

Response to review comments and revision of ESSD-2019-180

Sval_Imp: A gridded forcing dataset for climate change impact research on Svalbard

by: Thomas Vikhamar Schuler and Torbjørn Ims Østby

We thank the reviewers for their constructive comments that have been helpful to improve the quality of our manuscript. Below, we respond to the comments point by point and outline where and how we implemented them in the revised version. To illustrate the flow of discussion, we use different font colours for the comments by the reviewers (black) and our responses (red).

The attached difference manuscript illustrates the changes in the revised text: blue fonts denote new text and text removed is shown in red color.

Reviewer Kabir Rasouli

General comments

1. The accumulated snow on ice cannot be representative of precipitation as snow cover and depth on ice are not uniform because of blowing wind effect on redistribution of snow, roughness of ice surface, and spatial variability of blowing snow sublimation (Line 11-12 and Fig. 6). This is clearly shown by a poor relationship between unscaled ERA-interim winter precipitation and snow water equivalent on Figure 6. Either clarify this or remove the text and figures related to this argument.

We agree that redistribution of snow by wind and mass fluxes caused by sublimation/ deposition may impede the comparison of snow accumulating on the ground and precipitation. The redistribution of snow causes considerable spatial variability depending on terrain roughness (e.g. Aas et al., 2016), typically on spatial scales that are below the resolution of our dataset (1 km). However, the measurements used in our comparison (except for those from Hansbreen), are from glaciers that have very gentle surface topography and smooth surfaces (they are not crevassed), hence the influence of redistribution is small (e.g. Taurisano et al., 2007). As described on page 10 line 7-12 (original MS), the rough topography surrounding Hansbreen introduces a cross-glacier variability of snow accumulation that may be responsible for the poor match with downscaled values. Similar mismatch has been found also by others (Aas et al., 2016; Van Pelt et al., 2019).

Concerning sublimation, Svalbard has high air humidity throughout the year, limiting the potential for sublimation. In an energy-balance study, Østby et al. (2017) estimated sublimation to about 0.016 m w.e yr⁻¹, which is 1-2 orders of magnitude below annual precipitation sums.

We will extend the discussion section in our manuscript to enhance clarity of our argument (page 10, L180ff of the revised MS)

We disagree with the reviewer's point about Fig. 6. If snow sublimation were responsible for the poor agreement between measured snow water equivalent and

winter precipitation, the accumulated snow should be smaller than the precipitation. However, the opposite is true and the unscaled ERA precipitation is much smaller than the observed snow water equivalent. Our argument is, that the highly smoothed orography used for the ERA reanalysis is responsible for underestimating the orographic effect on precipitation. When accounting for this in our downscaling method, the winter precipitation comes much closer to the observed snow water equivalent. Nevertheless, we do not rule out that sublimation takes place, but as discussed above, this could not serve as an alternative explanation.

The y-axis in Figure 6 is mislabelled and will be changed to “ERAi precipitation (Oct-Apr)”, such that it applies to both datasets displayed. We add a legend to discriminate the two datasets. See below, where we present a new, enhanced version of the Fig.6 (see also new Fig. 6 in the revised MS).

2. It is not clear if monthly data for precipitation were used for downscaling the ERA reanalysis products or daily?

No, all variables have been downscaled at steps of 6 hours. We will modify the text to make this explicit. (P2, L45ff of the revised MS)

If monthly data were used, how reliable is monthly-to6hourly temporal downscaling? If daily data were used, why number of months for precipitation is provided in Table 2?

Comparison between downscaled and measured precipitation (for operational weather stations) has been conducted using monthly values. Precipitation in reanalysis is largely unconstrained and small mismatches in timing of precipitation (<1 day) would penalize a method that otherwise is successful in reducing the underestimation of the reanalysis (at least on monthly and seasonal scale). Table 1 shows the number of values that have been used in the evaluation of different variables. While T2, RH etc have been evaluated using daily values, precipitation has been evaluated using monthly values. We will modify the text and the caption to better explain our procedure (P9, L160 ff in the revised MS). We believe that the reviewer refers to this table and not Table 2 that lists the files in the dataset, organized in monthly chunks.

For other variables if daily variables recorded at the stations were used how were the daily values disintegrated to 6-hourly data?

The observational records have been used to evaluate the downscaled variables. The 6-hours values of the downscaled variables have been aggregated to daily values for the evaluation. In the revised version, we better explain this point (P9, L160ff, in the revised MS).

3. I am wondering how many of the stations that were used for validation of the downscaled meteorological variables were originally used to assimilate the reanalysis products. Is it only the Ny-Ålesund station? If the station data have been used in assimilating reanalysis products, it is not surprising to see high correlations between time series of ERA interim grids and stations.

Presumably, all available data of the met-office operated weather stations is used for constraining the reanalysis, but a detailed examination of which dataset has been used and when, is difficult. The comment by the reviewer is in line with our

argumentation on P11, L30 (original MS) to explain the superior performance at Ny Ålesund. In contrast, records from project stations represent independent measurements (for instance the stations on Etonbreen and Holtedahlfonna).

Specific comments: (P: Page, L: Line)

1. I recommend removing the index of "Sval_Imp_v1" from the title and across the manuscript.

We will follow the advice of the reviewer and refer to the dataset as "Sval_Imp". This has been implemented throughout the revised MS.

2. P 2 L 13: Rewrite "Whereas operational records are biased to low-elevations . . .".

Operational records are biased to low-elevations around the fringes of the archipelago. Therefore, we stress the hitherto under-used potential of project-based measurements in the interior, high-elevation regions for evaluating atmospheric models. (modified text in abstract, P1, L9-11 of revised MS).

3. P 4 L 1: Replace "In contrast, elevation in our 1×1 km topography peaks 1600 m asl" with "In contrast, the highest elevation in our gridded topography map is 1600 m asl".

Done.

4. P 4 L 2: Check the grammar in "present" and also in the next line in "and use". Do you mean you have used linear theory?

Changed to: "...is not represented by..." and "We assume that this is the main reason for the poor performance of reanalyzed precipitation. To account for orographic enhancement, we use a linear theory (LT) of orographic precipitation (Smith and Barstad, 2004)." (revised text Sec 2.1 of revised MS).

5. P4 L10: Add ", which was" before "not present in the ERA products".

Done.

6. P4, L14-15: The authors have mentioned "we modified the TopoSCALE methodology regarding downscaling of direct shortwave radiation and air temperature, as described in the following." However, the following section is about precipitation and not about radiation or temperature. Use more specific section numbers or names.

Changed to "regarding downscaling of air temperature and shortwave radiation, as described in Sections 2.3 and 2.4". (P4, L73-74 of revised MS).

7. Use "air" temperature instead of temperature when you refer to air temperature. This can be mixed up with surface or soil temperatures if not specified.

Done.

8. P10 L12: Change "Grabiec et al. (2006)." to "(Grabiec et al., 2006)."

Done.

9. Is the dataset presented in this paper and stored in the website only downscaled products or both raw unscaled and processed downscaled data (e.g., Table 2)?

The published dataset contains only the downscaled data. In the data availability section, we refer to the availability of the unscaled reanalyses.

10. Check for the typos and English grammar errors across the manuscript.

We have re-checked the manuscript to our best knowledge, but of course cannot rule out that it is free of typographical or grammatical errors. Any specific comment is appreciated.

Reviewer Andrew Newman:

1) Although the authors give citations to other papers that evaluate this product, it would be beneficial to have a more explicit summary of those results in this paper so they are more readily available in one location.

As stated at the onset of Sec 3 (p8, l9-11, original MS), our manuscript summarizes the evaluations presented in previous papers in the subsequent subsections. We make this more transparent by writing: "... in this paper, we summarize their main results in the subsequent subsections, and present additional evaluation of the precipitation using snow measurements." (P9, L159-160 of revised MS).

2) The paper needs more discussion of the differences in performance between the ERA-40 and ERA-Interim time periods using the overlap period wherever possible. This will be very useful to users of the full dataset. There is some discussion of this for temperature, but not for any other variables.

Due to sparsity of available data in the overlap period 1979-2002, we have not evaluated the performance of Sval_Imp for other variables than air temperature.

However, Østby et al. (2017) have evaluated the effect of this dataset discontinuity by simulating glacier mass balance using both, ERA-40 and ERA-Interim to investigate whether this discontinuity could be responsible for a notable drop in simulated mass balance around year 1980.

They found that the ERA40-based simulation yields an about 13 cm w.e. higher mass balance than the ERA-Interim-based one, but ERA-40- based simulations still show a 20 cm drop of mass balance between 1970 and 1990, larger than that caused by the data set discontinuity. This suggests that this change in mass balance regime was not caused by the heterogeneity of our composite forcing.

Nevertheless, we cannot rule out the possibility that this change was caused by the discontinuity inherent in both reanalyses due to the availability of satellite observations after 1979. (new text in Sec 3.2 of revised MS).

3) Are there any other snow transect data available that could be added to this analysis? It appears that another paper evaluated this product on another glacier named Hansbreen, could those data be reproduced here? Following that, it may be worth adding a spatial plot of the precipitation differences using the transects.

Østby et al. (2017) evaluated glacier mass balance that has been simulated using the presented dataset to force a coupled surface energy balance – snowpack model. These measurements do not represent spatially "continuous" transects but a collection of 10 point measurements. A map representation of differences would not provide much insight. Nevertheless, we came over an earlier snow transect dataset by Sand et al (2003) that covers several regions across Svalbard. We include this in our revised version to better evaluate the spatial pattern of precipitation.

Here is a revised version of Fig 6 (p11 of revised MS), now including an evaluation of the spatial pattern using the 1999 dataset by Sand et al. (2003).

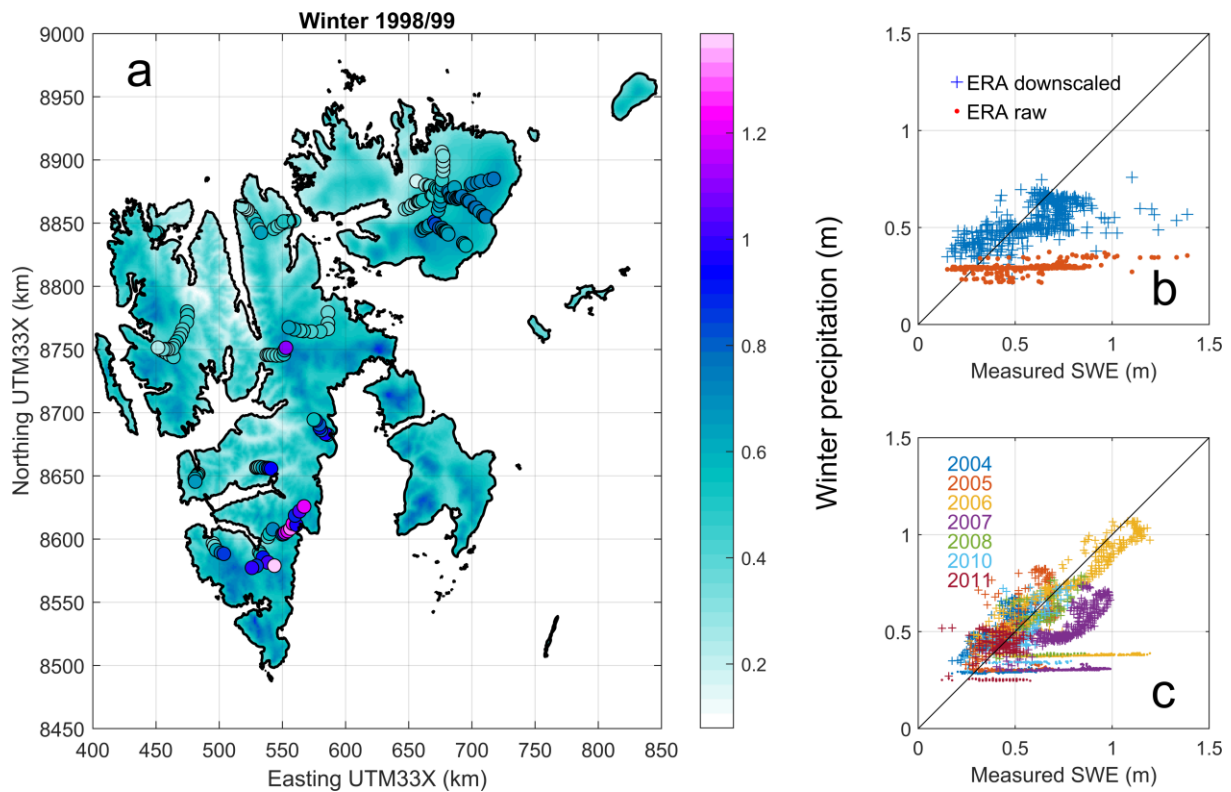


Figure 6: a) Map view of Sval_Imp precipitation accumulated over Oct 1998 to Mar 1999, overlaid by coloured circles, indicating the measured snow water equivalent (SWE) by Sand et al. (2003). b) scatterplot comparing the 1999 measurements to winter precipitation according to Sval_Imp (crosses) and to ERA-interim (dots). c) similar scatterplot as in b) but only for the Austfonna dataset that provides multi-temporal coverage.

4) What is the specific 'simple' 2D interpolation method used in sections 2.3 and 2.5?

Instead of interpolating a 3D data volume to the surface elevation of the high resolution topography, for some variables, we have bilinearly interpolated the 2D field representing the values at 2 m height. We modify the text to be more explicit in this regard. (P7, L129 ff and P8 L154 ff of revised MS)

5) Is the code used to generate this dataset available?

Unfortunately, the code has been developed to solve the task at hand but not having a wider user community in mind. Nevertheless, it is available on request, but sufficient instructions are required to make it applicable. The code for precipitation downscaling for instance, has been used by Roth et al. (2018). Future work will aim at making the code a more useful tool for others.

References:

- Aas KS, Gishås K, Westermann S, Berntsen TK. (2016). A tiling approach to represent sub-grid snow variability in coupled land-surface – atmosphere models. *J. Hydrometeor.*, doi: 10.1175/JHM-D-16-0026.1.
- Roth, A.; Hock, R.; Schuler, T.V.; Bieniek, P.A.; Pelto, M.; Aschwanden, A. (2018). Modeling Winter Precipitation Over the Juneau Icefield, Alaska, Using a Linear Model of Orographic Precipitation, *Frontiers in Earth Science*, 6, 20, doi:10.3389/feart.2018.00020
- Sand K; Winther JG; Maréchal D; Bruland O; Melvold K. (2003). Regional Variations of Snow Accumulation on Spitsbergen, Svalbard, 1997-99. *Hydrology Research* 34 (1-2): 17-32.
<https://doi.org/10.2166/nh.2003.0026>

Sval_Imp_v1: A gridded forcing dataset for climate change impact research on Svalbard

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Abstract. We present Sval_Imp_v1, a high resolution gridded dataset designed for forcing models of terrestrial surface processes on Svalbard. The dataset is defined on a 1km grid covering the archipelago of Svalbard, located in the Norwegian Arctic (74-82°N). Using a hybrid methodology combining multi-dimensional interpolation with simple dynamical modelling, the atmospheric reanalyses ERA-40 and ERA-interim by the European Centre for Medium-Range Weather Forecasting have been
5 downscaled to cover the period 1957-2017 at steps of 6h. The dataset is publicly available from a data repository. In this paper, we describe the methodology used to construct the dataset, present the organization of the data in the repository and discuss the performance of the downscaling procedure. In doing so, the dataset is compared to a wealth of data available from operational as well as project-based measurements. The quality of the downscaled dataset is found to vary in space and time, but generally represents an improvement compared to unscaled values, especially for precipitation. Whereas operational records are biased
10 to low-elevations around the fringes of the archipelago, we stress the hitherto under-used potential of project-based measurements at higher elevation and in the interior of the archipelago for evaluating atmospheric models. For instance, records of snow accumulation on large ice masses may represent measures of seasonally-integrated precipitation in regions sensitive to the downscaling procedure, thus providing added value.

Sval_Imp_v1 (Schuler, 2018) is publicly available from the Norwegian Research Data Archive NIRD, a data repository
15 (<https://doi.org/10.11582/2018.00006>).

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1 Introduction

The non-linearity of many surface processes poses challenges on appropriateness of atmospheric forcing for impact studies
20 in terms of accuracy and precision (e.g., Liston and Elder, 2006). Especially in mountainous areas, the variability of surface systems is typically governed by spatial scales not resolved in regional climate models and adjustments have to be made to overcome this (e.g., Fiddes and Gruber, 2014). A variety of methods has been developed for this purpose, differing in terms of

data requirements and computational cost. While empirical-statistical scaling requires reference data for training and assumes a temporal robustness of the employed statistical relations (e.g., Ehret et al., 2012; Maraun, 2013), dynamic downscaling by means of high-resolution atmospheric modelling has high computational costs (e.g., Gutmann et al., 2016).

In this paper, we present Sval_Imp ~~v1~~ (Schuler, 2018), a high resolution gridded dataset obtained using a hybrid methodology combining multi-dimensional interpolation with simple dynamical modelling. The dataset is defined on a 1km grid covering the archipelago of Svalbard, located in the Norwegian Arctic (74-82°N, 10-35°E). The atmospheric reanalyses ERA-40 and ERA-interim by the European Centre for Medium-Range Weather Forecasting have been downscaled to cover the period 1957-2017 at ~~a resolution of 6h~~ 6 hours temporal resolution. The dataset comprises the near-surface variables required to compute the surface energy balance, namely air temperature, precipitation, relative humidity, wind speed, and downwelling components of shortwave (solar) and longwave (thermal) radiation. Sval_Imp ~~v1~~ is publicly available from the Norwegian Research Data Archive NIRD, a data repository (<https://doi.org/10.11582/2018.00006>). In the following, we describe the methodology used to derive the dataset, present the organization of the data in the repository and discuss the performance of the downscaling procedure. For the latter, the dataset is compared to a wealth of data available from long-term operational as well as short-term scientific records of meteorological and glaciological measurements. ~~Whereas operational~~ Operational records are biased to low-elevations around the fringes of the archipelago. Therefore, we stress the hitherto under-used potential of project-based measurements in the interior, high-elevation regions for evaluating atmospheric models. For instance, records of snow accumulation on large ice masses may represent measures of seasonally-integrated precipitation in regions sensitive to the downscaling procedure, thus providing added-value. Sval_Imp ~~v1~~ has been employed entirely or in parts by a range of projects for forcing process models of the surface energy and mass balances of glaciers (Østby et al., 2017), precipitation patterns and meltwater production in the Kongsfjord area (Pramanik et al., 2018), for assimilation of remotely-sensed snow cover using a snow distribution model (Aalstad et al., 2018) as well as for assessing growing conditions for fungi (Botnen et al., in prep.). Further, the dataset has been used to assess changes and trends in climate conditions of Svalbard (Hanssen-Bauer et al., 2019).

45 2 Methodology

To generate fields of near-surface air temperature, precipitation, relative humidity, wind and downwelling shortwave and longwave radiation, we have downscaled the ERA-40 and ERA-interim reanalyses of the European Centre for Medium-Range Weather Forecasts (Uppala et al., 2005; Dee et al., 2011). The reanalysis data is provided at 6-hour intervals and has been retrieved on a $0.75^\circ \times 0.75^\circ$ spatial grid (~~Figure 1~~), covering the periods 1957-2002 (ERA-40) and 1979-2017 (ERA-interim). These data have been downscaled to a 1km grid covering the region of interest (Fig. 1) using the scheme described in the following to produce Sval_Imp, a high-resolution, 6-hour dataset of precipitation, temperature, relative humidity, windspeed as well as downwelling shortwave and longwave radiation fluxes.

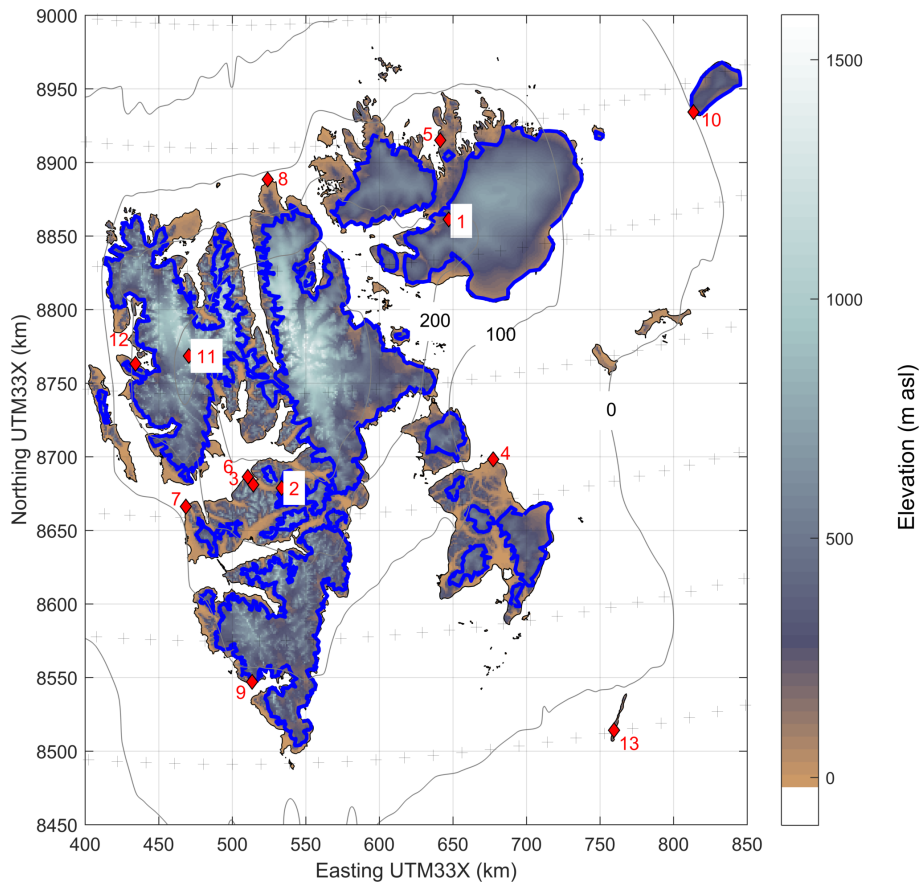


Figure 1. The map shows the Svalbard archipelago, shading indicates surface elevation, glacierized areas are outlined in blue. The locations of meteorological stations are represented by red diamonds, the numbers refer to the station names: 1 - Etonbreen, 2 - Janssonhaugen, 3 - Gruvefjellet, 4 - Kapp Heuglin, 5 - Rijpfjorden, 6 - Svalbard Airport, 7 - Isfjord Radio, 8 - Verlegenuken, 9 - Hornsund, 10 - Kvitøya, 11 - Holtedahlfonna, 12 - Ny-Ålesund, 13 - Hopen. The black crosses indicate the grid points of the ERA reanalyses, and the grey countourlines indicate the topography of Svalbard in the ERA reanalyses at 0, 100, 200 and 300 m asl.

2.1 Downscaling

Precipitation is often heavily biased in coarsely-resolved reanalyses, especially in environments with pronounced topography, where it typically is too low and lacks spatial detail (Schuler et al., 2008). This is associated with the smoothed representation of the actual topography in the large-scale model used for the reanalysis (Figure Fig. 1), leading to an underestimate of orographic precipitation. Figure 1 shows that ERA greatly generalizes the high resolution topography, representing Svalbard as a wide and flat bump, that exceeds sea-level far off the actual coastlines, while surface elevation in the interior does not exceed 400 m asl. In contrast, the highest elevation in our 1×1-km topography peaks gridded topography map is 1600 m asl. The roughness of the actual topography that gave rise to the name of the main island 'Spitsbergen' (sharp tops) is not ~~present in~~ represented by the smoothed topography used for the ERA reanalyses. We assume that this is the main reason for the poor performance of reanalyzed precipitation, ~~and use instead~~. To account for orographic enhancement, we use a linear theory (LT) of orographic precipitation (Smith and Barstad, 2004) ~~to account for orographic enhancement~~.

The other required climate variables are downscaled to the 1 km grid largely following the TopoSCALE methodology (Fiddes and Gruber, 2014) which also builds on the assumption that weaknesses in the representation of topography at the coarse scale are mainly responsible for the misfit between coarse scale and point observations. TopoSCALE exploits the relatively high vertical resolution of the reanalysis data to downscale variables to the elevation of the actual topography, based on the properties of the vertical structure in the reanalysis. The downscaled fields preserve the horizontal gradients present in ERA, but include additional features caused by the real topography which were not present in ~~ERA (Figure 1)~~ the ERA products. In doing so, we add spatial detail to the reanalysis fields that is consistent with the temporal evolution of atmospheric conditions of the reanalysis. This approach is assumed to outperform simpler bias corrections, since transient properties of the atmosphere are accounted for. For example, transient lapse rates including inversions in the reanalysis data will be preserved in the downscaled product.

In our application, we modified the TopoSCALE methodology regarding downscaling of direct shortwave radiation and air temperature, as described in ~~the following~~ Sections 2.3 and 2.4.

2.2 Precipitation

The LT-model describes an air parcel as it moves across a prescribed surface topography. The air parcel is characterized by its temperature, stability, wind direction and speed. Terrain induced uplift of the air parcel results in condensation and eventually precipitation of moisture downstream of the uplift. This model has been successfully evaluated using precipitation gauges (Barstad and Smith, 2005) and snow measurements (Schuler et al., 2008; Østby et al., 2017) and applied for downscaling precipitation (e.g. Crochet et al., 2007; Jarosch et al., 2012; Roth et al., 2018). The linear theory utilizes a Boussinesq description of mountain wave to derive a transfer function that, for given wind conditions, relates the orographically enhanced precipitation to terrain topography.

By spectral decomposition and algebraic manipulation, Smith and Barstad (2004) derived the following transfer function

$$85 \quad \hat{P}(k, l) = \frac{C_w i \sigma \hat{h}(k, l)}{(1 - imH_w)(1 + i\sigma\tau_f)(1 + i\sigma\tau_c)}. \quad (1)$$

relating $\hat{P}(k, l)$, the Fourier-transform of the precipitation enhancement, to the Fourier-transform of terrain elevation $\hat{h}(k, l)$, with k and l being the horizontal wave numbers. This relation depends on the uplift sensitivity factor C_w , thickness of the moist layer H_w , the intrinsic frequency $\sigma(k, l) = Uk + Vl$ (U and V being the east and north components of the wind vector), and the conversion and fallout time scales τ_c and τ_f , respectively. In Equation (1), the vertical wave number m controls the depth and tilt of the forced air uplift and is a function of the moist Brunt-Väisälä frequency, N_m , a quantity describing atmospheric stability.

Precipitation rates are obtained by retransforming \hat{P} and adding it to the background precipitation P_∞ , that accounts for large-scale frontal and convective precipitation separate from orographic precipitation P_{oro} . P_∞ has been corrected for the orographic effect already present in the ERA reanalyses $P_{\text{oro}}(h_{\text{ERA}})$ by estimating this effect applying Equation 1 to the large-scale topography h_{ERA} and removing the result from the ERA precipitation $P_\infty = P_{\text{ERA}} - P_{\text{oro}}(h_{\text{ERA}})$ (Schuler et al., 2008). Total precipitation, P_{total} , is then

$$P_{\text{total}}(x, y) = \max \left[f \iint \hat{P}(k, l) e^{i(kx + yl)} dk dl + P_\infty, 0 \right]. \quad (2)$$

Since the theory assumes saturated conditions, we account for reduced orographic enhancement at lower humidity by adopting a correction factor f proposed by Sinclair (1994)

$$100 \quad f = \begin{cases} \left(\frac{RH - 0.8}{0.2} \right)^{1/4} & : RH \geq 0.8 \\ 0 & : \text{otherwise} \end{cases} \quad (3)$$

which suppresses orographic enhancement when $RH < 0.8$.

Instead of treating N_m , τ_f and τ_c as adjustable, constant parameters, we exploit the evolution of the moisture bearing layer of the atmosphere, described in the reanalyses to derive transient values. In doing so, we remove calibration parameters from our method and enable weather dependent variation of N_m , τ_f and τ_c . Values of N_m are calculated following

$$105 \quad N_m^2 = \frac{g}{\bar{T}} (\Gamma_m - \Gamma_e) \quad (4)$$

where g is gravitational acceleration and \bar{T} is vertically averaged air temperature weighted by the moisture content at several pressure levels (Jarosch et al., 2012). Environmental lapse-rates Γ_e are derived from air temperature at 700 hPa and 850 hPa and corresponding geopotential heights. Γ_m is the moist adiabatic lapse rate, calculated according to Stone and Carlson (1979) using vertically averaged values of atmospheric properties from the reanalyses weighted by moisture content. This follows the convention that a positive lapse rate represents cooling with increasing elevation. Barstad and Smith (2005) report that typical values of N_m range between 0 s^{-1} , representing an atmosphere with no stratification, and 0.01 s^{-1} representing a stably stratified atmosphere. To avoid conditions inconsistent with the assumptions of the theory, we limit N_m to this range. The quantities H_w , C_w and m are derived from N_m (Smith and Barstad, 2004).

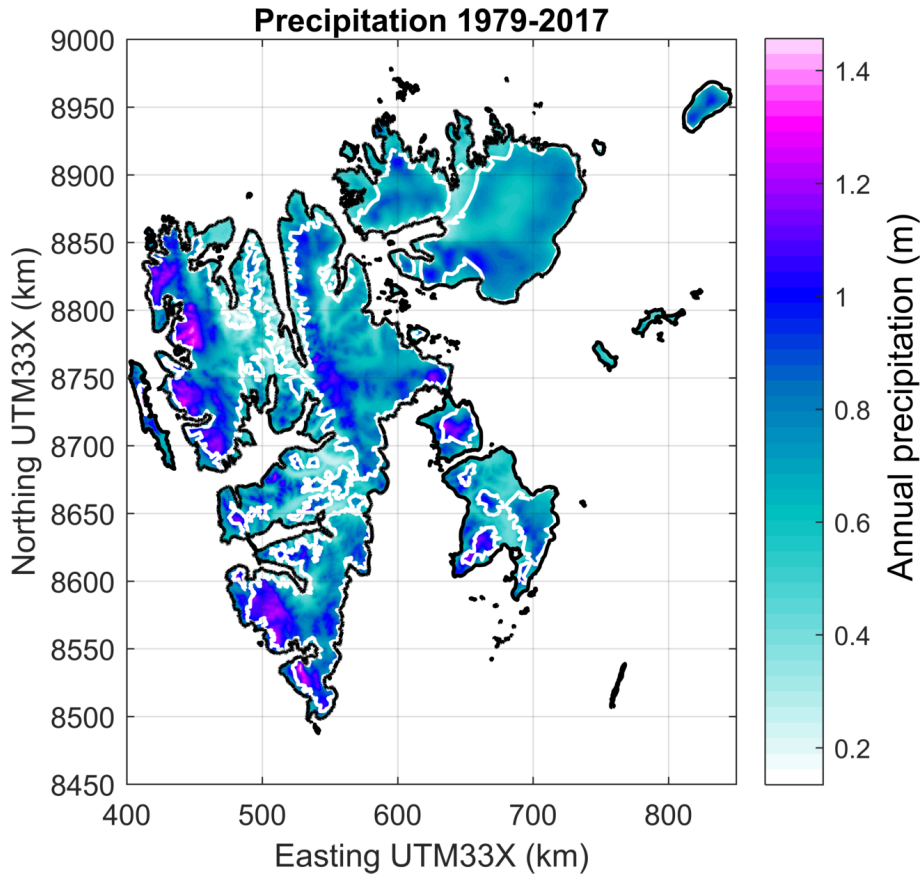


Figure 2. Example plot of longterm mean annual precipitation (m) over 1979-2017, downscaled from ERA-interim.

Advection time scales τ_c and τ_f are assumed equal and $\tau = \tau_c = \tau_f = H_w/v$ is derived from the thickness of the moist
 115 layer H_w and accounting for a typical hydrometeor fall speed v , which is taken as constant but allowed to take different
 values for solid and liquid hydrometeors. This phase transition is determined by a threshold temperature of 273 K, hence
 $v(T \leq 273K) = 1 \text{ m s}^{-1}$ for solid and $v(T \geq 273K) = 2 \text{ m s}^{-1}$ for liquid precipitation. In Equation 1, terrain elevation h is
 the only gridded variable, the other variables represent averages over the volume of the described air parcel. To characterize
 this air parcel, we first vertically average the values defined at the nodes of the horizontal domain over the 700 hPa and 850 hPa
 120 pressure-levels weighted by the moisture content of the individual layers. These vertically averaged values are then horizontally
 averaged over an area defined by a 200 km buffer around the 200 m contour of the reanalysis topography, the latter roughly
 outlining the extend of the archipelago (Fig. 1).

This setup is then applied to each 6h timestep and the resulting timeslices are progressively added to the record.

2.3 ~~Temperature~~Air temperature

125 The downscaling for near-surface air temperature at 2 m level (T_2) closely follows the TopoSCALE procedure Fiddes and Gruber (2014), thereby we assume that the vertical structure of the free atmosphere determines the distribution of T_2 with terrain elevation. For each 6h-time step, T_2 is derived from a ~~three-dimansional~~three-dimensional interpolation of the vertical air temperature structure of the large-scale reanalysis to the location of the grid nodes representing the high-resolution terrain elevation. We notice, that for a melting snow or ice surface, skin temperature is bounded to 273 K, influencing the near surface

130 air temperature and resulting in reduced along-surface air temperature lapse-rates (e.g., Marshall et al., 2007). To account for this effect, we apply a simple horizontal interpolation of the two-dimensional $T_{2\text{ERA}}$ field where $T_2 > 273$ K, instead of interpolating a three-dimensional data volume to the surface elevation of the high resolution topography. This strategy is motivated by the discovery of unrealistic warm air temperatures at higher elevations in a test application. The occurrence of this unphysical temperature inversion was restricted to the melting period, caused by extrapolation of surface inversions close

135 to a snow/ ice surface the temperature of which is capped at 273 K. To avoid this effect, we assume that where $T_2 > 273$ K, the T_2 of the reanalysis is consistent with a melting surface and hence more realistic than a free-atmosphere interpolation.

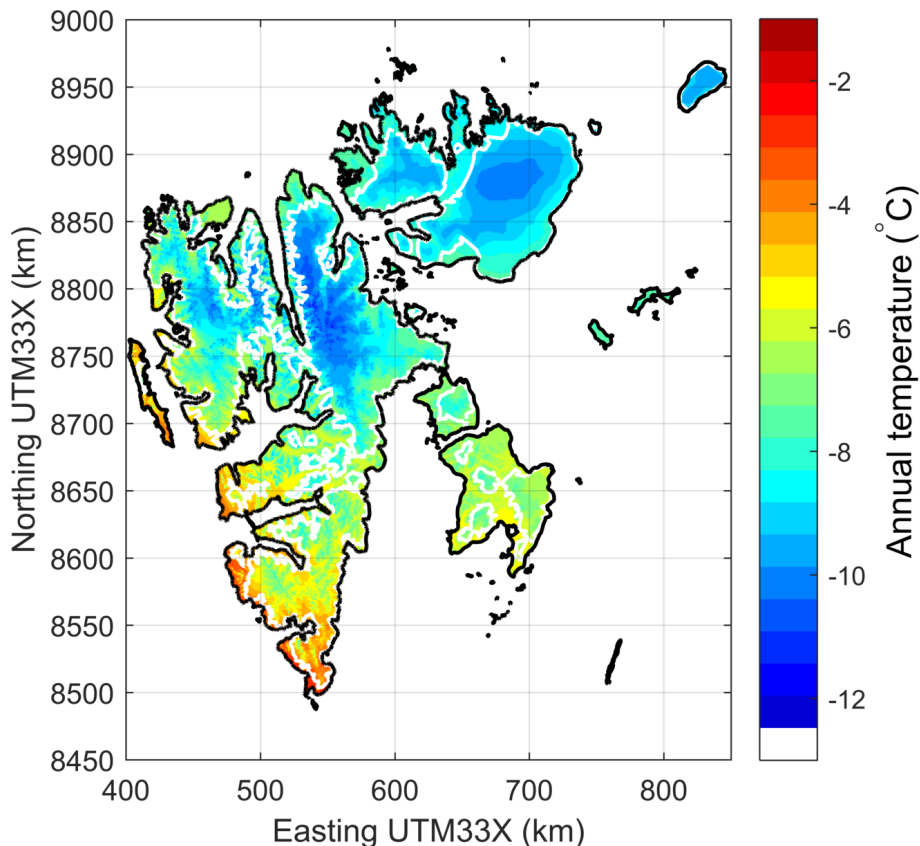


Figure 3. Example plot of mean air temperature (2 m) in $^{\circ}\text{C}$, over the period 1979-2017, downscaled from ERA-interim.

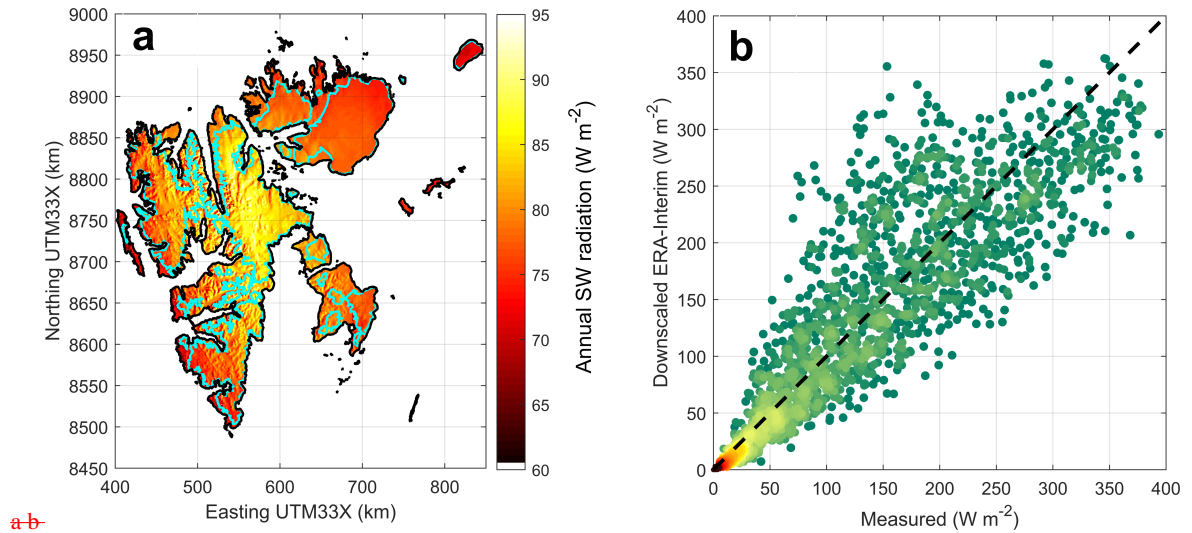


Figure 4. a) Example plot of 1979-2017 incident shortwave radiation (W m^{-2}), downscaled from ERA-interim; b) comparison between measured (Maturilli et al., 2013) and downscaled daily values of SW at Ny-Ålesund. The color indicates the density of points from red (high) to green (low).

2.4 Radiation

Downscaling of shortwave and longwave downwelling radiative fluxes (SW and LW , respectively) was conducted by adopting the TopoSCALE methodology (Fiddes and Gruber, 2014) with a few adjustments. The shortwave radiation at surface level of the reanalysis is projected to the high-resolution topography in a three-step procedure: first the surface SW flux is separated into direct and diffuse components; second, the direct component is corrected for the elevation difference between the reanalysis surface and the high-resolution topography considering an effective atmospheric transmissivity that is derived from top-of-atmosphere and surface fluxes; third a topographic correction is applied to account for effects of slope and aspect of the high-resolution topography, as well as shading by surrounding topography. To compute direct solar radiation we apply the relationship of Kumar et al. (1997) for atmospheric attenuation rather than the one given by Fiddes and Gruber (2014). Solar geometry variables such as solar zenith and azimuth, and topographic shading due to local slope and aspect are calculated following Reda and Andreas (2004). Cast shadow and hemispherical obstructions caused by surrounding topography are calculated following Ratti (2001). The longwave surface flux is downscaled by correcting for the elevation difference between reanalysis and high-resolution grids using an atmospheric emissivity. This emissivity is estimated by accounting for a clear-sky component that depends on humidity and ~~temperature~~ air temperature and a cloud component that is estimated from the difference between the clear-sky component and the reanalysis longwave flux. Further terrain effects are incorporated through multiplication with the sky-view factor.

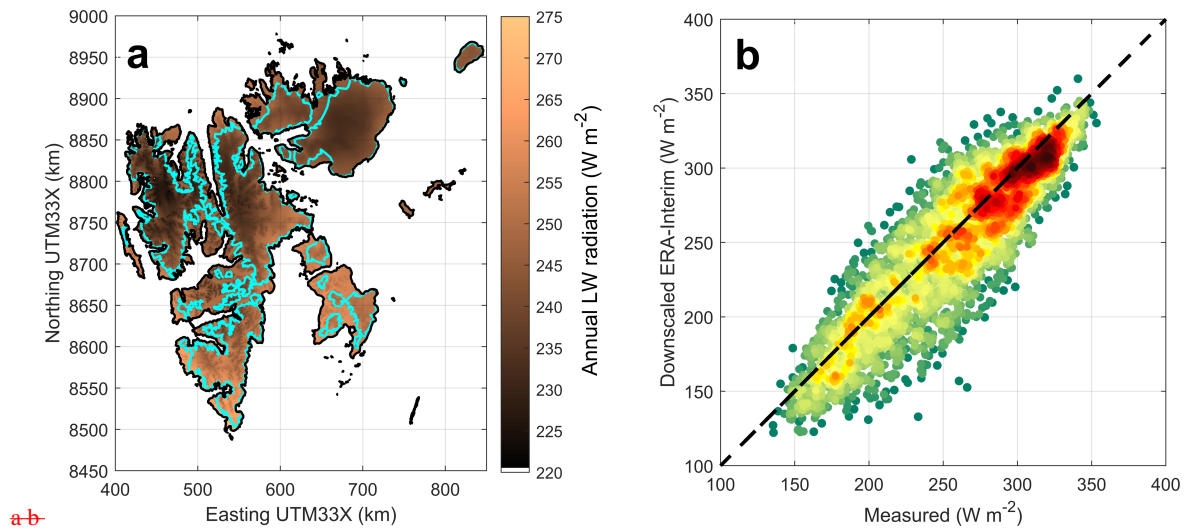


Figure 5. a) Example plot of 1979-2017 downwelling longwave radiation (W m^{-2}), downscaled from ERA-interim; b) comparison between measured (Maturilli et al., 2013) and downscaled daily values of LW at Ny-Ålesund. The color indicates the density of points from red (high) to green (low).

2.5 Relative humidity and windspeed

Similar to our assumption about T_2 over a melting surface, we suggest that windspeed and RH in the boundary layer are more affected by surface rather than by free-atmosphere conditions and we hence apply a simple **2D two-dimensional** interpolation of the near-surface values of the reanalysis, instead of interpolating a three-dimensional data volume to the surface elevation of the high resolution topography.

3 Performance evaluation

Østby et al. (2017) and Vikhamar-Schuler et al. (2019) have conducted thorough evaluation-evaluations of the Sval_Imp ~~v1~~ dataset using data from meteorological stations. For details, we refer to the paper by Østby et al. (2017); in this paper, we Here, we summarize their main results and in the subsequent subsections and refer to Østby et al. (2017) for details. Furthermore, we present additional evaluation of the precipitation using snow measurements. Typically, meteorological records are available as daily mean values and 6-hourly, downscaled variables have been temporally aggregated to match the time step of measurements. Precipitation in reanalysis is not constrained by data assimilation, giving rise to uncertainty in timing as well as amount. Our downscaling aims for reducing the bias in precipitation amount but does not treat the timing. For a performance evaluation, we therefore use monthly precipitation sums which are regarded as robust against timing mismatches, whereas a higher temporal resolution could penalize a method that otherwise is successful in reducing the underestimation of the reanalysis.

3.1 Precipitation

At the operational weather stations (Fig. 1), downscaled precipitation (Fig. 2) is overestimated by 5 to 25 mm per month at the weather stations, with a slightly higher bias during winter (Table 1). This is also consistent with the findings of Vikhamar-Schuler et al. (2019) who evaluated the performance at 6 weather stations for several 30-year reference periods (1961-1990, 1971-2000, and 1988-2017). These biases are partly caused by too low precipitation measurements, the values of which are heavily affected by wind-induced undercatch, especially for solid precipitation. Førland and Hanssen-Bauer (2000) suggest that for solid precipitation, the actual precipitation at wind-exposed sites may be up to 80% higher than the gauge record. A newly developed correction scheme for Norwegian mountain environments (Wolff et al., 2015) supports the finding of large undercatch for solid precipitation, however, this correction has not yet been applied for arctic conditions in Svalbard.

In addition to gauge measurements from low-elevation stations along the coast, we also used snow survey transects across Austfonna, a large ice cap in NE Svalbard (Fig. 1) to evaluate the ~~Sval-Imp~~ Sval_Imp precipitation. We suggest that snow deposition on large glacier areas, measured at the end of the winter, represents seasonally integrated precipitation. While these measurements do not allow temporal resolution below one snow season (typically Oct-May), they provide useful information about spatial precipitation patterns, ~~far-off in areas and elevations not covered by~~ the operational meteorological stations. This approach builds on the implicit assumption of negligible sublimation, such that accumulated snow water equivalent represents the sum of precipitation over the winter season. Svalbard has high air humidity throughout the year, limiting the potential for sublimation. In an energy-balance study, Østby et al. (2017) estimated sublimation to about 0.016 m w.e year⁻¹, which is 1-2 orders of magnitude smaller than typical annual precipitation sums. There is generally good agreement concerning the spatial pattern across the Austfonna ice cap (Fig. 6), where snow accumulation reveals a distinctive SE-NW asymmetry (Taurisano et al., 2007; Schuler et al., 2007; Dunse et al., 2009) caused by orographic enhancement of precipitation coming from the SE sector (i.e., the Barents Sea), although in individual years the downscaled values underestimate the measured accumulation, especially in 2007 (Fig. 6). Even though, there is considerable scatter between observed and downscaled winter precipitation, there is positive correlation, indicating that the spatial pattern is matched and in most years there is no systematic bias, showing that the overall precipitation amount is adequately represented. On the other hand, the unscaled ERA-interim winter precipitation shows almost no spatial variation and considerably underestimates observed values (Fig. 2).

Østby et al. (2017) found that the winter mass balance of Hansbreen was not well reproduced both in terms of spatial pattern as well as accumulation amount. Aas et al. (2016) similarly reported the lowest performance for Hansbreen although they had used a much more complex precipitation scheme than the one presented here. The generally low performance of several precipitation distribution schemes compared to the Hansbreen record has been interpreted to result from local conditions at Hansbreen where the spatial distribution of snow is caused by wind redistribution rather than by the spatial precipitation pattern ~~Grabiec et al. (2006)~~ (Grabiec et al., 2006).

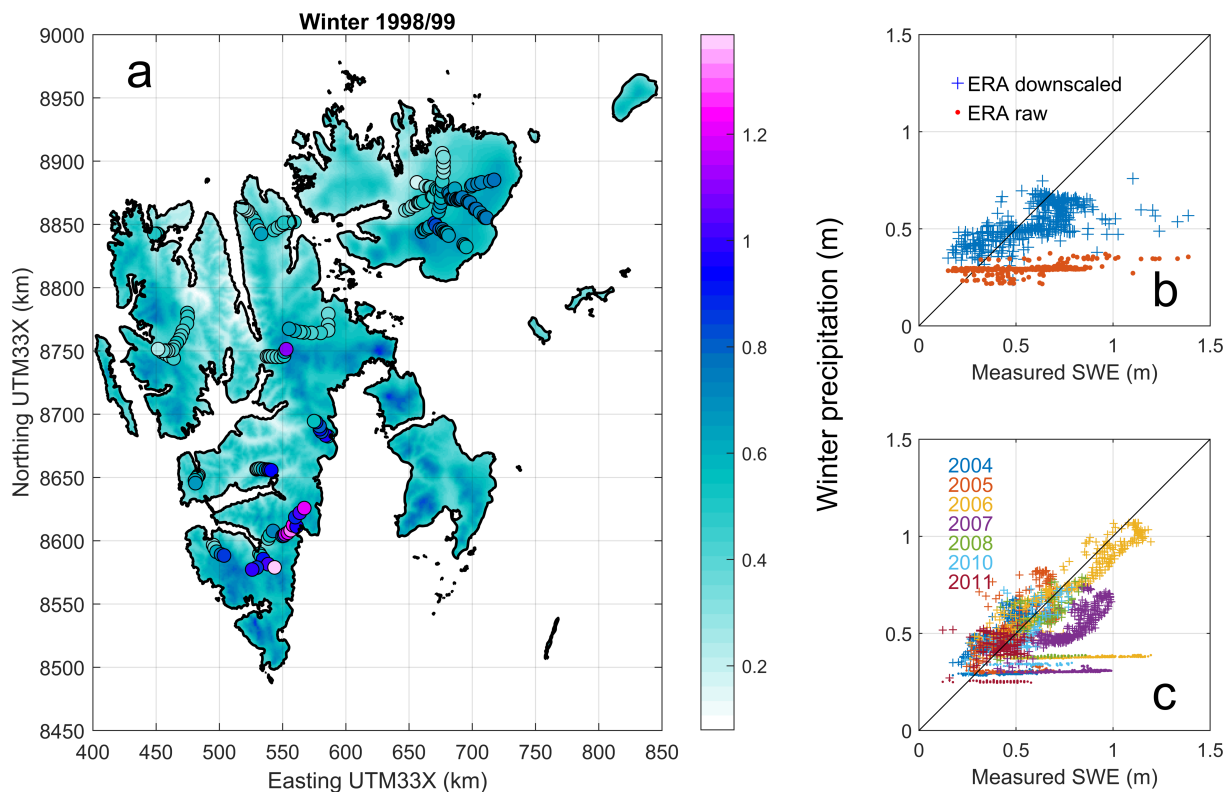


Figure 6. Comparison-a) Map view of Sval Imp precipitation accumulated over Oct 1998 to Mar 1999, overlaid by coloured circles, indicating the measured snow water equivalent from ground-penetrating radar (GPR SWE) transects across the Austfonna ice cap (Taurisano et al., 2007; Dunse et al., 2009) with the seasonally (Oct–Apr)-accumulated precipitation product by Sand et al. (2003). Dots refer to b) scatterplot comparing the downscaled-1999 measurements to winter precipitation, whereas according to Sval Imp (crosses represent unsealed) and to ERA-interim winter precipitation (dots). c) similar scatterplot as in b) but only for the Austfonna dataset that provides multi-temporal coverage (Taurisano et al., 2007; Dunse et al., 2009).

3.2 Temperature Air temperature

200 Downscaled temperatures air temperatures (Fig. 3) are compared to observations at the meteorological stations listed in Table 1 mostly for the period after 2004. Despite altitude differences of up to 100 m between measuring site and corresponding grid node in the model, no altitude correction is performed, due to unknown lapse rates. In general the agreement is good between downscaled ERA and observed air temperatures, with biases mostly below 1.5 K (Tab. 1). Despite a small bias for mean annual temperatures, there is a clear seasonal bias, with ERA temperatures too warm during winter and too cold during summer
 205 (Table 1). Although the biases are negative during summer, ERA is too warm over the glaciers during summer, when 2-m air temperatures are above freezing. These findings are consistent with those of Vikhamar-Schuler et al. (2019) who evaluated differences in seasonal mean values for different 30-year periods 1961-1990, 1971-2000 and 1988-2017.

At Svalbard Airport, the performances of downscaled ERA-40 and ERA-interim are investigated for the entire model period. Over 1957-1979 only monthly measured ~~temperatures~~ air temperatures are available at Svalbard Airport, where downscaled ERA-40 has a monthly root mean square error (RMSE) of 2.3 °C. For the 1979-2002 period the reanalysis products overlap with monthly RMSE of 1.8 °C and 1.5 °C at Svalbard Airport for ERA-40 and ERA-interim, respectively. We attribute the lower performance prior to 1979 to the lack of satellite observations to constrain sea surface temperatures and sea ice cover in the reanalysis. Since the Svalbard Airport air temperature record and other sites at the west coast are likely incorporated into the reanalysis, the quality of the reanalysis in the pre-satellite era is possibly even lower in remote areas with no observations. Due to sparsity of available data in the overlap period 1979-2002, we have not evaluated the performance of Sval_Imp for other variables than air temperature. However, Østby et al. (2017) have evaluated the effect of this dataset discontinuity by simulating glacier mass balance using both, ERA-40 and ERA-interim to investigate whether this discontinuity could be responsible for a notable drop in simulated mass balance around year 1980. They found that the ERA-40 based simulation yields an about 0.13 m w.e. higher mass balance than the one based on ERA-interim, but ERA-40 based simulations still show a 0.2 m drop of mass balance between 1970 and 1990, larger than that caused by the data set discontinuity. This suggests that the change in mass balance regime was not caused by the heterogeneity of our composite forcing. Nevertheless, we cannot rule out the possibility that this change was caused by the discontinuity inherent in both reanalyses due to the availability of satellite observations after 1979. The annual observed air temperature trend for the period 1957-2013 at Svalbard Airport is 0.70 ± 0.22 °C decade⁻¹, while the downscaled ERA data has an insignificantly lower warming trend of 0.67 ± 0.19 °C decade⁻¹ at Svalbard Airport.

225 3.3 Radiation

To evaluate the quality of ~~Sval-Imp~~ Sval_Imp radiation components, we use available records from two stations, roughly 300 km apart from each other. The record from Ny-Ålesund is from a daily serviced Baseline Surface Radiation Network station (Maturilli et al., 2013) whereas the Austfonna measurements are collected by an autonomously recording weather station (Schuler et al., 2014).

230 In Ny-Ålesund the model largely reproduces observations both for short and longwave radiation (Figs. 5 and 4, Tab. 1). During winter, downwelling longwave radiation is slightly underestimated, while there is no bias during summer. Since there is no ~~temperature~~ air temperature bias in Ny-Ålesund during winter, the underestimation of longwave radiation is indicative of a too thin cloud cover in the reanalysis. In general, the representation of clouds are among the major issues of the reanalysis (Aas et al., 2016). Downwelling shortwave radiation is overestimated by 7 W m^{-2} over the summer season in Ny-Ålesund. There is a much better agreement with radiation observations in Ny-Ålesund than on Etonbreen (Fig. 1), in northeastern Svalbard. This is to be expected, since radio soundings and other observation data from Ny-Ålesund are assimilated into ERA-interim. Therefore, cloud cover at Ny-Ålesund is much better represented by the reanalysis than at Austfonna. On Etonbreen during summer, ~~Sval-Imp~~ Sval_Imp underestimates downwelling shortwave radiation by 40 W m^{-2} while downwelling longwave radiation is overestimated by 12 W m^{-2} , both indicative of a too thick atmosphere or too many clouds in the reanalysis. 240 However, these biases could also be partly explained by measurement uncertainty caused by rime on the sensor or by sensor

tilt. The latter issue is caused by the fact that the ice foundation of an autonomous weather stations may melt and deform causing tilt and thereby large errors, especially at high solar zenith angles (Bogren et al., 2016).

3.4 Relative humidity and windspeed

For relative humidity the reanalysis represents the seasonality well, and in late summer both the humidity and the biases are of largest magnitude. At the two coastal stations at Hopen and Rjipfjorden, the downscaled reanalysis is too dry whereas it is too humid at the two higher elevation stations. The coarse land mask of the reanalysis and the poor representation of sea ice are most likely the main causes for these biases.

Wind speeds are reproduced reasonably well, including the seasonal cycle (Tab. 1). Biases are within $\pm 1.5 \text{ m s}^{-1}$ with no clear seasonal trend. It is likely that the biases are caused by site specific effects, such as deceleration of air flow in the lee of a topographic obstacle or acceleration due to channelizing through valleys.

4 Dataset structure

The downloadable dataset comprises individual files for each of the variables precipitation, ~~temperature~~air temperature, relative humidity, windspeed, incident shortwave and downwelling longwave radiation. The records are organized in one file per month for each of the reanalysis periods; ERA-40: September 1957 to August 2002, and ERA-interim: January 1979 to December 2017. Each file contains the discovery metadata, and the complete metadata to locate the stack of fields in space and time. The grid is regular and rectangular in UTM33X projection, the coordinates of which are defined by the vectors X (m easting in UTM33X, 448 elements) and Y (m northing in UTM33X, 548 elements). In geographical coordinates the grid is non-regular and therefore the location of each grid node is defined, rendering Latitude and Longitude (in decimal degrees) each a 448×548 matrix. The timestamp is given in days since 1 January 1900 using a standard Gregorian calendar having 365 days per year, i.e. without accounting for leap years. In addition, there is one file containing the stationary fields, i.e. the surface topography and land-ocean mask. The file format is netCDF according to the CF conventions (<http://cfconventions.org/>), with all required metadata included. The metadata adhere to ISO19115 geospatial metadata standards and the Directory Interchange Format (DIF) requirements of the Global Change Master Directory GCMD (<https://gcmd.nasa.gov/DocumentBuilder/defaultDif10/guide/index.html>), and global attributes comply to the Attribute Convention for Data Discovery ACDD (http://wiki.esipfed.org/index.php/Attribute_Convention_for_Data_Discovery_1-3).

Table 2 gives an overview over the number of files and their sizes for the different epochs (ERA-40, ERA-interim) and variables contained in the dataset. The naming convention for the individual files is `<EPOCH>_<VAR>_<YYYYMM>.nc`, where EPOCH is either "ERA40" or "ERAi", VAR is an abbreviation of the variable of interest (one of "precip", "temp", "RH", "windspeed", "SWi" or "LWi") and YYYYMM identifies year and month, for instance *ERAi_temp_200410.nc* is the name of the file containing ~~temperature~~air temperature from ERA-interim for October 2004.

Table 1. Meteorological stations used for validation of the downscaled reanalysis and their elevation (second line). N indicates the number of daily averages used in the validation, except for precipitation for which monthly sums have been evaluated. Seasonal biases in meteorological variables (downscaled minus observational averages) at all sites are averaged over each site’s observation period. Shown are air temperature T (K), relative humidity, RH (%), wind speed, WS (ms^{-1}), shortwave radiation, SW , and longwave radiation, LW (both in Wm^{-2}) and precipitation, P (mm). Column headings S and W denote summer (Jun-Aug) and winter (Sep-May), respectively. Positive numbers indicate that the model results are larger than the observations. The second row at each site is the bias between the raw ERA data and the observations.

Location	ΔT			ΔRH			ΔWS			ΔSW			ΔLW		ΔP		
	S	W	N_T	S	W	N_{RH}	S	W	N_{WS}	S	W	N_{rad}	S	W	S	W	N_P
Etonbreen [†]	0.2	1.3	3295	-2.2	-5.4	2738	0.3	0.2	2913	-40	-10	3240	12	-14	-	-	0
369 m asl	<i>1.1</i>	<i>1.9</i>		<i>-2.2</i>	<i>-5.4</i>		<i>0.3</i>	<i>0.2</i>		<i>-37</i>	<i>-9</i>		<i>17</i>	<i>-16</i>	-	-	
Janssonhaugen	-1.1	0.3	910	-	-	0	-1.8	-1.3	945	-	-	0	-	-	-	-	0
270 m asl	<i>-1.0</i>	<i>-0.6</i>		-	-		<i>-1.8</i>	<i>-1.3</i>		-	-		-	-	-	-	
Gruvefjellet	0.2	0.8	2555	3.1	-2.9	2555	0.0	-0.2	2551	-	-	0	-	-	-	-	0
464 m asl	<i>0.7</i>	<i>0.9</i>		<i>3.1</i>	<i>-2.9</i>		<i>0.0</i>	<i>-0.2</i>		-	-		-	-	-	-	
Kapp Heuglin	-0.0	0.7	2099	-	-	0	-0.0	1.0	2112	-	-	0	-	-	-	-	0
18 m asl	<i>0.3</i>	<i>1.0</i>		-	-		<i>-0.0</i>	<i>1.0</i>		-	-		-	-	-	-	
Rijpfjorden	-0.3	0.9	1495	5.7	2.6	1495	0.8	0.9	1304	-	-	0	-	-	-	-	0
10 m asl	<i>0.0</i>	<i>0.6</i>		<i>5.7</i>	<i>2.6</i>		<i>0.8</i>	<i>0.9</i>		-	-		-	-	-	-	
Svalbard Airport	-2.4	-0.4	12777	-	-	0	-1.3	-1.0	12724	-	-	0	-	-	25	26	199*
28 m asl	<i>-2.4</i>	<i>-2.2</i>		-	-		<i>-1.3</i>	<i>-1.0</i>		-	-		-	-	-	-	
Isfjord Radio	-1.6	-1.2	1666	-	-	0	-	-	0	-	-	0	-	-	-	-	0
13 m asl	<i>-1.5</i>	<i>-0.5</i>		-	-		-	-		-	-		-	-	-	-	
Verlegenuken	-0.5	0.0	986	-	-	0	-1.9	-1.7	1700	-	-	0	-	-	-	-	0
8 m asl	<i>-0.3</i>	<i>0.5</i>		-	-		<i>-1.9</i>	<i>-1.7</i>		-	-		-	-	-	-	
Hornsund	-0.2	0.4	4635	-	-	0	-0.0	0.4	4473	-	-	0	-	-	5	19	95*
10 m asl	<i>-0.0</i>	<i>0.8</i>		-	-		<i>-0.0</i>	<i>0.4</i>		-	-		-	-	-	-	
Kvitøya	-0.1	-0.1	740	-	-	0	-0.9	-1.3	702	-	-	0	-	-	-	-	0
10 m asl	<i>0.3</i>	<i>0.6</i>		-	-		<i>-0.9</i>	<i>-1.3</i>		-	-		-	-	-	-	
Holtedahlfonna [†]	1.3	-	317	-	-	0	-0.7	-	265	-	-	0	-	-	-	-	0
688 m asl	<i>3.2</i>	-		-	-		<i>-0.7</i>	-		-	-		-	-	-	-	
Ny-Ålesund	-1.7	-0.0	12666	7.6	3.2	12708	0.7	0.8	12349	-7	4	3652	2	9	23	18	212*
8 m asl	<i>-1.6</i>	<i>-1.2</i>		<i>7.6</i>	<i>3.2</i>		<i>0.7</i>	<i>0.8</i>		<i>-8</i>	<i>3</i>		<i>0</i>	<i>15</i>	-	-	
Hopen	1.9	5.2	13178	-	-	0	0.3	-0.1	13044	-	-	0	-	-	7	10	306*

*: Number of months

[†]: Station located on glacier.

Table 2. Overview file structure of the Sval_Imp_v1 dataset

Sval_Imp_v1												
Stationary fields	Svalbard_DEM_mask_pcorr.nc											
Variables	T2		P		WS		RH		SW		LW	
Reanalysis	ERA40	ERAint	ERA40	ERAint	ERA40	ERAint	ERA40	ERAint	ERA40	ERAint	ERA40	ERAint
Number of files	540	468	540	468	540	468	540	468	540	468	540	468
Size (GB)	22.8	19.8	33.1	28.8	34.1	29.8	25.6	22.6	21.7	19.0	31.3	27.5

5 Conclusions

We present a gridded dataset of near-surface, meteorological variables at 1km resolution covering the Svalbard archipelago. The set of variables enables application of energy balance models and comes at a time steps of 6 h. The high-resolution grids are derived from coarse-scale reanalyses ERA-40 for the period 1957-2002 and from ERA-interim for 1979-2017. We describe the intermediate-complexity downscaling procedure used to generate this dataset. Furthermore, we evaluate the performance of the downscaled data using a suite of different meteorological and glaciological measurements and refer to several applications of this dataset in different disciplines, all of them requiring longterm coverage at small spatial scales.

6 Data availability

The dataset is openly available from the National e-Infrastructure for Research Data (NIRD) archive at <https://doi.org/10.11582/2018.00006> and referred to as *Svalbard impact assessment forcing dataset, version 1*, (Schuler, 2018).

ERA-40 (Uppala et al., 2005) and ERA-interim (Dee et al., 2011) data were retrieved from the ECMWF Public Datasets web interface at <https://apps.ecmwf.int/datasets/>.

Weather station data are provided by the Norwegian Meteorological Institute and are available at <https://eklima.met.no>, and by the University Centre of Svalbard at <https://www.unis.no/resources/weather-stations/>. Radiation from the BRSN-station in Ny-Ålesund are provided by Maturilli et al. (2014).

Author contributions. TVS retrieved reanalysis data, developed code and performed the downscaling for precipitation, air temperature, RH and windspeed; TIØ developed code and performed downscaling of radiation components. Evaluation performance was conducted collaboratively. TVS was responsible for formatting, providing metadata and archiving the dataset; he led writing of the manuscript, TIØ contributed to writing.

Competing interests. There are no competing interests present.

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