Quality-controlled meteorological datasets from SIGMA automatic weather stations in northwest Greenland, 2012–2020

Motoshi Nishimura[1*], Teruo Aoki[1], Masashi Niwano[2], Sumito Matoba[3], Tomonori Tanikawa[2], Tetsuhide Yamasaki[4], Satoru Yamaguchi[5], Koji Fujita[6]

[1]National Institute of Polar Research, Tokyo, Japan

[2]Meteorological Research Institute, Japan Meteorological Agency, Ibaraki, Japan

[3]Institute of Low Temperature Science, Hokkaido University, Hokkaido, Japan

[4]Avangnaq Arctic Project, Osaka, Japan

[5]Snow and Ice Research Center, National Research Institute for Earth Science and Disaster Resilience, Niigata, Japan

[6]Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan

Correspondence to: Motoshi Nishimura (nishimura.motoshi@nipr.ac.jp)

Abstract. In situ meteorological data are essential to better understand ongoing environmental changes in the Arctic. Here, we present a dataset of quality-controlled meteorological observations by two automatic weather stations in northwest Greenland from July 2012 to the end of August 2020. The stations were installed in the accumulation area on the Greenland Ice Sheet (SIGMA-A site, 1490 m a.s.l.) and near the equilibrium line of the Qaanaaq Ice Cap (SIGMA-B site, 944 m a.s.l.). We describe the two-step sequence of quality-control procedures that we used to create increasingly reliable datasets by masking erroneous data records. Those data sets are archived in the Arctic Data archive System (ADS) (SIGMA-A; http://doi.org/10.17592/001.2022041303, SIGMA-B; http://doi.org/10.17592/001.2022041306). We analyzed the resulting 2012–2020 time series of air temperature, surface height, surface albedo, and histograms of longwave radiation (a proxy of cloudiness formation frequency). We found that surface height increased and no significant albedo decline in summer was observedalbedo remained steady at the SIGMA-A site., In contrast,whereas high air temperatures and frequent clear-sky conditions in the summers of 2015, 2019, and 2020 at the SIGMA-B site causedprevailed while surface height was significantly albedo and surface lowering and albedo decreased in the summers of 2015, 2019, and 2020 at the SIGMA-B site. Therefore, it appears that these weather conditions difference, and it led to apparent surface height decrease at the SIGMA-B site but not at the SIGMA-A site. We anticipate that this quality-control method and these datasets will aid in climate studies of northwest Greenland as well as contribute to the advancement of broader polar climate studies.

1. Introduction

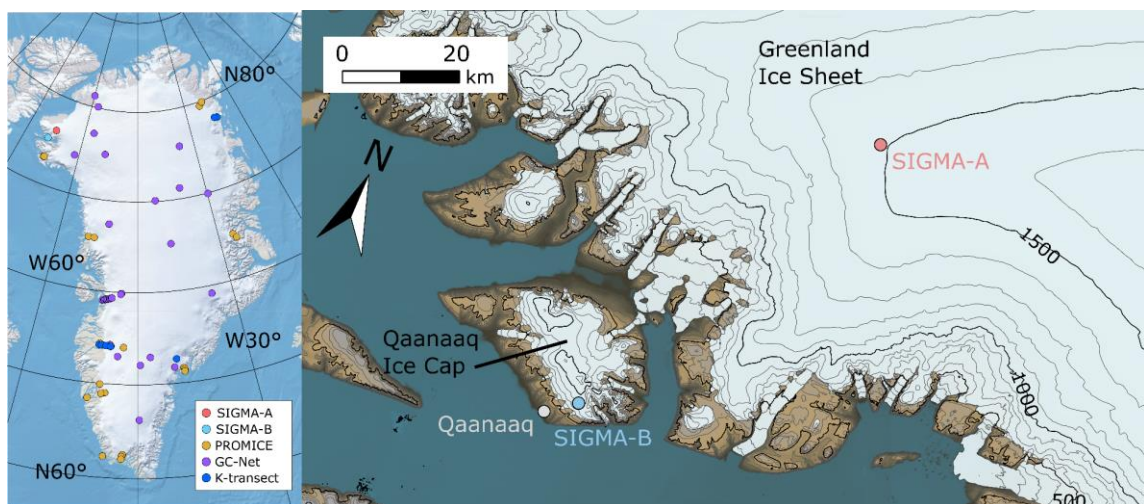
Automatic weather observation in Greenland started with GC-Net (Greenland Climate Network; Steffen and Box, 2001), which was established as a network of automatic weather stations (AWS) in Greenland after 1990. This observation network intended to provide long-term observations of climatological and glaciological factors over Greenland. This was followed by the PROMICE (van As et al., 2011; Fausto et al., 2021) led by the Geological Survey of Denmark and Greenland (GEUS) and the K-transect network (van de Wal et al., 2005), led by Utrecht University in the Netherlands, has been deployed. PROMICE is currently operating the largest observation network in Greenland by contracting the maintenance of GC-Net equipment, and K-transect has deployed equipment mainly in the western part of the country and continues to monitor the area closely. Both networks have provided important long-term meteorological data.

To contribute to these efforts and to fill a spatial gap, we established two AWS systems in northwest Greenland (Fig. 1), where rapid environmental changes have occurred in recent years (Aoki et al., 2014). Recent studies of this region have documented a drastic mass loss since the mid-2000s (Mouginot et al., 2019), an expansion of the ablation area (Noël et al., 2019), and a hot spot of increasing rainfall (Niwano et al., 2021). The two sites were established in 2012 as a part of the Snow Impurity and Glacial Microbe effects on abrupt warming in the Arctic (SIGMA) Project, which aimed to clarify the dramatic enhancement of melting of the Greenland Ice Sheet induced by snow impurities (e.g., black carbon, mineral dust). The observational data acquired since that time have been used by glaciological (Yamaguchi et al., 2014; Tsutaki et al., 2017; Matoba et al., 2018; Kurosaki et al., 2020), meteorological (Aoki et al., 2014; Tanikawa et al., 2014; Niwano et al., 2015; Hirose et al., 2021), and biological studies (Onuma et al., 2018; Takeuchi et al., 2018). These data are also valuable because they support the evaluation and development~~output~~ of numerical models (e.g., Niwano et al., 2018; Fujita et al., 2021)~~and form the basis for robust analytical results~~.

The datasets from AWS generally contain erroneous data records that are attributed to natural factors (e.g., riming, ice accretion, snow accumulation on sensors) or technical issues (e.g., "Zero Offset"; (Behrens, 2021~~)~~, faulty sensors) for radiation sensors. Various procedures exist for improving the quality~~accuracy~~ of such datasets (e.g., Fiebrich et al., 2010; Fausto et al., 2021). In particular, careful Quality Control (QC) procedures, which is a process to improve the quality of data by removing outliers, are required for downward radiation sensors, which are sensitive to solar zenith angle, icing, riming, and snowfall (van den Broeke et al., 2004a, b; Moradi, 2009). Other QC procedures deal with error sources through range, step, and internal consistency tests (Estévez et al., 2011). The specifics of QC methods, for example, the threshold value for detecting erroneous data records, should be adjusted for each observation environment. In this paper, we describe the QC methods used for the in situ meteorological observation data from northwest Greenland, which include existing QC methods, new ones, and combinations of both.

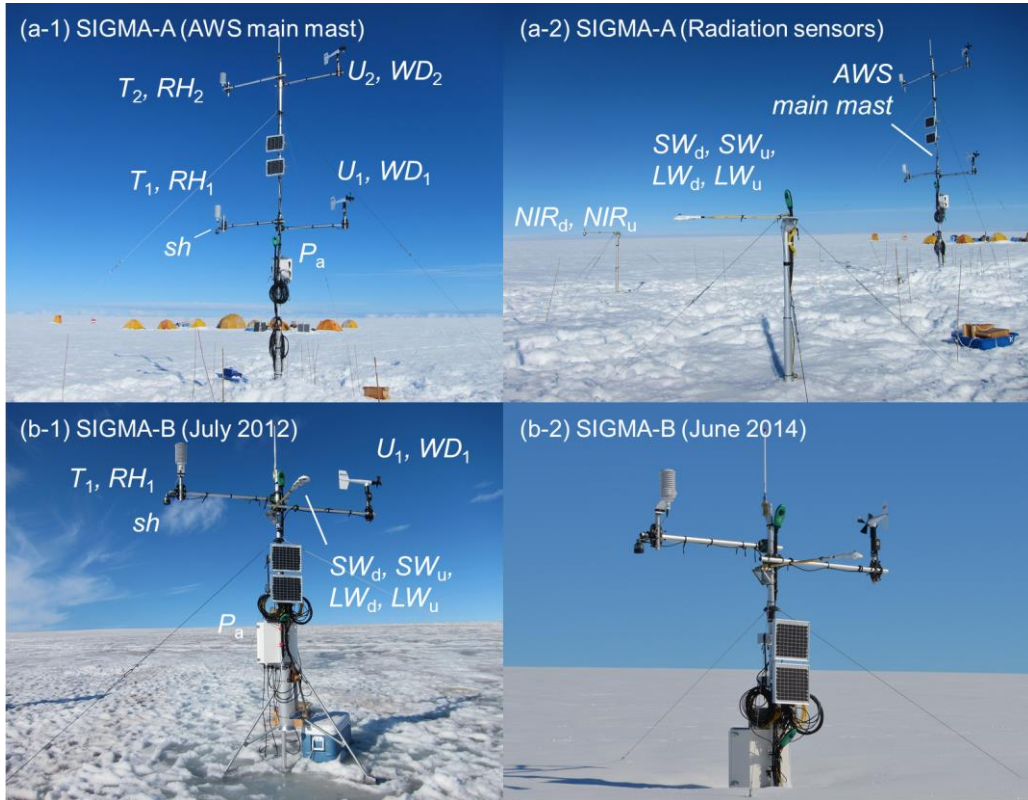
69   After describing the AWS sites (Sect. 2) and their datasets (Sect. 3), this paper introduces the two
70   separate QC methods used sequentially to mask erroneous data records (Sect. 4). We then present
71   examples of time series of meteorological variables in northwest Greenland, infer their implications
72   for interannual variations in weather conditions, and describe the differences between the two sites
73   (Sect. 5).

2. AWS general description

75   The two AWSs are installed at the SIGMA-A site (78.052° N, 67.628° W; 1490 m a.s.l.), on the
76   northwest Greenland Ice Sheet, and the SIGMA-B site (77.518° N, 69.062° W; 944 m a.s.l.), on the
77   Qaanaaq Ice Cap, a peripheral ice cap on the Greenland coast (Fig. 1). They have been in operation
78   since July 2012 (Aoki et al., 2014). The observed parameters and th~~ose~~e sensor specifications including
79   abbreviations are listed in Table 1~~,~~. ~~and t~~The other key constants, variables, and their abbreviations
80   used in this study are also in Table 2.
81   The SIGMA-A site is 70 km inland from the coast on a ridge of the Greenland Ice Sheet extending
82   northwest from the Greenland Summit; it sits on a flat snow surface with no obstacles around the site
83   (see Fig. 2). This site is in an accumulation area of~~for~~ the ice sheet (Matoba et al., 2018) based on the
84   analysis of ice-core data (Yamaguchi et al., 2014; Matoba et al., 2017). The SIGMA-B site is 3 km
85   north of the village of Qaanaaq. This site is considered to be located ~~at~~ near the equilibrium line (910
86   m a.s.l.; Tsutaki et al., 2017) on the Qaanaaq Ice Cap, which ranges in elevation between 30 and 1110
87   m a.s.l. (Sugiyama et al., 2014). The surface condition at this site varies (see Fig. 2), and significant
88   surface lowering ~~height decreasing~~ has occurred in warm years (e.g., Aoki et al., 2014). The site is
89   located on a southwest-facing slope (azimuth 220°) with an angle of 4° according to 10 m DEM data
90   (Porter et al., 2018).
91

93   Figure 1. Location map of Greenland showing PROMICE, GC-Net, and K-transect AWS sites (left)

94   and a local map of northwest Greenland showing locations of AWS sites SIGMA-A and SIGMA-B.

95   Contour interval in the right panel is 100 m.

96

97

98   Figure 2. Setting and instrumentation at the SIGMA-A site (top) and the SIGMA-B site (bottom).

99   Surface conditions at SIGMA-B are shown in July 2012 and June 2014. Sensors are labeled with the

100   observation parameters they measure (see Table 1).

101

102   Table 1. Meteorological observation parameters and sensor specifications.

observation parameter	abbreviation	unit	sensor	observaion range	accuracy
wind speed	$U_n{}^a$	m s^{-1}	Young, 05103	0 to 100 [m s^{-1}]	± 0.3 m s^{-1} or 1%
wind direction	$WD_n{}^a$	degree	Young, 05103	360° mechanical, 355° electrical (5° open)	± 3°
air temperature	$T_n{}^a$	°C	Vaisala, HMP155^b	−80 to +60 [°C]	±0.17 °C
relative humidity^c	$RH_n{}^a$	%	Vaisala, HMP155^b	0 to 100%	±1% (0 to 90%) ±1.7% (90 to 100%)
atmospheric pressure	P_a	hPa	Vaisala, PTB210	500 to 1100 [hPa]	±0.30 hPa at 20 °C
downward and upward shortwave radiation	SW_d, SW_u	W m^{-2}	Kipp & Zonen, CNR4	0.3 to 2.8 [µm]	±5% (daily total)
downward and upward longwave radiation	LW_d, LW_u	W m^{-2}	Kipp & Zonen, CNR4	4.5 to 42 [µm]	±10% (daily total)
downward and upward near-infrared radiation	NIR_d, NIR_u	W m^{-2}	Kipp & Zonen, CMP6 with a RG715 cut-off filter	0.715 to 2.8 [µm]	±5% (daily total)
surface height	sh	cm	Campbell, SR50	0.5 to 10 [m]	1 cm or 0.4%
snow temperature	$st_n{}^a$	°C	Climatec, C-PTWP-10	−40 to +60 [°C]	±0.15°C
tilts of the main mast	$Tilt_X, Tilt_Y$	degree	TURCK, B2N85H-Q20L60-	−85° to +85°	±0.5°

a: "n" suffix is appended to distinguish the observation height or depth.
b: protected from direct solar irradiance by a naturally-aspirated 14-plate Gill radiation shield
c: Relative humidity is measured relative to water even in sub-freezing environments

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104

105 Table 2. Key constants, variables, and their symbols used in this paper.

symbol	name	value	unit
constant			
f_{nir}	a fraction of near-infrared radiant flux in the shortwave radiant flux at the top of the atmosphere	0.5151	no dimension
I_0	solar constant	1361	W m^{-2}
n	cloud cover coefficient	0.5	no dimension
r_m	annual mean distance between the Sun and the Earth	1.496×10^8	km
$sh_{initial}$	initial height of the surface height sensor	300	cm
α_{sw_max}	maximum value of surface albedo	0.95	no dimension
α_{nir_max}	maximum value of surface near-infrared albedo	0.90	no dimension
κ	constant depending on cloud type	0.26	no dimension
ε	snow/ice surface emissivity	0.98	no dimension
σ	Stefan-Boltzmann constant	5.67×10^8	W m^{-2} K^{-4}
variable			
d	diffuse fraction in global radiation		no dimension
I_d	diffuse solar radiation		W m^{-2}
I_s	direct solar radiation		W m^{-2}
LW_d	downward longwave radiation		W m^{-2}
LW_{std}	standard atmospheric longwave radiation		W m^{-2}
LW_u	upward longwave radiation		W m^{-2}
NIR_d	downward near-infrared radiation		W m^{-2}
NIR_u	upward near-infrared radiation		W m^{-2}
P_a	atmospheric pressure		hPa
r	distance between the Sun and the Earth		m
$RH_{1,2}$[a]	relative humidity		%
sh	surface height		cm
sh_{raw}	raw data of surface height		m
$solz$	solar zenith angle		degree
$solz_{slope}$	solar zenith angle for a slope		degree
$st_{1\text{-}6}$[b]	snow temperature		°C
$st\_depth_{1\text{-}6}$[b]	snow temperature sensor depth		m
SW_d	downward shortwave radiation		W m^{-2}
SW_{d_slope}	downward shortwave radiation for a slope		W m^{-2}
SW_{TOA}	downward shortwave radiation at the top of the atmosphere		W m^{-2}
SW_u	upward shortwave radiation		W m^{-2}
t_r	transmissivity of the atmosphere for shortwave radiation		no dimension
$T_{1,2}$[a]	air temperature		°C
$WD_{1,2}$[a]	wind direction		degree
$U_{1,2}$[a]	wind speed		m s^{-1}
α_{sw}	surface albedo		no dimension
$\alpha_{sw,i}$	daily integrated surface albedo		no dimension
α_{nir}	surface near-infrared albedo		no dimension
$\alpha_{nir,i}$	daily integrated surface near-infrared albedo		no dimension
β	slope angle		radian
ε_0	clear-sky atmospheric emissivity		no dimension
ε^*	atmospheric emissivity		no dimension
θ	solar zenith angle		radian
θ_{slope}	solar zenith angle for a slope		radian
ϕ	solar azimuth angle		radian
ϕ_{slope}	solar azimuth angle of a slope		radian

[a] 1: observed at lower height, 2: observed at upper height (only at the SIGMA-A site)

[b] 1-6: observing depth

106

symbol	name	value	unit
	constant		
f_{nir}	a fraction of near-infrared radiant flux in the shortwave radiant flux at the top of the atmosphere	0.5151	no dimension
I_0	solar constant	1361	W m^{-2}
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r_m	annual mean distance between the Sun and the Earth	1.496×10^8	km
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α_{nir_max}	maximum value of surface near-infrared albedo	0.90	no dimension
κ	constant depending on cloud type	0.26	no dimension
ε	snow/ice surface emissivity	0.98	no dimension
σ	Stefan-Boltzmann constant	5.67×10^8	W m^{-2} K^{-4}
	variable		
d	diffuse fraction in global radiation		no dimension
I_d	diffuse solar radiation		W m^{-2}
I_s	direct solar radiation		W m^{-2}
LW_d	downward longwave radiation		W m^{-2}
LW_{std}	standard atmospheric longwave radiation		W m^{-2}
LW_u	upward longwave radiation		W m^{-2}
NIR_d	downward near-infrared radiation		W m^{-2}
NIR_u	upward near-infrared radiation		W m^{-2}
P_a	atmospheric pressure		hPa
r	distance between the Sun and the Earth		m
$RH_{1,2}$[a]	relative humidity		%
sh	surface height		cm
sh_{raw}	raw data of surface height		m
solz	solar zenith angle		degree
$solz_{slope}$	solar zenith angle for a slope		degree
st_{1-6}[b]	snow temperature		°C
st_depth_{1-6}[b]	snow temperature sensor depth		cm
SW_d	downward shortwave radiation		W m^{-2}
SW_{d_slope}	downward shortwave radiation for a slope		W m^{-2}
SW_{TOA}	downward shortwave radiation at the top of the atmosphere		W m^{-2}
SW_u	upward shortwave radiation		W m^{-2}
t_r	transmissivity of the atmosphere for shortwave radiation		no dimension
$T_{1,2}$[a]	air temperature		°C
$WD_{1,2}$[a]	wind direction		degree
$U_{1,2}$[a]	wind speed		m s^{-1}
α_{sw}	surface albedo		no dimension
$\alpha_{sw,i}$	daily integrated surface albedo		no dimension
α_{nir}	surface near-infrared albedo		no dimension
$\alpha_{nir,i}$	daily integrated surface near-infrared albedo		no dimension
β	slope angle		radian
ε_0	clear-sky atmospheric emissivity		no dimension
ε^*	atmospheric emissivity		no dimension
θ	solar zenith angle		radian
θ_{slope}	solar zenith angle for a slope		radian
ϕ	solar azimuth angle		radian
ϕ_{slope}	solar azimuth angle of a slope		radian

[a] 1: observed at lower height, 2: observed at upper height (only at the SIGMA-A site)

[b] 1-6: observing depth

3. Description of AWS systems and datasets

3.1. Specifications

Each AWS main mast is set in a hole drilled using a hand auger. Sensors for air temperature, relative humidity, and wind speed and direction are mounted at the ends of horizontal poles to exclude possible thermal and wind disturbances from the main mast. The SIGMA-A sensors are placed 3 m and 6 m above the surface, as signified by subscripts "1" (lower) and "2" (upper) in the corresponding data variables. The SIGMA-B sensors are set at 3 m above the surface and have subscripts of "1". The surface height sensor at both sites is mounted at 3 m height beneath the air temperature and relative humidity sensors. Six snow temperature sensors have been set as follows. Four sensors were set at 19:00 UTC on 29 June 2012 at depths of 100 cm (st_1), 70 cm (st_2), 40 cm (st_3), and 5 cm (st_4) belowunder the snow surface. At 21:00 UTC on 27 July 2013, sensors st_3 and st_4 were relocated to depths of 46 cm and 16 cm, respectively. Sensors st_5 and st_6 were set at 5 cm under the surface and 45 cm above the surface, respectively, at 14:00 UTC on 9 June 2014. Sensors for shortwave, longwave, and near-infrared radiation are installed at SIGMA-A on separate poles 10 m from the main mast (Fig. 2a-2). A pyranometer and a pyrgeometer at SIGMA-B are mounted on the main mast facing directly south. Tilt angles of the main mast in the north-south ($Tilt_X$) and east-west ($Tilt_Y$) directions are monitored with an inclinometer attached to the main mast. The additional suffix "A" or "B" represents the site name in the variables introduced below.

Electric power is supplied to the AWS systems by a lead-acid battery that is charged constantly by solar panels attached to the main mast. All parameters are recorded once per minute and stored in a data logger (C-CR1000, Campbell Scientific, USA), except for the main mast's surface height and tilt angles, which are recorded every hour. Hourly data are calculated for the other parameters by averaging the 1-min data. All hourly data are sent regularly to the data server via the Argos satellite channel.

Surface height is measured with an ultrasonic snow gauge (Table 1). The raw data from this sensor (sh_{raw}) is the distance from the sensor to the snow surface, which has a temperature dependence. The temperature-corrected surface height (sh) is calculated from

$$sh = sh_{initial} - sh_{raw} \times \sqrt{\frac{T_2 + 273.15}{273.15}} \times 100, \tag{i}$$

where $sh_{initial}$ (= 300 cm) is the initially installed sensor height from the surface and T_2 is air temperature.

3.2. Data processing

We describe the calculations for some variables used in the QC process in this section. To

142 accurately calculate the surface albedo and surface energy balance at the SIGMA-B site, we considered

143 the impact of the sloping surface on the vertical radiant flux. To account for this effect, we derived the

144 slope-corrected downward shortwave radiation (SW_{d_slope}) using the methods in Jonsell et al. (2003)

145 and Hock and Holmgren (2005). The SW_{d_slope} is calculated by

146 $$SW_{d\_slope} = I_s + I_d, \tag{ii}$$

147 where I_s and I_d are the direct and diffuse shortwave radiation for a slope, respectively:

148 $$I_s = SW_d \times d, \tag{iii}$$

149 $$I_d = SW_d \times (1-d) \times \frac{\cos\theta_{slope}}{\cos\theta}, \tag{iv}$$

150 where d is the ratio of total diffuse radiation to global radiation and θ and θ_{slope} [radian] are the solar

151 zenith angle and the solar zenith angle for a slope, respectively. The ratio d is obtained from

152 atmospheric transmittance t_r by

153 $$d = \begin{cases} 0.15 & \text{for } 0.8 \leq t_r, \\ 0.929 + 1.134t_r - 5.111t_r{}^2 + 3.106t_r{}^3 & \text{for } 0.15 < t_r < 0.8, \\ 1.0 & \text{for } t_r \leq 0.15, \end{cases} \tag{v}$$

154 where

155 $$t_r = \frac{SW_d}{SW_{\text{TOA}}}, \tag{vi}$$

156 where SW_{TOA} is the downward shortwave radiation at the top of the atmosphere, calculated by

157 $$SW_{\text{TOA}} = I_0 \left(\frac{r_m}{r}\right)^2 \cos\theta, \tag{vii}$$

158 where I_0 (= 1361 W m^{-2}) is the solar constant (Rottman, 2006; Fröhlich, 2012), r is the distance

159 between the Sun and the Earth (assuming an elliptical orbit with an eccentricity of 0.01637), and r_m is

160 its annual mean (= 1.496×10^8 km).

161   The solar zenith angle for a slope in Eq. (iv) is calculated by

162 $$\cos\theta_{\text{slope}} = \cos\beta\cos\theta + \sin\beta\sin\theta\cos(\varphi - \varphi_{\text{slope}}), \tag{viii}$$

163 where β is the slope angle from a horizontal plane, and φ and φ_{slope} are the solar azimuth and the solar

164 azimuth for the slope direction, respectively. Solar zenith and azimuth angles are calculated from the

165 geographic position of the observation site and the date and time.

166   Shortwave and near-infrared albedos (a_{sw} and a_{nir}, respectively) are calculated as the ratio of

167 upward and downward radiant fluxes, as shown for a_{sw} by

168 $$\alpha_{\text{sw}} = \frac{SW_u}{SW_d}, \tag{ix}$$

169 where SW_u is the upward shortwave radiant flux and SW_d is the downward shortwave radiant flux.

170 *SW_{d_slope} is used for SW_d when calculating a_{sw} at the SIGMA-B site.* The daily integrated shortwave

171 albedo ($a_{\text{sw,i}}$) is calculated as the ratio of cumulative upward and downward radiant fluxes for the past

172   24 h:

173         $\alpha_{\mathrm{sw,i}} = \sum_{24\mathrm{h}} SW_{\mathrm{u}} / \sum_{24\mathrm{h}} SW_{\mathrm{d}}.$ (x)

174   The near-infrared albedo (a_{nir}) and daily integrated near-infrared albedo ($a_{\mathrm{nir,i}}$) are calculated in the

175   same way. The near-infrared fraction is the ratio of the downward near-infrared radiant flux (NIR_{d}) to

176   SW_{d}.

177   Note that some parameters may require correction or caution depending on the observation

178   environment. First, since temperature and humidity shelters are naturally ventilated, air temperature

179   value may have a positive bias due to shelter heating from solar radiation (e.g., Morino et al, 2021).

180   In addition, in sub-freezing conditions, relative humidity may not be measured correctly because the

181   sensor used in this study (Vaisala, HMP155) calculates relative humidity as liquid water vapor pressure

182   even in sub-freezing environments and when~~if~~ the shelter is covered by rime or frost (Makkonen and

183   Laakso, 2005). Aoki et al. (2011) pointed out that the pole on which the radiometer is mounted casts

184   a shadow on the radiation sensor~~.~~ In addition, reflected and shielding scattered radiations due to the

185   AWS including solar panels ~~which~~ may result in incorrect radiation measurements, although no

186   anomalous radiation data due to these factors were found. Although the possibility of data correction

187   as described above is recognized, the focus of this paper is to open the observed values themselves,

188   without any correction or data processing that might involve the implementer's intention. Therefore,

189   we will note only the correction possibilities and present the observed data in this study.

190   **4. Quality control**

191   The datasets of observations at sites SIGMA-A and SIGMA-B are classified into four QC levels

192   numbered 1.0 to 1.3. A Level 1.0 dataset, which is not archived in any repository, is a raw dataset

193   without data processing. A Level 1.1 dataset is a raw dataset with flags added to indicate missing data

194   for periods when the data logger was inoperative. A Level 1.2 dataset has undergone an initial control,

195   which uses a simple masking algorithm to eliminate anomalous values that violate physical laws or

196   are impossible in the observed environment. The initial control improves the accuracy of the statistical

197   processing that follows and reduces the possibility of excluding true values. A Level 1.3 dataset has

198   undergone a secondary control, in which statistical methods are used on Level 1.2 data to identify and

199   mask outlier values. It has also undergone a final manual masking procedure, in which a researcher

200   visually checks the dataset and masks outliers based on subjective criteria.

201   The initial control method is described in Sect. 4.1 and the secondary control method is described

202   in Sect. 4.2. In these sections, the parameter suffixes related to the differences in observation height

203   (1 and 2) and sites (A and B) are omitted except when needed for clarity, and subscripts indicating

204   upward and downward radiation (d; downward, u; upward) is denoted as χ in the equation. Erroneous

205   records are flagged with one of the following numerical expressions to signify the reason they have

206   been flagged:

207   −9999: a missing or erroneous data record attributed to a mechanical malfunction or a local

208   phenomenon such as sensor icing, riming, or burial in snow.

209   −9998: an erroneous radiation record when the radiant sensor was covered with snow or frost.

210   −9997: a record of snow temperature sensor depth when the sensor was suspected to be located above,

211   not below the snow surface.

212   −8888: a record flagged during the manual masking procedure.

4.1. Initial QC for Level 1.2 datasets

214   The objectives of the initial control are to eliminate erroneous records due to mechanical

215   malfunctions or local phenomena and pre-treat Level 1.1 datasets for the secondary control. The initial

216   control consists of a range test (e.g., Fiebrich et al., 2010; Estévez et al., 2011) and a manual mask

217   procedure. The range test sets variation ranges (see Tables 3 and 4) for each observed parameter in

218   northwest Greenland on the basis of simple statistics based on (maximum, minimum, and mean values)

219   derived from records in the Level 1.1 dataset during a period with no obvious erroneous data. Records

220   outside this statistical range are flagged with a "−9999" code. Tables 3 and 4 list the parameters

221   subjected to this test and their assigned ranges. The manual masking procedure identified specific

222   erroneous values that resulted from an electrical malfunction and flagged them with a "−8888" code.

223   The following subsections offer detailed and additional explanations of the initial control, however,

224   the range test for each parameter is listed in Table 3, in the detail description of it for each parameter

225   is omitted in the following sections description, only the procedure numbers in Table 3 are referenced

226   as necessary, and the explanation of the range test is omitted.

4.1.1. Wind speed and wind direction

228   U_{max} used in the range test is the maximum value between the beginning of observation and 31

229   August 2020, and +15.0 m s^{-1} was taken as the range margin for the upper limit of U_n. In addition to

230   the range test, the following basic processing was also performed. When U_n was zero (no wind), WD_n

231   was flagged as erroneous:

232        $U_n = 0$ and $WD_n > 0$ $\rightarrow$ WD_n flagged −9999.   (1.1.1)

233   When WD_n had a negative value, it was flagged as erroneous:

234        $WD_n \leq 0$ $\rightarrow$ WD_n flagged −9999.   (1.1.2)

4.1.2. Air temperature and relative humidity

236   T_{n_max} and T_{n_min} were determined from the entire observation period ending 31 August 2020. The

237   range margin for T_n was set as ±10.0 °C. Discrepancies arising from the dual sensors at SIGMA-A

| 238 | were addressed in the secondary control (see Sect. 4.2.2). |

4.1.3. Shortwave and near-infrared radiation

The main objective of the initial control for shortwave radiation was to mask erroneous records attributed to Zero Offset (Behrens, 2021). Zero Offset is a few watts of radiation that occurs at night caused by the slight temperature difference between the two detectors (inside of the dome shelter and sensor body). However, since the value is an observation error, the observed value may be different from the original radiation balance and need to be masked.

The range test is based on the assumption that SW_d cannot exceed the maximum of SW_{TOA} (SW_{TOA_max}) during the observation period (761.6 W m^{-2} at SIGMA-A and 772.2 W m^{-2} at SIGMA-B), and albedos a_{sw} and a_{nir} cannot be higher than a_{sw_max} and a_{nir_max} ($a_{sw\_max} = 0.95$ and $a_{nir\_max} = 0.90$), respectively, as determined from the radiative transfer model calculation (Aoki et al., 2003). Moreover, the fraction of the near-infrared spectral domain at the top of the atmosphere (f_{nir}) is assumed to be equal to 0.5151 based on the extraterrestrial spectral solar radiation (Wehrli, 1985). Based on those assumptions, upward and downward radiation fluxes were flagged as erroneous according to the range tests in Table 3.

The following procedures were also applied to mask erroneous records due to Zero Offset. These parameters were flagged as erroneous (-9999) in a following case (using SW_χ as an example):

$$SW_\chi < 0 \ \text{ and } \ solz < 90.0 \ \rightarrow SW_\chi \text{ flagged } -9999, \tag{1.3.1}$$

$$SW_\chi < 0 \ \text{ and } \ solz \geq 90.0 \ \rightarrow SW_\chi = 0. \tag{1.3.2}$$

4.1.4. Longwave radiation

The range tests were performed for LW_d and LW_u under the conditions in Table 3. LW_{d_max} and LW_{u_max} were determined as follows:

$$LW_{d\_max} = \varepsilon_{max}\sigma\, T_{max}, \tag{1.4.1}$$

$$LW_{u\_max} = \varepsilon\sigma\, T_{s\_max}. \tag{1.4.2}$$

However, T_{max} is T_{2A_max} for the SIGMA-A site and T_{1B_max} for the SIGMA-B site. Maximum values were determined under the following assumptions: (1) T_{2A} and T_{1B} cannot be larger than T_{2A_max} and T_{1B_max}, respectively, (2) atmospheric emissivity is set to unity (ε_{max}), and (3) the value of LW_{u_max} is determined as the amount of radiation corresponding to longwave emission at T_{s_max} ($= 10\ °C$), which includes errors due to longwave emissions from the poles of the AWS system and similar sources, and that the emissivity of the snow/ice surface (ε) is 0.98 (Armstrong and Brun, 2008).

Both upward and downward longwave fluxes were considered erroneous when the sensor appeared to be covered with snow or frost:

$$|LW_d - LW_u| \leq 1.0 \ \rightarrow LW_d \ \text{ and } \ LW_u \ \text{ flagged } -9998. \tag{1.4.3}$$

4.1.5. Surface height

The range test for surface height (*sh*) was imposed separately for each period between maintenances to the SIGMA-A site, when the main mast extension was adjusted to prevent the sensors from being buried in snow. (A single range test sufficed for SIGMA-B.) For each test, the range was set so that *sh* varied from the median by ±100 cm or ±150 cm, a margin that was determined depending on the variation of the data records in each period. The objective of this range test (Procedure 1.5.1; Table 3) was to mask the most obvious outliers. In addition, corrections were made to the *sh* records after each of three maintenance visits to the AWS at SIGMA-A.

4.1.6. Atmospheric pressure

P_{a_ave} used in the range test is the average atmospheric pressure for the observation period at each AWS site (Table 3). The additional margin that defined the range was ±100 hPa.

4.1.7. Snow temperature

The range test for snow temperature was conducted using following threshold values; T_{1_min} is the minimum air temperature for the site and the upper threshold, 0.2 °C, incorporates the sensor's absolute error of 0.15 °C and the requirement that the snow temperature cannot be positive.

Table 3. Range test coverage for each parameter used in the QC procedures. The variable subscripts "n" (1 or 2) and χ indicate the distinction of sensors height and the direction of radiation flux (upward or downward), respectively.

parameter	variable	unit	range test value range	procerdure No.
wind speed	U_1, U_2	m s^{-1}	$0 < U_n < U_{max} + 15.0$	1.1.3
wind direction[a]	WD_1, WD_2	degree	$0 < WD_n \leqq 360$	1.1.4
air temperature	T_1, T_2	°C	$T_{n\_min} - 10.0 < T_n < T_{n\_max} + 10.0$	1.2.1
relative humidity	RH_1, RH_2	%	$0 \leqq RH_n \leqq 100$	1.2.2
shortwave radiation	SW_d, SW_u	W m^{-2}	$SW_d < SW_{TOA\_max}$	1.3.3
			$SW_u < SW_{TOA\_max} \times a_{sw\_max}$	1.3.5
			$SW_d < T_{rA\ (or\ B)} \times SW_{TOA\_max}$	2.3.2
near-infrared radiation[b]	NIR_d, NIR_u	W m^{-2}	$NIR_d < f_{nir} \times SW_{TOA\_max}$	1.3.4
			$NIR_u < f_{nir} \times SW_{TOA\_max} \times a_{nir\_max}$	1.3.6
			$NIR_d < T_{rA} \times f_{nir} \times SW_{TOA\_max}$	2.3.3
surface albedo	a_{sw}	–	$0.6 < a_{sw} < 0.95$ (for October–April in SIGMA-A)	2.4.1
			$0.4 < a_{sw} < 0.95$ (for May–September in SIGMA-A)	2.4.2
			$0.4 < a_{sw} < 0.95$ (for October–April in SIGMA-B)	2.4.3
			$0.1 < a_{sw} < 0.95$ (for May–September in SIGMA-B)	2.4.4
surface near-infrared albedo	a_{nir}	–	$0.5 < a_{nir} < 0.90$ (for October–April in SIGMA-A)	2.4.5
			$0.3 < a_{nir} < 0.90$ (for May–September in SIGMA-A)	2.4.6
longwave radiation	LW_d, LW_u	W m^{-2}	$0 < LW_\chi < LW_{\chi\_max}$	1.4.4
surface height	sh	cm	median_sh $- 100.0$ or $150.0^c < sh <$ median_sh $+ 100.0$ or 150.0^c	1.5.1
atmospheric pressure	P_a	hPa	$P_{a\_ave} - 100.0 < P_a < P_{a\_ave} + 100.0$	1.6.1
snow temperature[b]	st	°C	$T_{1\_min} - 10.0 < st_n < 0.2$	1.7.1

[a] in case of $U_n > 0$
[b] only SIGMA-A site
[c] the margin is changed depending on a variation of the data record in each applied period.

291

292 Table 4. Statistical~~Threshold~~ values used in the range tests, determined from the entire observation

293 period up to 31 August 2020.

meteorological parameter	unit	threshold value			
		SIGMA-A		SIGMA-B	
		parameter name	value	parameter name	value
wind speed	$\mathrm{m\ s^{-1}}$	U_{1A_max}	23.9	U_{1B_max}	21.9
		U_{2A_max}	25.5	−	−
air temperature	°C	T_{1A_max}	7.2	T_{1B_max}	10.7
		T_{2A_max}	7.2	−	−
		T_{1A_min}	−49.9	T_{1B_min}	−40.5
		T_{2A_min}	−49.9	−	−
longwave radiation	$\mathrm{W\ m^{-2}}$	LW_{dA_max}	418.8	LW_{dB_max}	440.1
		LW_{uA_max}	357.2	LW_{uB_max}	357.2
atmospheric pressure	hPa	P_{a_aveA}	833.1	P_{a_aveB}	894.2

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4.2. Secondary QC for Level 1.3 datasets

297   The secondary control applies another range test, an anomaly test, and a manual mask procedure.

298 The range test sets a more precise variation range than the initial control and masks erroneous data

299 records. The anomaly test sets a median and standard deviation (SD), which govern statistical tests as

300 follows;

301    $\beta < \mathrm{median}\_\beta + \mathrm{SD}\_\beta \times \gamma,$ (2.0.1)

302 where β is an arbitrary variable and the multiplier γ is 1, 2, or 3 depending on the intensity of the

303 anomaly variation, and determined based on the test results in each case. Those statistical values and

304 the multiplier can be referred in the QC program. This study determined the possible range of

305 correct~~normal~~ values in the Level 1.2 dataset and identify and mask outliers if the variable deviates

306 from its normal range. The manual mask procedure identifies and masks any remaining erroneous

307 records. As a result of data masking by the initial control and the secondary control, the percentage of

308 unmasked records for each parameter at three data levels is shown in Table 5, and the effects of the

309 two controls are illustrated in Fig. 3 and described in detail below.

310

311 Table 5. Percentage of unmasked data for each parameter in each dataset.

	SIGMA-A			SIGMA-B		
	Level 1.1	Level 1.2	Level 1.3	Level 1.1	Level 1.2	Level 1.3
	%	%	%	%	%	%
U_1	98.0	98.0	92.1	99.7	99.7	97.7
WD_1	98.0	96.7	91.8	99.7	99.2	97.2
T_1	98.0	73.4	68.4	99.7	99.7	99.7
RH_1	98.0	50.7	43.6	99.7	99.7	98.8
U_2	98.0	98.0	94.1	–	–	–
WD_2	98.0	97.1	93.8	–	–	–
T_2	98.0	98.0	97.8	–	–	–
RH_2	98.0	98.0	98.0	–	–	–
SW_d	98.0	97.9	86.2	99.7	99.5	85.2
SW_u	98.0	97.9	98.1	99.7	99.7	99.7
LW_d	98.0	75.3	68.9	99.7	91.0	91.0
LW_u	98.0	68.7	67.4	99.7	91.0	91.0
NIR_d	98.0	97.9	86.6	–	–	–
NIR_u	98.0	97.9	98.0	–	–	–
sh	98.0	85.5	75.8	99.7	90.2	87.1
P_a	98.0	97.9	97.9	99.7	99.7	99.7
st_1	98.0	97.6	96.7	–	–	–
st_2	98.0	97.9	97.3	–	–	–
st_3	98.0	88.8	87.2	–	–	–
st_4	98.0	97.0	96.2	–	–	–
st_5	98.0	94.9	72.3	–	–	–
st_6	98.0	95.2	56.7	–	–	–
a_{sw}	–	–	31.6	–	–	32.4
a_{nir}	–	–	33.5	–	–	–
st_depth_1	–	–	75.8	–	–	–
st_depth_2	–	–	75.8	–	–	–
st_depth_3	–	–	75.8	–	–	–
st_depth_4	–	–	75.8	–	–	–
st_depth_5	–	–	52.7	–	–	–
st_depth_6	–	–	36.9	–	–	–
SW_{d_slope}	–	–	–	–	–	83.7

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	SIGMA-A			SIGMA-B		
	Level 1.1	Level 1.2	Level 1.3	Level 1.1	Level 1.2	Level 1.3
	%	%	%	%	%	%
U_1	98.0	98.0	92.1	99.7	99.7	97.7
WD_1	98.0	96.7	91.8	99.7	99.2	97.2
T_1	98.0	73.4	68.4	99.7	99.7	99.7
RH_1	98.0	50.7	43.6	99.7	99.7	98.8
U_2	98.0	98.0	94.1	–	–	–
WD_2	98.0	97.1	93.8	–	–	–
T_2	98.0	98.0	97.8	–	–	–
RH_2	98.0	98.0	98.0	–	–	–
SW_d	98.0	97.9	86.0	99.7	99.5	85.2
SW_u	98.0	97.9	97.8	99.7	99.7	99.7
LW_d	98.0	75.3	68.9	99.7	91.0	91.0
LW_u	98.0	68.7	67.4	99.7	91.0	91.0
NIR_d	98.0	97.9	86.4	–	–	–
NIR_u	98.0	97.9	97.8	–	–	–
sh	98.0	85.5	75.8	99.7	90.2	87.1
P_a	98.0	97.9	97.9	99.7	99.7	99.7
st_1	98.0	97.6	96.7	–	–	–
st_2	98.0	97.9	97.3	–	–	–
st_3	98.0	88.8	87.2	–	–	–
st_4	98.0	97.0	96.2	–	–	–
st_5	98.0	94.9	72.3	–	–	–
st_6	98.0	95.2	56.7	–	–	–
a_{sw}	–	–	31.6	–	–	32.4
a_{nir}	–	–	33.5	–	–	–
st_depth_1	–	–	75.8	–	–	–
st_depth_2	–	–	75.8	–	–	–
st_depth_3	–	–	75.8	–	–	–
st_depth_4	–	–	75.8	–	–	–
st_depth_5	–	–	52.7	–	–	–
st_depth_6	–	–	36.9	–	–	–
SW_{d_slope}	–	–	–	–	–	83.7

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Figure 3. Examples of the initial and secondary controls for the SIGMA-A site: (a) wind speed (U_{1A}),
(b) air temperature (T_{1A}), (c) downward shortwave radiation, (d) surface albedo, (e) downward
longwave radiation, (f) surface height, and (g) snow temperature (st_3). In all panels except (d), the dark
gray areas represent time periods in which data records in the Level 1.0 dataset were masked to
produce the Level 1.1 dataset, light blue dots denote records masked by the initial control, red dots

denote records masked by the secondary control, and dark blue dots are the Level 1.3 data records. In panel (d), the gray shaded area represents the masked (-9999) data records that cannot be calculated due to the absence of, masked SW_d, or for other reasons. The light blue, red and yellow dots represent data points masked by three QC operations during the secondary control; see Sect. 4.2.4 for explanation.

4.2.1. Wind speed and wind direction

When U_n was zero for more than 6 continuous hours, U_n and WD_n were both flagged as erroneous (-9999) under the assumption that the wind sensor was blocked by snow and ice. Although the initial control eliminated no U_n records, this step masked many values in the winter (Fig. 3a).

4.2.2. Air temperature and relative humidity

Anomaly tests for air temperature and relative humidity were only applied to the lower-level sensor records for SIGMA-A (i.e., T_{1A} and RH_{1A}). The anomaly test compared the difference (ΔT and ΔRH) between readings of the upper and lower sensors (i.e., $|T_{1A} - T_{2A}|$ and $|RH_{1A} - RH_{2A}|$) to the respective medians and SDs of those parameters. The medians were calculated from the data before 1 September 2017, because the data after that date appeared to include many erroneous T_{1A} records due to deterioration of the data logger or sensor. The SD criterion (γ in Procedure 2.0.1) was adjusted modestly ($\gamma = 3$) before 1 September, 2017 and more stringently ($\gamma = 1$) to detect outliers in the records of T_{1A} and RH_{1A} after the date, which were flagged as erroneous (-9999). The effectiveness of this adjustment is shown~~clear~~ in Fig. 3b.

4.2.3. Shortwave and near-infrared radiation

The anomaly test for shortwave and near-infrared radiation was intended to mask the noise resulting from a weak electric pulse at large solar zenith angles. The median and SD values were calculated only from ~~only~~ the records (SW_d, SW_u, NIR_d, and NIR_u) at $solz > 90.0°$ to distinguish this noise source according to Procedure 2.0.1 for above parameters, where $\gamma = 3$. If the record is in~~deviates from~~ its anomaly range, the records were identified as noise and modified to zero.

The downward radiation components were sometimes overestimated as a result of icing or riming over the glass dome of the pyranometer. To mask these erroneous values, we applied range tests based on SW_{TOA} and threshold values of atmospheric transmittance for each site T_{rA} and T_{rB} ($T_{rA} = 0.881$ and $T_{rB} = 0.872$) calculated by a radiative transfer model (Aoki et al., 1999, 2003) shown in Table 3. Values of SW_d and NIR_d that were outside the range were flagged as erroneous (-9999).

To recognize other instances when the radiation sensor was covered with snow or frost, SW_d and NIR_d records corresponding to the following case that downward radiation is smaller than upward

352   radiation was flagged as erroneous (−9998), using SW_χ as an example:

353       $SW_d < SW_u.$ (2.3.1)

354   Figure 3c shows that the initial control eliminated a few erroneous SW_d data recorded in August 2015,

355   whereas the secondary control masked many records, especially in February–May, that were affected

356   by riming or frost.

357   **4.2.4. Shortwave and near-infrared albedo**

358   We calculated albedos a_{sw} and a_{nir} from the SW_d and NIR_d datasets that were ~~completed~~ passed the

359   secondary control. This calculation was done in four separate steps, shown by the color of dots in Fig.

360   3d.

361   (1) Flagging for low pyranometer sensitivity

362   At solar zenith angles near 90.0°, SW_d and NIR_d may not be an accurate measurement because of

363   the low sensitivity of the pyranometer. We therefore masked a_{sw} and a_{nir} values at $solz > 85.0°$ or when

364   the SW_d (NIR_d) value was below the median SW_d (NIR_d) value for $solz > 85.0°$. Records masked in this

365   step are shown in Fig. 3d as light blue dots (d-i).

366   (2) Range test for cold and warm periods

367   The range test used the upper and lower thresholds for a_{sw} and a_{nir} shown in Table 3, as determined

368   by the radiative transfer calculation of Aoki et al. (2003, 2011) plus a small error margin. Those

369   thresholds correspond to the assumed surface conditions during two parts of the year. For the cold

370   period of October–April, we used the lower thresholds for dry snow at the SIGMA-A site and dry or

371   wet snow at the SIGMA-B site conditions. For the warm period of May–September we used the

372   thresholds for wet snow at the SIGMA-A site and wet snow or dark ice at the SIGMA-B site conditions.

373   Records with albedo values beyond these theoretical thresholds were masked.

374   (3) Anomaly test in low atmospheric transmittance condition

375   The range test was augmented by an anomaly test to identify underestimates of a_{sw} and a_{nir} when

376   SW_d (NIR_d) was low and atmospheric transmittance (t_r) was small, typically at large solar zenith angles.

377   We masked a_{sw} (a_{nir}) values that were unnaturally low owing to low t_r and SW_d (NIR_d) in $solz > 80.0°$

378   condition. Data records that were masked in either the range or anomaly tests are shown in Fig. 3d as

379   red dots (d-ii).

380   (4) Final steps

381   In cases where LW_d was flagged as "−9998" during the initial control (see Sect. 4.1.4), a_{sw} and a_{nir}

382   were flagged as "−9999" under the assumption that the radiation sensors were covered with snow or

383   frost. The final step was a manual mask procedure. Data records that were masked in this phase are

384   shown in Fig. 3d as orange dots (d-iii), and the final Level 1.3 dataset is displayed as blue dots (d-iv).

4.2.5. Longwave radiation

The anomaly test for LW_d and LW_u was conducted only for the SIGMA-A dataset using a standard longwave radiant flux (LW_{std}), a measure of the amount of longwave radiation from the near-surface atmosphere that was calculated from the air temperature measurement by Brock and Arnold (2000)

$$LW_{std} = \varepsilon^* \sigma (T_{2A} + 273.15)^4, \qquad (xi)$$

$$\varepsilon^* = (1 + \kappa n)\varepsilon_0, \qquad (xii)$$

$$\varepsilon_0 = 8.733 \times 10^{-3} \times (T_{2A} + 273.15)^{0.788}, \qquad (xiii)$$

where ε^* is the atmospheric emissivity, σ (= 5.670×10^{-8}) is the Stefan–Boltzmann constant, κ (= 0.26) is a constant depending on cloud type (Braithwaite and Olsen, 1990), n is the cloud cover amount (n: [0, 1] and set at 0.5 because it could not be determined), and ε_0 is the clear-sky emissivity. We assumed that LW_{std} was a close approximation of the true longwave radiant fluxes and used the absolute difference between LW_{std} and LW_d or LW_u (i.e., ΔLW_d or ΔLW_u) and its median and SD as the basis of the anomaly test as following Procedure 2.0.1.

Because parts of the LW_d dataset contained many erroneous records attributed to degradation of the data logger (see Fig. 3e), we reduced the SD criterion ($\gamma = 1$) in 7 April to 7 June 2017 and after 1 September 2017. Except for those two periods, γ was set to "2" for both ΔLW_d and ΔLW_u. LW_d and LW_u records that were outliers under the criteria were flagged as erroneous (-9999). Figure 3e shows that the initial control (see Sect. 4.1.4) improved this anomaly test's efficacy, and the secondary control yielded a clean LW_d time series.

4.2.6. Surface height

The anomaly test for surface height masked data that displayed unrealistic fluctuations. Differences (Δsh) were determined with respect to mean and SD values from the preceding 72 h values during period 1, before 1 September 2017 (sh_{mean1}) and period 2, after 1 September 2017 (sh_{mean2}). The Δsh values were compared to the median plus SD of Δsh for that period. In the period 1, the SD criterion in Procedure 2.0.1 was strict ($\gamma = 1$), and in the period 2, the criterion was relaxed ($\gamma = 3$). In addition, because surface height increased steadily in period 2, we derived the regression equation for this increase and identified outliers with respect to the SD of the regression, i.e. Δsh_{reg} as follows:

$$\Delta sh_{reg} < SD_{reg\_}sh \qquad \text{for after 1 September 2017.} \qquad (2.6.1)$$

Records of sh that varied beyond the anomaly ranges were flagged as erroneous (-9999).

A manual mask procedure was added as a final step. The result of QC procedure is shown in Fig. 3f. The initial control, which corrected gaps resulting from the AWS maintenance (see Sect. 4.1.5), yielded the smoothed data record that enabled the application of the anomaly test. Sensor height dataset was made using initial sensor height (3 or 6 m) and the QC completed temporal surface height data. Therefore, QC for sensor height data has already been implemented through the QC for surface height

419   data.

4.2.7. Snow temperature

421   In the first step, data records were masked when the snow temperature sensor was suspected to be
422   located above the snow surface:

423    $st\_depth_n < -1.0 \rightarrow st_n$ flagged -9999.   (2.7.1)

424   where st_depth_n [cm] was calculated using surface height data and the initial setting depth of sensor
425   "n" (see Sect. 3). The threshold of st_depth_n included a margin of 1.0 cm to reflect the accuracy of the
426   surface height sensor. The st_n was flagged as "-9997" if we could not judge whether the snow
427   temperature sensor was located below the snow surface.

428   The anomaly test for st_n consisted of two procedures. The first procedure relied on a temperature
429   gap (Δst_{d1}) between st_4 and data from each of the other five levels (st_{not4}) (i.e., $\Delta st_{d1} = |st_4 - st_{not4}|$),
430   because st_4 had very few erroneous data. The SD criterion (γ) for this anomaly test was changed for
431   each parameter depending on the variability of the data. The second procedure used the difference
432   (Δst_{d2}) between st_n and its mean value st_{n_mean} from the previous 72 h ($\Delta st_{d2} = |st_n - st_{n\_mean}|$),
433   calculated using the same method as sh_{mean} (see Sect. 4.2.6). The SD criteria (γ) were all unity in this
434   test. In both procedures, the median and SD terms were calculated from records for the full time period.
435   Records detected as outliers were flagged as "-9999". Figure 3g shows the results of all procedures,
436   using st_3 as an example.

4.2.8. Atmospheric pressure

438   The time series of P_a included only a few erroneous records. We masked outliers on the basis of
439    $|P_a - P_{a\_mean}| > 20.0$,   (2.8.1)

440   where P_{a_mean} is the average for the past 3 h (excluding masked data records). We set the threshold at
441   20.0, a higher value than the SD, because using the SD could have masked valid records. This
442   threshold value of 20 hPa is set on the assumption that a 20 hPa pressure jump is unlikely to occur in
443   a few hours. This procedure success to mask properly only the erroneous data of both sites.

5. Temporal variations of meteorological parameters

445   This section shows the results of simple analyses of the Level 1.3 dataset.

5.1. Air temperature and surface height

447   Figure 4 shows the air temperature fluctuations and surface height (*sh)* variations at both sites.
448   Mean air temperatures (2013–2019) were -18.1 °C at the SIGMA-A site and -12.3 °C at the SIGMA-

B site. The annual maxima of monthly data were recorded every July at both sites, except for August
2019 at the SIGMA-B site. At the SIGMA-A site, ~~The~~that annual maximum in 2015 was slightly
positive (+0.1 °C in July) but others were negative. ~~at the SIGMA-A site, and~~At the SIGMA-B site,
~~it~~those ~~was~~ere above freezing in all years ~~at the SIGMA-B site~~. ~~In contrast, t~~The annual minima
occurred in different months between December and March. ~~The maximum was slightly positive at~~
~~the SIGMA-A site, and it was above freezing in all years at the SIGMA-B site.~~Unusually high hourly
temperatures were recorded in mid-July 2015 (7.2 °C at SIGMA-A and 10.7 °C at SIGMA-B). Air
temperatures exceeding 5.0 °C at SIGMA-A and 10.0 °C at SIGMA-B were common during that
period.

Surface height steadily increased at the SIGMA-A site during the 8-year study period (Fig. 4), in
which sh rose approximately 1 m in the mass-balance years (September to August) of 2013/14,
2016/17, and 2017/18, and decreased slightly in the summers of 2011/12, 2014/15, and 2019/20.
Accumulations were notable in autumn and relatively small in winter. At the SIGMA-B site, in contrast,
increases and decreases in sh were observed during each mass-balance year. Decreases in sh during
summers were rare during the summers of 2012/13 and 2017/18 but common during the 2013/14,
2014/15, 2015/16, 2018/19, and 2019/20 summers, when decreases were greater than 1 m.
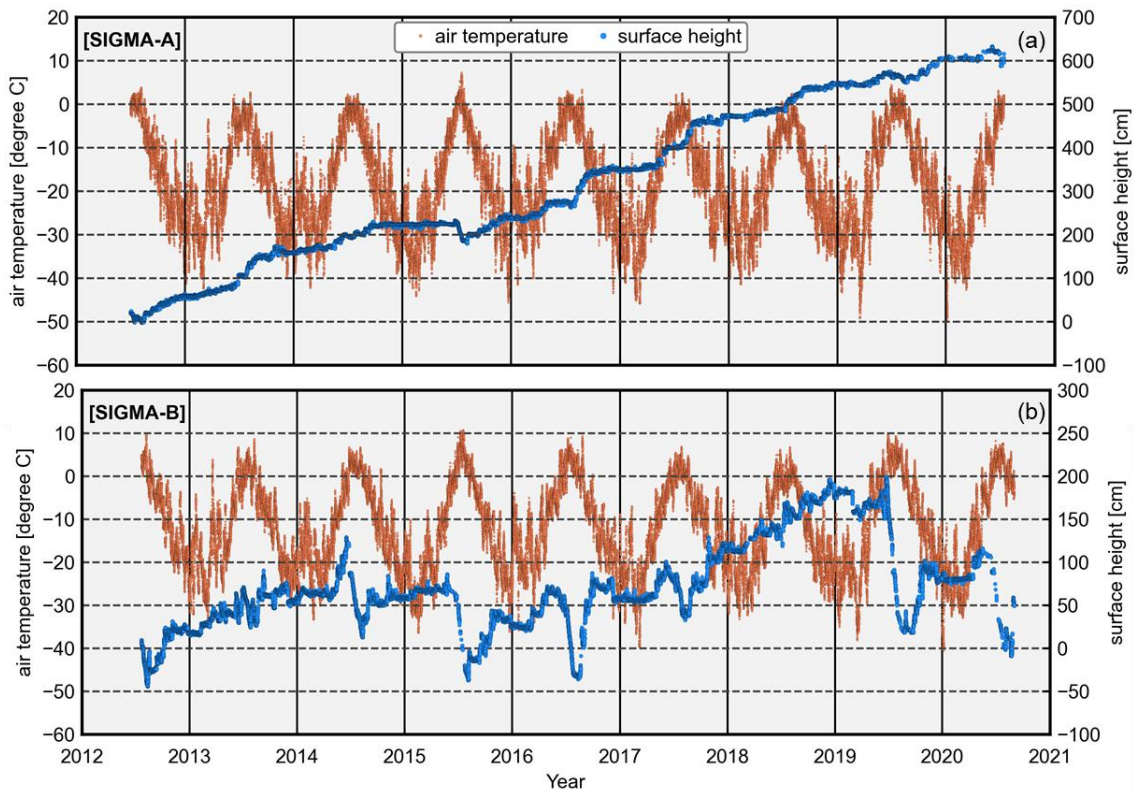
Figure 4. Time series of hourly air temperature and surface height at the (a) SIGMA-A (showing T_2
data) and (b) SIGMA-B sites.

469

5.2. Atmospheric pressure and seasonal variation of temperature lapse rate

The time series of atmospheric pressure (P_a) at the SIGMA-A and SIGMA-B sites show a clear seasonal variation, high in summer and low in winter (Fig. 6). The two data records had similar variation patterns that were strongly correlated ($r = 0.98$). The mean values for the whole observation period were 833.1 hPa at site SIGMA-A and 894.2 hPa at site SIGMA-B (Table 4). The difference in monthly mean P_a between the sites was smaller in summer and larger in winter (Fig. 7a), and the amplitude of the annual cycle was greater at the SIGMA-A site.

477
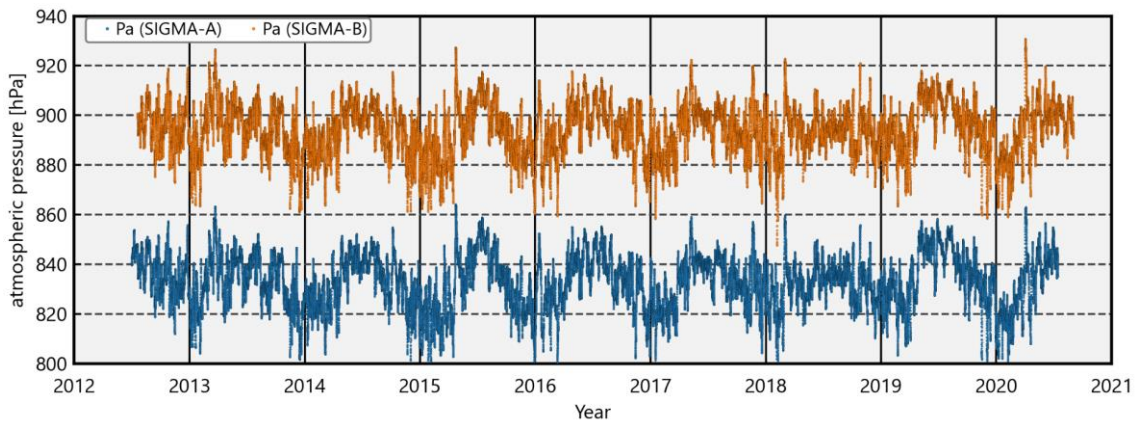
Figure 6. Time series of hourly atmospheric pressure (P_a) at the SIGMA-A and SIGMA-B sites.

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481
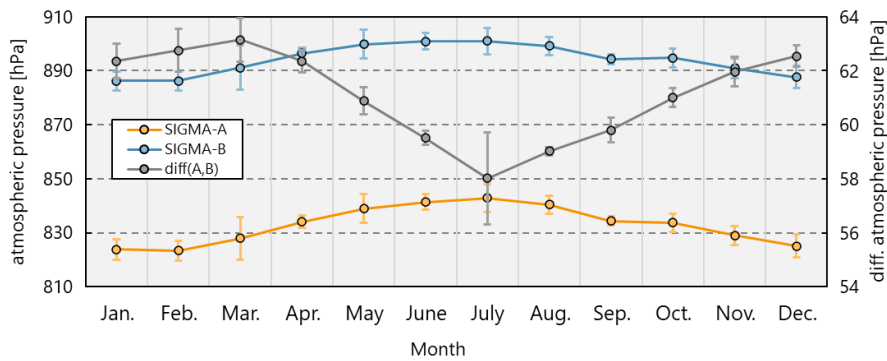
Figure 7. Time series of ensemble averages of monthly mean atmospheric pressures during all years at both sites and their difference. Error bars indicate ±1 SD.

485

5.3. Albedo

Whereas shortwave albedo (a_{sw}) was rarely lower than 0.7 at site SIGMA-A, near-infrared albedo

488   (a_{nir}) was below 0.6 in 2012, 2015, 2016, 2019, and 2020 (Fig. 8). Because a_{nir} depends on the snow

489   grain size (Wiscombe and Warren, 1980), this finding implies that snow metamorphism progressed at

490   the SIGMA-A site in those years (Hirose et al., 2021). A strong decrease in a_{sw} was observed at the

491   SIGMA-B site during those same summers, which corresponded to notable decreases in surface height

492   (Fig. 4b) and high PDDs (Fig. 5). The decreases in albedo may have accelerated snowmelt and caused

493   the decreases in surface height at SIGMA-B during the warm summers of those years (see Sect. 5.1).

494   It appears that the difference in albedo reduction between the SIGMA-A and SIGMA-B sites in

495   summer originated from the difference in air temperature between the sites.

496

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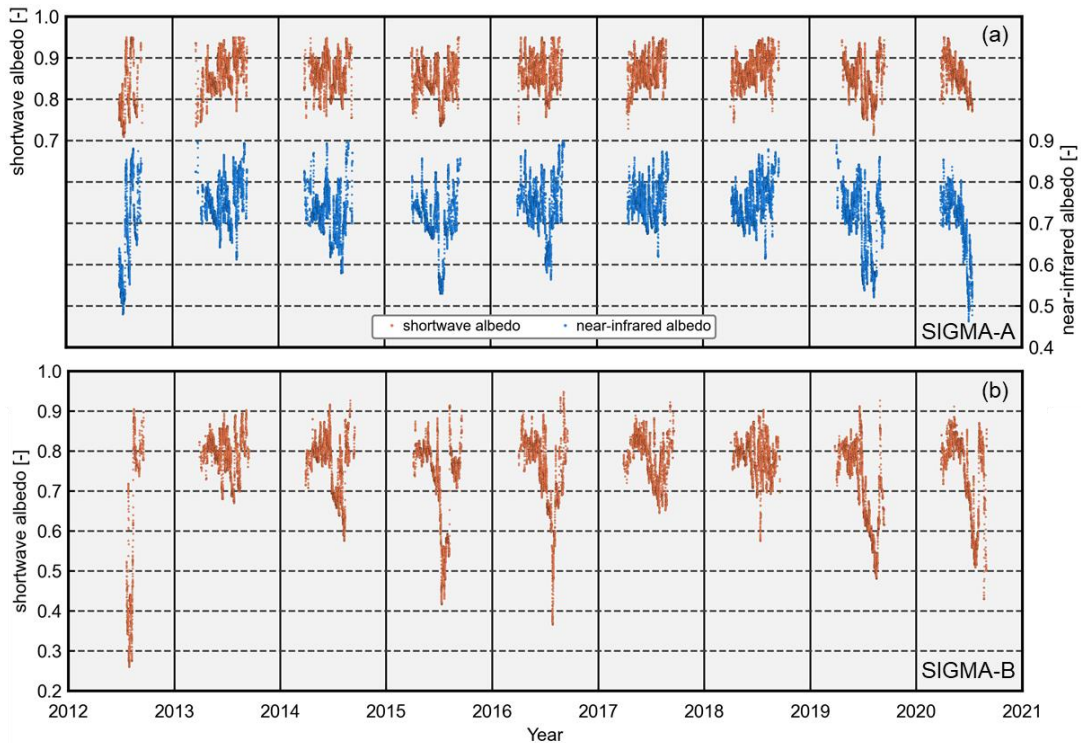

498

499   Figure 8. Time series of hourly shortwave and near-infrared albedos at the (a) SIGMA-A and (b)

500   SIGMA-B sites.

501

5.4. Snow temperature

503   Figure 9 shows the time series of snow temperatures (st_1–st_6) and snow sensor depths (st_depth_{1-}

504     $_6$). The sensor depths were calculated from each sensor's initial depths (see Sect. 3.1) and the surface

505   height variations at the SIGMA-A site. Seasonal and short-term snow temperature fluctuations were

506   observed, which became smaller after the 2016/17 winter season, when snow accumulation was very

507   large (Fig. 4). We assumed that the sensors were buried more deeply at that time, resulting in smaller

508   fluctuations in snow temperature. The annual mean snow temperatures after 2016, a year in which

509   snow temperatures were relatively stable and less variable, were between -18.9 ± 0.5 °C (st_4) and

510   -19.5 ± 1.7 °C (st_5).

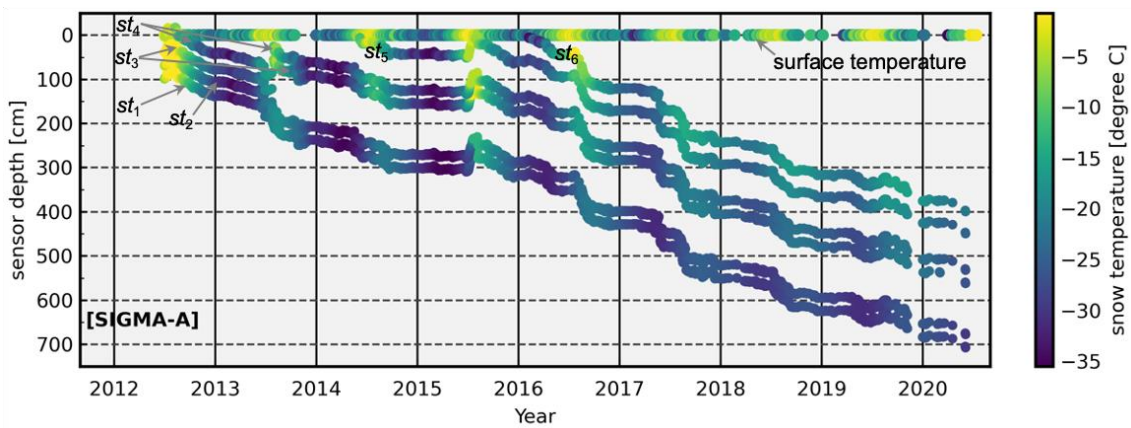
511   Sensors recorded relatively high snow temperatures when they were positioned at shallow depths

512   below the snow surface. However, in the summer of 2015, sensors st_3 and st_4 registered 0 °C even

513   though they were more than 1 m below the snow surface. Air temperatures above freezing, and a large

514   decrease in surface height were observed in this period (Figs. 4 and 5); thus, it is plausible that

515   snowmelt occurred from the surface to depths near 120 cm, where st_3 was located at that time.

516

517

518 Figure 9. Time series of hourly snow temperatures (st_1–st_6), sensor depth, and surface temperature

519 (calculated from upward longwave radiation) at the SIGMA-A site.

520

521 **5.5. Longwave radiation**

522   The ~~occurrence~~ frequency distribution of longwave radiation, taken to represent the atmospheric

523 condition, is often used as an indicator of climatological cloudiness (Stramler et al., 2011). Figure 10

524 shows the histograms of occurrence frequency of downward (LW_d) and net longwave radiation (LW_{net}

525 $= LW_d - LW_u$) during July of all years at the SIGMA-A and SIGMA-B sites. The corresponding

526 histograms for the four seasons (autumn: SON, winter: DJF, spring: MAM, summer: JJA) are shown

527 in Figs. S1 and S2. The July LW_d data from both sites had bimodal distributions, with a lower mode

528 of 220–240 W m^{-2} at SIGMA-A and 240–260 W m^{-2} at SIGMA-B, and a higher mode of 290–310 W

529 m^{-2} at SIGMA-A and 310–330 W m^{-2} at SIGMA-B. The histograms of July and seasonal LW_{net} had

530 similar but clearer bimodal distributions, with modes at approximately 0 W m^{-2} and -70 W m^{-2} (Figs.

531 10c-d and S2).

532   LW_{net} can be regarded as an indicator of cloudiness~~, which can significantly change the downward~~

533 ~~longwave radiation and thus the surface temperature of the snow or ice.~~, because blackbody radiation

534 from the cloud cover increase ~~B~~both downward and net longwave radiation ~~increase under overcast~~

535 ~~conditions because of blackbody radiation from the cloud cover that is absent in clear-sky conditions~~.

536 Stramler et al. (2011) and Morrison et al. (2012) have argued that surface net longwave radiative flux

537 has two modes in occurrence frequency (at -40 W m^{-2} and 0 W m^{-2}), which correspond to clear-sky

538 and overcast (low-level mixed-phase clouds) conditions. In overcast conditions, because the cloud

539 base and the surface are in thermal equilibrium, the vertical thermal gradient is small and the longwave

540 radiation budget is balanced ($LW_{net} = 0$ W m^{-2}) at the surface. The two modes of LW_{net} (0 W m^{-2} and

541 -70 W m^{-2}) at the two AWS sites appear to correspond to the modes proposed by these earlier studies.

542 The occurrence frequency of LW_{net} in JJA appears to be more variable than those for the other

543 seasons at both sites (Fig. S2). In these months, the air temperature rises and sea ice extent decreases,

544 increasing the water vapor supply and advection from the surrounding sea to coastal Greenland (Kim

545 and Kim, 2017; Liang et al., 2022). In such atmospheric conditions, the cloud formation process is

546 susceptible to synoptic-scale disturbances. The histogram of LW_{net} for July (Fig. 10) indicates a higher

547 frequency of clear-sky ($LW_{net} \cong -70$ W m^{-2}) in 2015, 2019, and 2020 and overcast conditions (LW_{net}

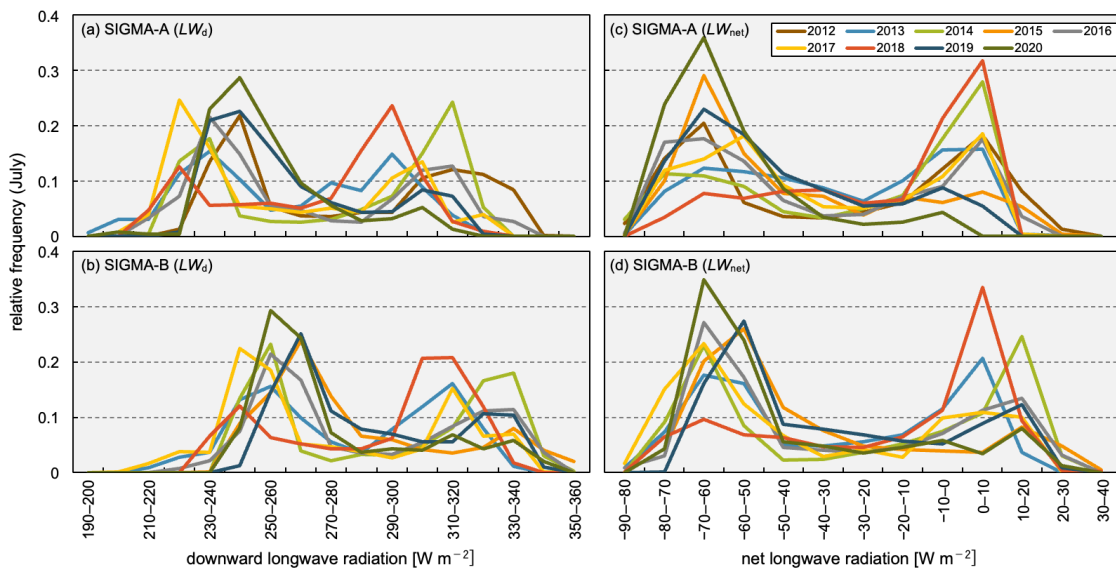
548 $\cong 0$ W m^{-2}) in 2014 and 2018. In SON and MAM, weather condition was less variable, and overcast

549 and clear-sky conditions dominated, respectively.~~In contrast, annual occurrence frequencies for SON~~

550 ~~and MAM were less variable than those for JJA. Overcast and clear-sky conditions dominated in SON~~

551 ~~and MAM, respectively.~~ Our analysis shows that cloudiness in JJA was more variable than in other

552 seasons, a result that is also borne out by satellite observations (Ryan et al., 2022).

553

555 Figure 10. Histograms of the occurrence frequency of hourly downward longwave radiation (LW_d) and

556 net longwave radiation (LW_{net}) observed at the SIGMA-A and SIGMA-B sites in July of all years in

557 the study period. Each relative frequency represents the fraction of the total contained in each 10 W

558 m^{-2} bin.

6. Data availability

The Level 1.1, 1.2, and 1.3 datasets from this study are archived and available from the Arctic Data archive System (ADS) in the National Institute of Polar Research (Table 6), where they are stored in text (CSV) file format. Detailed information on the data content is presented in the file "data_format_*site-name_data-level*.csv" associated with each of these dataset files.

Table 6. Information for the archived datasets from the SIGMA-A and SIGMA-B sites.

SIGMA-A	
Level 1.1	
data name:	Quality-controlled datasets of Automatic Weather Station (AWS) at SIGMA-A site from 2012 to 2020: Level: 1.1
file name:	SIGMA_AWS_SiteA_2012-2020_Lv1_1.csv
citation:	http://doi.org/10.17592/001.2022041301
reference:	Nishimura et al. (2023a)
Level 1.2	
data name:	Quality-controlled datasets of Automatic Weather Station (AWS) at SIGMA-A site from 2012 to 2020: Level: 1.2
file name:	SIGMA_AWS_SiteA_2012-2020_Lv1_2.csv
citation:	http://doi.org/10.17592/001.2022041302
reference:	Nishimura et al. (2023b)
Level 1.3	
data name:	Quality-controlled datasets of Automatic Weather Station (AWS) at SIGMA-A site from 2012 to 2020: Level: 1.3
file name:	SIGMA_AWS_SiteA_2012-2020_Lv1_3.csv
citation:	http://doi.org/10.17592/001.2022041303
reference:	Nishimura et al. (2023c)
SIGMA-B	
Level 1.1	
data name:	Quality-controlled datasets of Automatic Weather Station (AWS) at SIGMA-B site from 2012 to 2020: Level 1.1
file name:	SIGMA_AWS_SiteB_2012-2020_Lv1_1.csv
citation:	http://doi.org/10.17592/001.2022041304
reference:	Nishimura et al. (2023d)
Level 1.2	
data name:	Quality-controlled datasets of Automatic Weather Station (AWS) at SIGMA-B site from 2012 to 2020: Level 1.2
file name:	SIGMA_AWS_SiteB_2012-2020_Lv1_2.csv
citation:	http://doi.org/10.17592/001.2022041305
reference:	Nishimura et al. (2023e)
Level 1.3	
data name:	Quality-controlled datasets of Automatic Weather Station (AWS) at SIGMA-B site from 2012 to 2020: Level 1.3
file name:	SIGMA_AWS_SiteB_2012-2020_Lv1_3.csv
citation:	http://doi.org/10.17592/001.2022041306
reference:	Nishimura et al. (2023f)

7. Summary and conclusion

This paper describes the in situ meteorological datasets from the SIGMA-A and SIGMA-B AWS sites in northwest Greenland and details the QC methods used in preparing the datasets. At this time when drastic environmental change is proceeding in the Arctic region, sound meteorological data and

571 QC methods are of ever-growing importance.

572 The QC method offered here consists of two basic steps. The first step, the initial control, masks
573 observations that are affected by mechanical malfunctions or local phenomena and is a pre-treatment
574 for the second QC step. This step uses simple statistics to set the range of permissible variation in
575 northwest Greenland for each observational parameter and flags erroneous records on the basis of that
576 variation range. The second QC step, the secondary control, masks erroneous observations based on
577 more stringent variation ranges as determined by the median and SD values of the full observation
578 record. The QC procedures offered here may be valuable for scientists developing their own QC efforts.

579 We presented examples of time series of air temperature, surface height, atmospheric pressure,
580 snow temperature, surface albedos, and longwave radiation based on the resulting hourly
581 meteorological dataset for 2012–2020 in northwest Greenland. We also extracted information on
582 climatological cloudiness based on LW_{net} data derived from these in situ ground observations. Our
583 primary findings are summarized in the following four points: (1) ~~in the 2015 summer,~~ high air
584 temperature in the 2015 summer and~~, in addition, 2016, 2019, 2020 summers~~ low surface albedos in
585 2016, 2019, and 2020 summers were recorded at both SIGMA-A and SIGMA-B sites. (2)
586 Apparent~~Dramatic~~ decreases in surface height occurred in 2015 at both AWS sites and in 2016, 2019,
587 and 2020 at the SIGMA-B site. (3) Observed atmospheric~~Weather~~ conditions in JJA were relatively
588 variable in northwest Greenland compared to the other seasons. (4) Frequent ~~C~~clear-sky conditions
589 typified the summers of 2015, 2019, and 2020.

590 The datasets described here are archived in the open access Arctic Data archive System for all
591 scientific communities. We anticipate that they will not only aid in understanding and monitoring the
592 current climate in northwest Greenland but also contribute more broadly to the advancement of polar
593 climate studies.

594

Author contribution

596 All authors, excluding M. Nishimura, established the AWS systems and supported their
597 maintenance. In addition, M. Nishimura developed and carried out the QC procedures and analyzed
598 the observation data, TA designed and led the study project and provided technical support for the QC
599 procedures, M. Niwano conducted pre-treatments for the meteorological data record and constructed
600 a fundamental algorithm of the QC procedures, TY supported the field observations, especially
601 logistical support, and KF provided advice on interpreting the observational data. All authors
602 participated in the interpretation of results and gave final approval for publication.

Competing interests

604 The authors declare that they have no conflict of interest.

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