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Supplement of
Diagnosing the decline in climatic mass balance of glaciers in Svalbard over 1957-2014.
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S1   Meteorological measurements at Svalbard Airport

The 117 year long homogenized air temperature record after Nordli et al. (2014) from Svalbard airport is shown in Figure S1. Over the period all seasons has a positive trend with the largest warming during winter and lowest warming during summer. Summer temperature trend is not easily seen in Figure S1. Since 1976 daily meteorological measurements allow for estimating a common measure of glacier melt, yearly cumulative positive degree days (ΣPDD), which show a markedly increase over the last 40 years (Fig. S2).

S2   Glacier masks

Figure S3 shows the glacier coverage at three epochs, 1930-60s, 1990s, and 2000s, (Nuth et al., 2013). Regional glacier area for the applied temporally evolving glacier mask, which was is derived by interpolation of the Nuth et al. (2013) inventory, is shown in Figure S4. For some locations like Kvitøya, glacier coverage is only available for the last epoch and the glacier area is constant for the entire period. This approach assume linear glacier retreat or advance between the epochs and no changes are assumed after the 2000s epoch. Representation of glacier tongue retreats are somewhat unrealistic, since they disintegrate rather than displaying a frontal retreat.
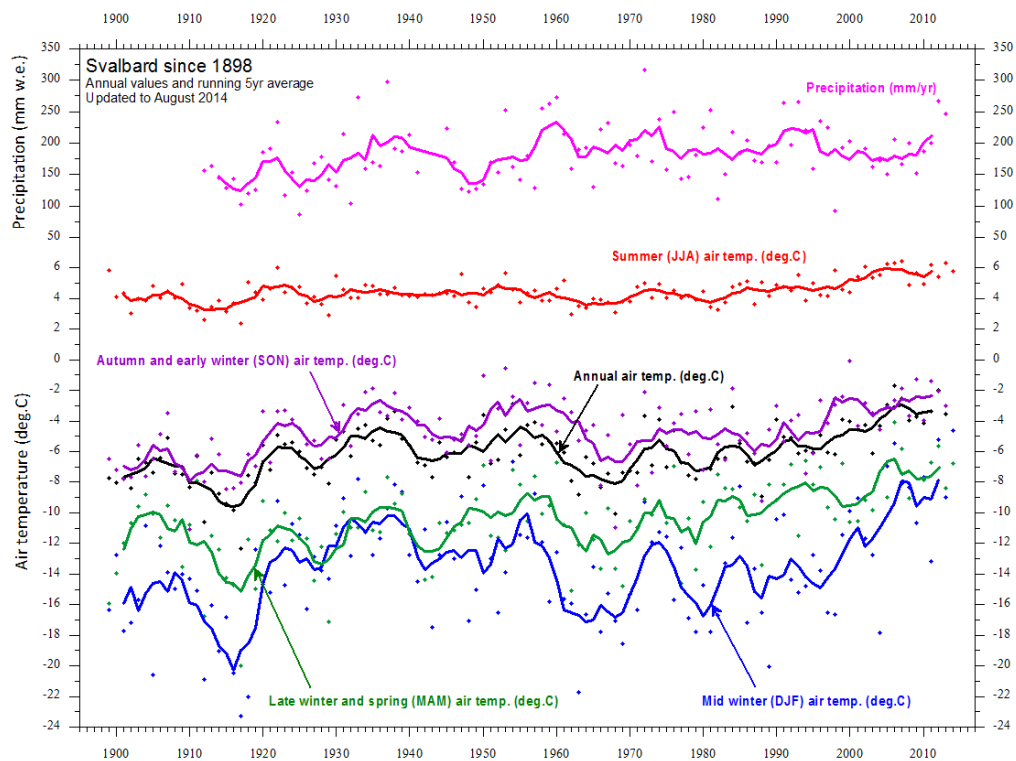
Figure S1. Air temperatures and precipitation at Svalbard Airport 1898-2014 from climate4you.com with data from eklima.no

S3   MODIS

Figure S5 shows MODIS-derived average over 2003-13 for: minimum summer (lower 5th percent) albedo and mean annual clear-sky skin surface temperatures.

S4   Calibration

20   Table S1 list relevant parameters employed in the model and how the respective values are determined. Only four parameters were determined during the calibration. Expert judgment are values based on one or more of the following: 1) from a pre-calibration step with many more than the 4 parameters, to aid the parameter choice in the next calibration exercise; 2) from fitting to observations, where direct comparison where possible; 3) from a mixture of values found in the literature.

25   ## S5   Regional Refreezing and Thermal regime

Figure S6 and S7 shows yearly amount of refreezing and 15 m temperatures with altitude resolved regionally. All regions show nearly the same response regarding thermal regime for the period 1957-
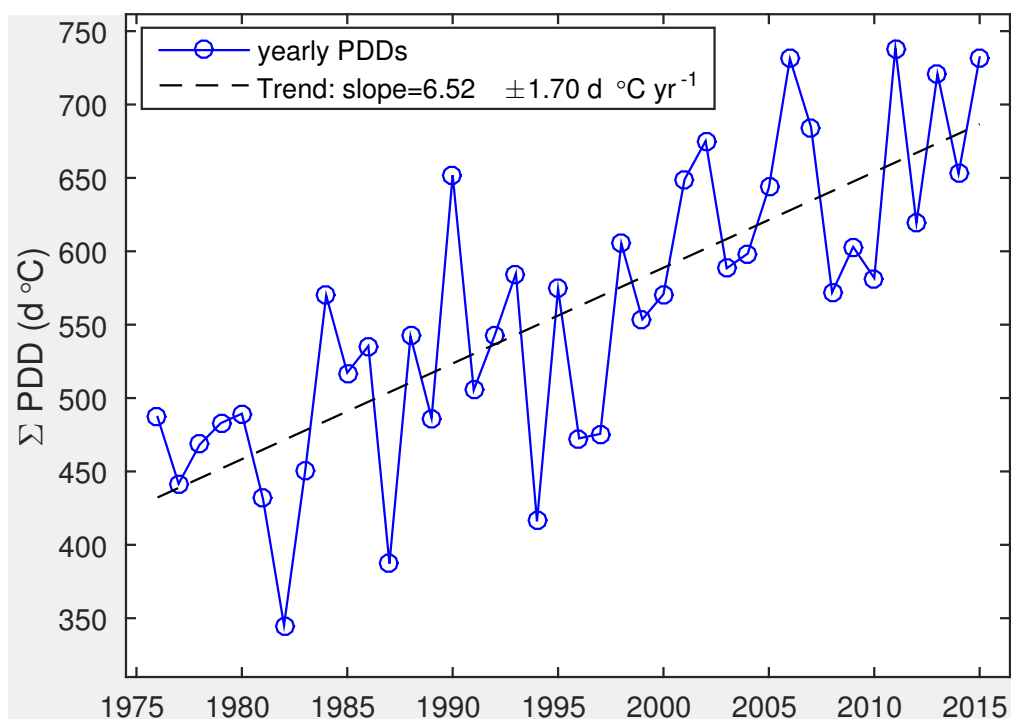
Figure S2. Accumulated positive degree days from Svalbard airport 1976-2015. Data from eklima.no

2014, thus occurring at different elevation. The main features are: 1) warming of the cold ice in the ablation area; 2) cooling of the the area around ELA, which climb increase as firn area shrinks with

30   the increasingly negative B_{clim}; 3) warming of the cold firn area which existed until 1975, when nearly all firn became temperate.
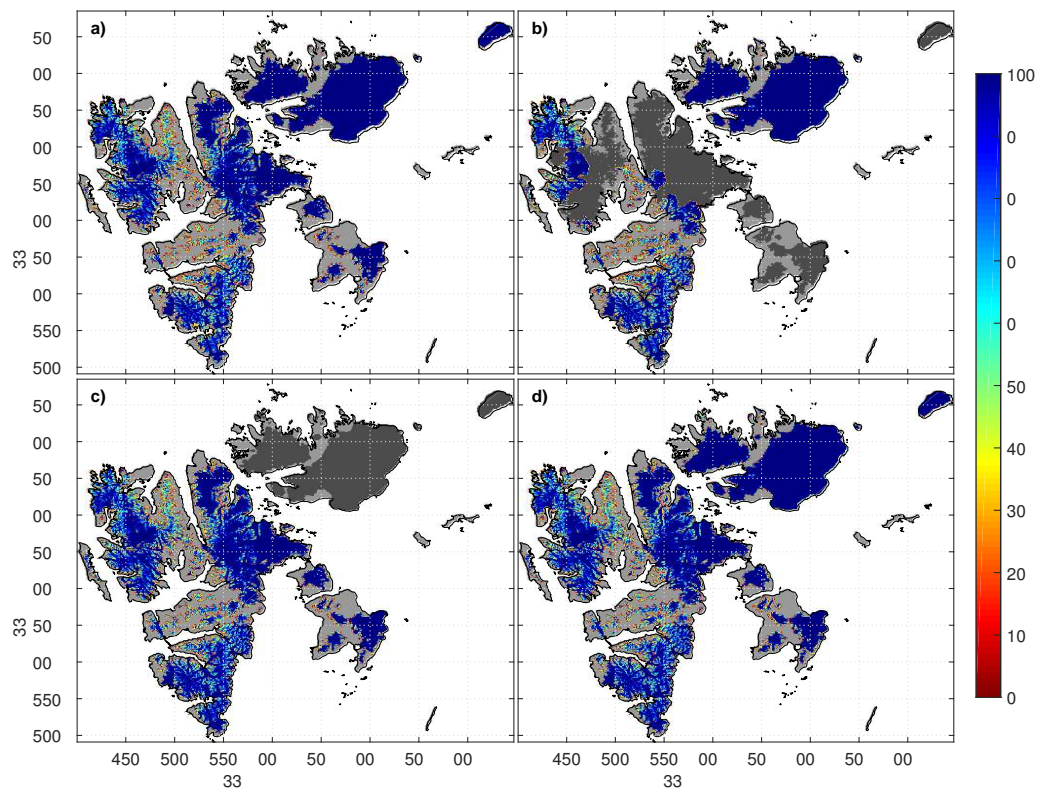
Figure S3. Fractional glacier cover (%) on 1000m DEM: a) 2000s, b) 1990s, c) 1930s/60s and d) reference mask
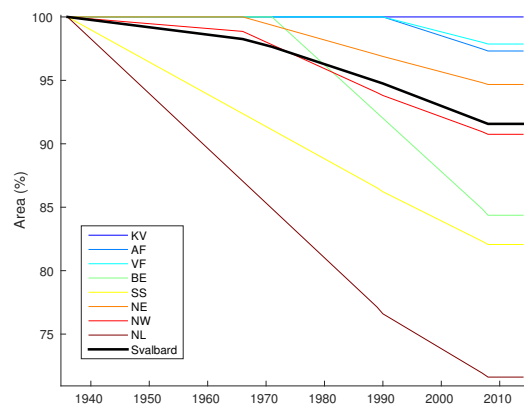
Figure S4. Glacier area evolution for Svalbard and it's regions in percent from the first data acquisition in 1936 and onwards constructed from the multi-temporal glacier inventory (Nuth et al., 2013).
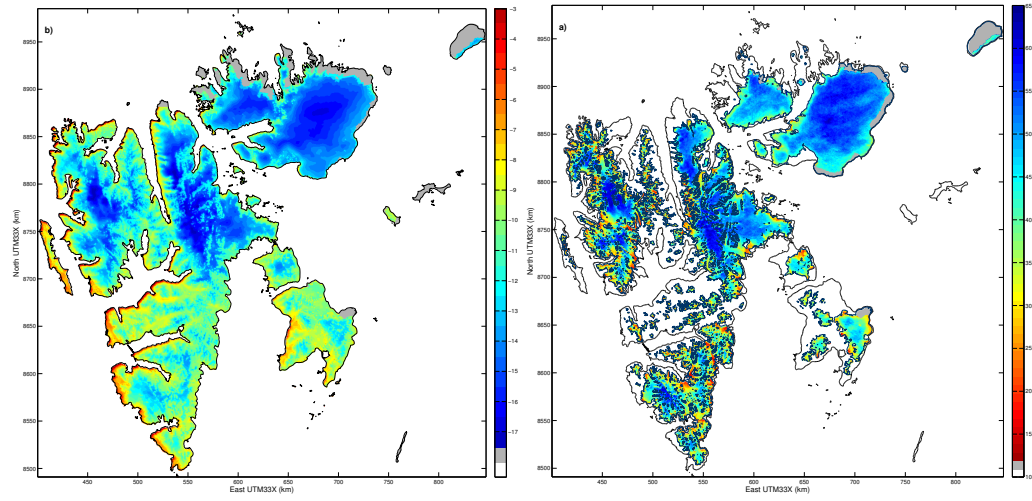
Figure S5. a) Mean annual clear-sky skin surface temperatures from MODIS over 2003-2013. b) Minimum (lower 5th percentile) summer albedo averaged over 2003-2013 derived from MODIS. Missing data (in gray) are caused by erroneous landmask in MODIS.
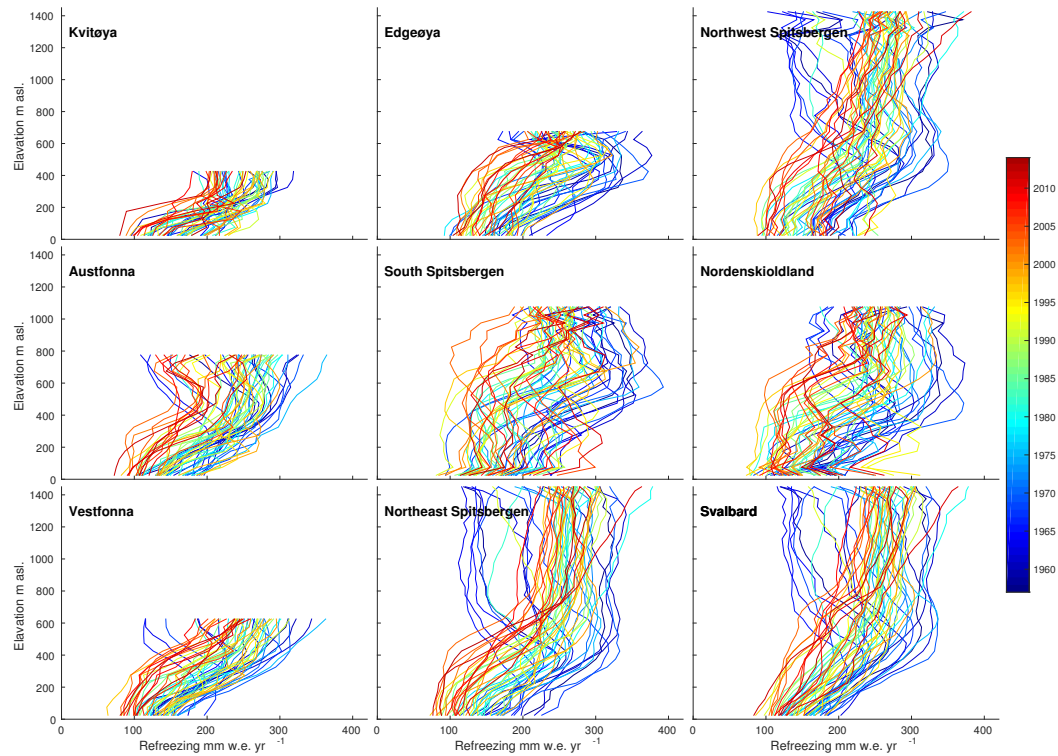
Figure S6. Refreezing averaged over 50 m altitude intervals for Svalbard and for 8 regions, for each year from 1957 (blue) to 2014 (red).

Table S1. Overview on parameters and parameterization employed in the model and their origin.

Process	Parameter	Symbol	Value	Source
Turbulent fluxes	Roughness lengths of momentum	zo_{ice} (mm)	0.18	Calibration
		zo_{snow} (mm)	0.06	Calibration
	Roughness length heat/moist	$zo_{T/q}$ (mm)	see	Andreas (1987)
Albedo	Ice	α_{ice} (–)	0.30	Calibration
	Firn/ min snow	α_{firn} (–)	0.62	Calibration
	New snow	α_{snow} (–)	0.85	Expert judgment
	Slush	α_{slush} (–)	0.55	Expert judgment
	Superimposed ice	α_{SI} (–)	0.67	Expert judgment
	Water	α_{water} (–)	0.15	Zuo and Oerlemans (1996)
	Slush	α_{slush} (–)	xx	Expert judgment
	Aging wet snow	t^*_{wet} (d)	5	Expert judgment
	Aging dry snow 0°C	$t^*_{dry(0°C)}$ (d)	15	Expert judgment
	Aging cold snow -10°C	$t^*_{dry(-10°C)}$ (d)	100	Expert judgment
	Depth scale snow	d^* (cm)	3	Oerlemans and Knap (1998)
	Depth scale water	w^* (cm)	30	Bougamont and Bamber (2005)
Long wave radiation	Emissivity	ϵ (–)	0.99	Snyder et al. (1998)
Heat conductivity	Ice conductivity	a (W m^{-1} K^{-1})	2.3	Expert judgment
(Douville et al., 1995)	Exponent	b (–)	2.35	Expert judgment
Runoff	timescales	τ_{steep}, $\tau_{1°}$, $\tau_{0°}$, Factor	see	Reijmer and Hock (2008)
Precipitation	Rain/snow threshold	$T_{rain/snow}$ (°C)	1.5	Expert judgment
Fresh snow density	Density	ρ_{fsn} (kg m^{-3})	300	Expert Judgment
Densification				Herron and Langway (1980)
Irreducible water content				Schneider and Jansson (2004)

References

Andreas, E.: A theory for the scalar roughness and the scalar transfer coefficients over snow and sea ice, Boundary-Layer Meteorology, 38, 159–184, 1987.

35 Bougamont, M. and Bamber, J.: A surface mass balance model for the Greenland ice sheet, Journal of Geophysical Research-Earth Surface, 110, f04018, doi:10.1029/2005JF000348, 2005.

Douville, H., Royer, J.-F., and Mahfouf, J.-F.: A new snow parameterization for the Meteo-France climate model. Part I: Validation in stand alone experiment., Climate Dynamics, 12, 21–35, 1995.

Herron, M. and Langway, J. C.: Firn densification: an empirical model, Journal of Glaciology, 25, 373–385,

40   1980.

Nordli, O., Przybylak, R., Ogilvie, A. E. J., and Isaksen, K.: Long-term temperature trends and variability on Spitsbergen: the extended Svalbard Airport temperature series, 1898-2012, Polar Research, 33, doi:10.3402/polar.v33.21349, 2014.
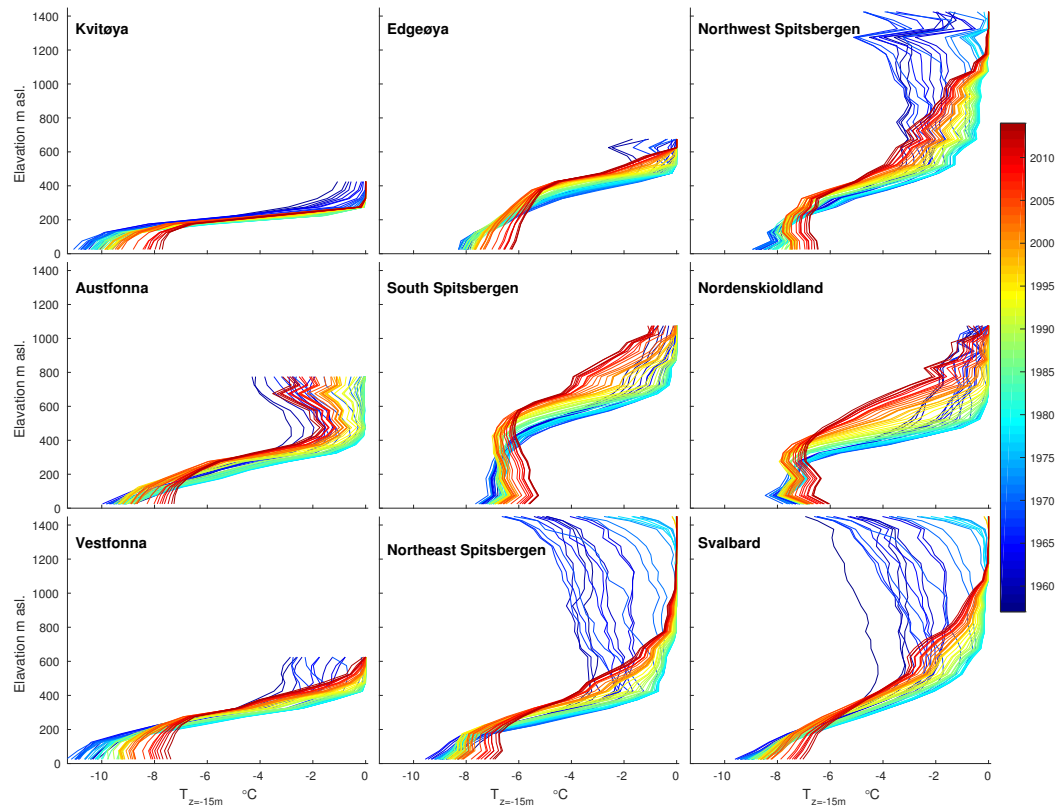
Figure S7. Subsurface temperatures at 15 m depth averaged over 50 m altitude intervals for Svalbard and for 8 regions, for each year from 1957 (blue) to 2014 (red).

Nuth, C., Kohler, J., König, M., von Deschwanden, A., Hagen, J. O., Kääb, A., Moholdt, G., and Pettersson, R.: Decadal changes from a multi-temporal glacier inventory of Svalbard, The Cryosphere, 7, 1603–1621, doi:10.5194/tc-7-1603-2013, http://www.the-cryosphere.net/7/1603/2013/, 2013.

Oerlemans, J. and Knap, W.: A 1 year record of global radiation and albedo in the ablation zone of Morteratschgletscher, Switzerland, Journal Of Glaciology, 44, 231–238, 1998.

Reijmer, C. H. and Hock, R.: Internal accumulation on Storglacidren, Sweden, in a multi-layer snow model coupled to a distributed energy- and mass-balance model, Journal of Glaciology, 54, 61–72, 2008.

Schneider, T. and Jansson, P.: Internal accumulation in firn and its significance for the mass balance of Storglaciaren, Sweden, Journal of Glaciology, 50, 25–34, 2004.

Snyder, W., Wan, Z., Zhang, Y., and Feng, Y.: Classification-based emissivity for land surface temperature measurement from space, International Journal of Remote Sensing, 19, 2753–2774, doi:10.1080/014311698214497, 1998.

Zuo, Z. and Oerlemans, J.: Modelling albedo and specific balance of the Greenland ice sheet: Calculations for the Sondre Stromfjord transect, Journal of Glaciology, 42, 305–317, 1996.