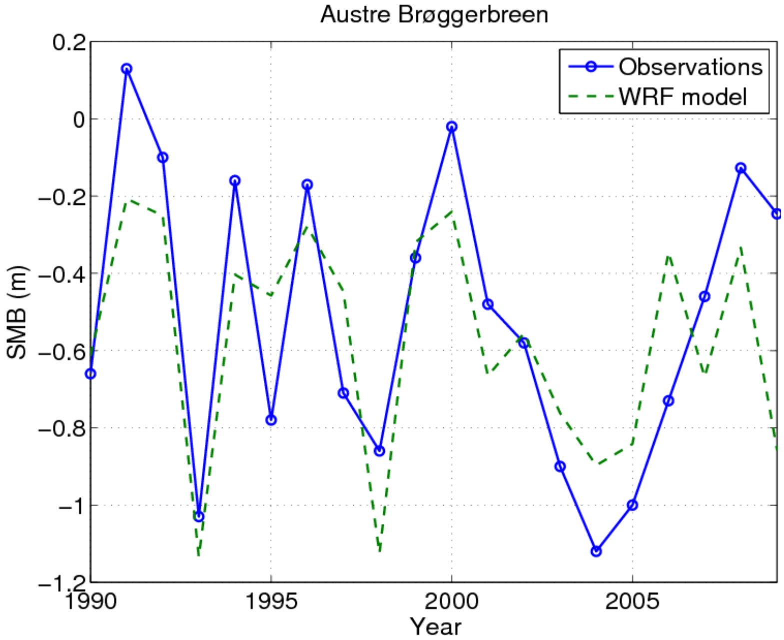

FIGURE 11. Observed and modelled net SMB at Austre Brøggerbreen.

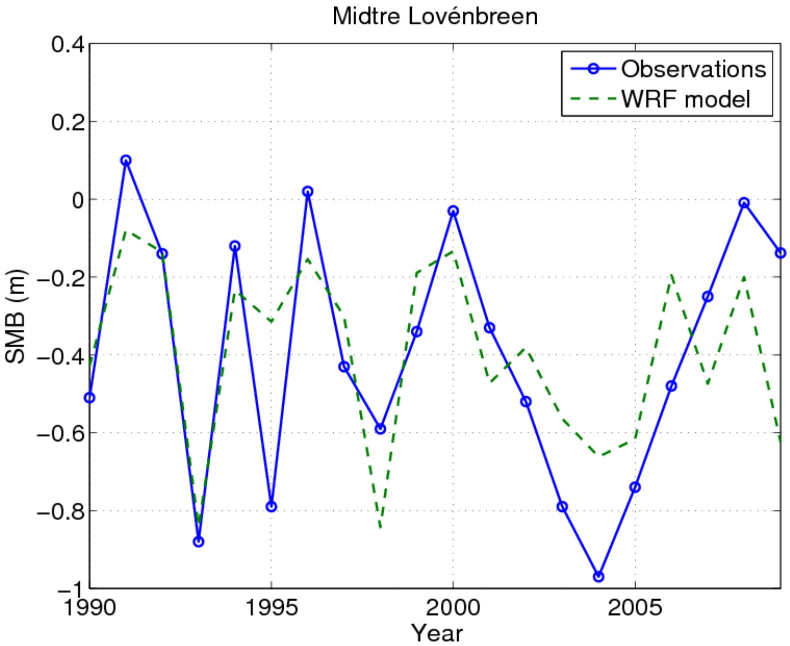

FIGURE 12. Observed and modelled net SMB at Midtre Lovénbreen.

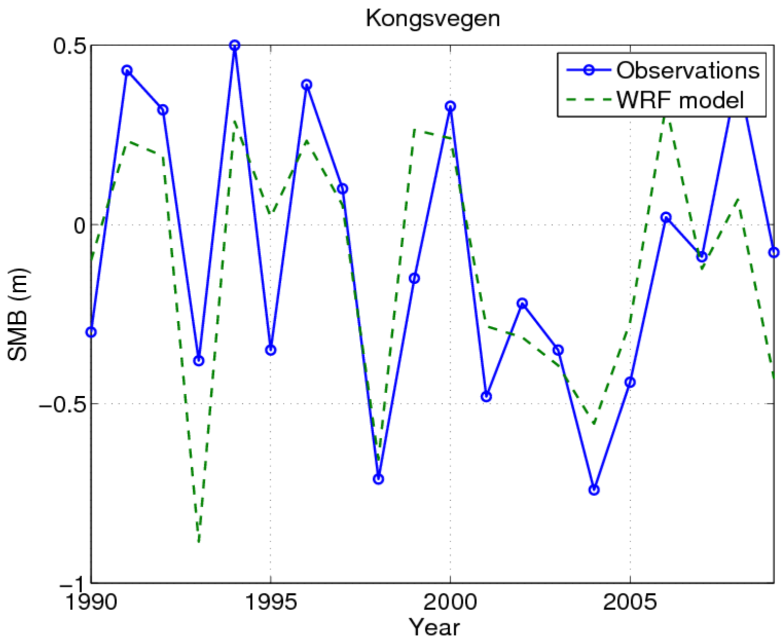

FIGURE 13. Observed and modelled net SMB at Kongsvegen.

4. Conclusions

This investigation has compared output precipitation from the atmospheric model WRF to observations of SMB. The winter SMB is not very affected from melting and should then be mainly determined from the precipitation. The analysis showed that the model both underestimated and overestimated (lower part of Vestfonna) the winter accumulation. Probably the general problem is the underestimation of the precipitation, especially for the sites with complex surrounding topography. For the rather large and flat Holtedahlfonna the winter accumulation was well simulated. The overestimation at Vestfonna is probably caused by drifting snow.

The summer balance is more difficult to estimate from the model due to additional influence from temperature. There was some correlation using a PDD (Positive degree day) model for Hansbreen and Holtedahlfonna but the DDFs (day degree factors) were between 13 and 23 mm K^{-1} day^{-1}, which is a rather large value and an indication of underestimated summer temperatures. This could be an artefact of using a constant lapse rate of –4 K km^{-1}. Vestfonna was better modelled with a DDF of 10 mm K^{-1} day^{-1}, which is more consistent with degree-day coefficients from other studies with snow covered ice..

Surprisingly, the net glacier mass balance at Kongsvegen, Austre Brøggerbreen and Midtre Lovénbreen was well modelled with a DDF of 8–11 mm K^{-1} day^{-1}, given that these glaciers had snow surfaces during most of the summer season. However Lomonosvfonna was very poor modelled, possibly due to large snow drift. The influence of snow drift has been studies in Sturm and Stuefer (2013) and can be considered in a future study of this effect on Svalbard by me next year.

<u>To conclude:</u>

- The WRF model probably generally underestimates the precipitation in the complex terrain of Svalbard and specifically in southern Spitsbergen in the 8 km resolution set-up.

- 2-meter temperature has some negative biases in the summer, underestimating the PDDs and overestimating the estimated DDFs.

- Glacier mass balance can be estimated from the model at some sites.
- Different resolution and microphysics schemes in WRF should be evaluated over Svalbard for precipitation sensitivity purposes.
- The influence from wind drift should be parameterized and evaluated.

Acknowledgements

Veijo Pohjola and Sergey Marchenko at Uppsala University are thanked for input and discussions. Mariusz Grabiec, formerly at Institute of Geophysics Polish Academy of Sciences, is thanked for providing the Amundsenisen data, Jack Kohler at NPI for the data from Holtedahlfonna, Marco Möller at Westfälischen Technischen Hochschule Aachen for the Vestfonna data and Carmen Vega at Uppsala University for the Lomonosovfonna data. The work was funded by the Nordic council of ministers (SVALI, www.ncoe-svali.org)

References

Claremar, B., Obleitner, F., Reijmer, C., Pohjola, V., Waxegård, A. et al. (2012). *Applying a Mesoscale Atmospheric Model to Svalbard Glaciers.* Advances in Meteorology. 321649

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., et al. (2011). *The ERA-Interim reanalysis: configuration and performance of the data assimilation system*. Q.J.R. Meteorol. Soc., **137**: 553–597. doi: 10.1002/qj.828

Jania, J. (1994). *Field investigations during glaciological expeditions to Spitsbergen in the period 1992 – 1994 (interim report).* Uniwersytet Śląski, Katowice: 40 pp.

H. Morrison, J. A. Curry, and V. I. Khvorostyanov (2005), A new double-moment microphysics parameterization for application in cloud and climate models. Part I: Description. *J. Atm. Sci.*, vol. 62, no. 6, 1665–1677.

Möller, M. (2011). *Observation and modelling of glacier mass balances in Patagonia and Svalbard – Application and enhancement of temperature-index based modelling approaches*. Dissertation at Fakultät für Georessourcen und Materialtechnik der Rheinisch -Westfälischen Technischen Hochschule Aachen

Nakanishi, M. and Niino H. (2006), An Improved Mellor–Yamada Level-3 Model: Its Numerical Stability and Application to a Regional Prediction of Advection Fog, *Boundary-Layer Meteorol.*, vol. 119, no. 2, pp. 397–407.

Szafraniec, J. (2002), *Influence of positive degree−days and sunshine durationon the surface ablation of Hansbreen, Spitsbergen glacier*. Polish Polar Research, **23**: 227–240.

Sturm M. and Stuefer, S. (2013), Wind-blown flux rates derived from drifts at arctic snow fences. J. Glaciology, 59: 21–34.

Wilson, A. B., D. H. Bromwich, K. M. Hines (2011): Evaluation of Polar WRF forecasts on the Arctic System Reanalysis domain: Surface and upper air analysis. *J. Geophys. Res.*, **116**, D11112, doi: 10.1029/2010JD015013

WGMS: World Glacier Monitoring Service (1991–2011). *GLACIER MASS BALANCE BULLETIN*. Bulletin No. 1–11. Available at http://www.geo.uzh.ch/microsite/wgms/gmbb.html.