Supplement of The Cryosphere, 17, 1675–1696, 2023
https://doi.org/10.5194/tc-17-1675-2023-supplement

The Cryosphere
Open Access

Supplement of

Characteristics of the 1979–2020 Antarctic firn layer simulated with IMAU-FDM v1.2A

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Introduction

Details of the in situ measurements, sensitivity analysis and atmospheric forcing are included here. Table S1 lists all in situ measurements that have been used, the corresponding coordinates, method and citation. Figure S1 shows a map with the locations used for the sensitivity analysis and a comparison of histograms of the temperature and accumulation distribution for the locations used in the sensitivity analysis and for the entire ice sheet. Figure S2 shows the spatial variable uncertainty in surface temperature and precipitation. Figure S3 shows the empirical relations between the sensitivity analysis uncertainties results and various climatic variables including accumulation, temperature and melt, for the 106 sample locations. These empirical relations are used to extrapolate the sensitivity of the sample locations to the entire ice sheet. Figures S4, S5 and S6 show maps of these ice-sheet-wide sensitivities in average FAC, surface elevation change and FAC change, respectively. Figure S7 shows time series of surface elevation and FAC uncertainties. Figure S8 shows maps of the comparison of the spin-up T_s, b experiment and the remote sensing altimetry dataset of Schröder et al. (2019) over the Antarctic Peninsula and Ellsworth Land. Figure S9 shows maps of mean annual accumulation, surface melt and sublimation.

Table S1 Location, citation and characteristics of in situ measurements.

Name	Method	Lon	Lat	Citation	Date	z_{550}	z_{830}	SSN	FAC
Up BC	core	-136.66	-82.89	Alley and Bentley, 1988	01/01/1986	yes	yes	yes	no
Upstream B	core	-138.1	-83.48	Alley and Bentley, 1988	01/01/1985	yes	yes	yes	no
D47	core	138.72	-67.38	Arnaud et al. 1998		yes	yes	yes	yes
DE08	core	113.19	-66.72	Arnaud et al. 1998		yes	yes	yes	yes
Km200	core	94.08	-68.25	Arnaud et al. 1998	01/01/1996	yes	yes	yes	yes
Dome C	core	123.35	-75.1	Barnes et al. 2002	01/01/1999	yes	yes	yes	no
Vostok	core	106.87	-78.45	Barnola et al. 1991	01/01/1996	yes	yes	yes	no
Siple Dome	core	-148.78	-81.65	Breant et al. 2017	01/01/1996	yes	yes	yes	yes
South pole	core	0	-90	Breant et al. 2017		yes	yes	yes	yes
Talos Dome	core	159.18	-72.82	Breant et al. 2017		yes	yes	yes	yes
G1 Amery	core	71.73	-69.48	Budd et al. 1982	01/01/1968	yes	yes	yes	no
LGB 46	core	71.5	-75.85	Craven and Allison, 1998		yes	no	no	no
LGB 35	core	65.02	-76.05	Craven and Allison, 1998		yes	yes	yes	no
LGB 20	core	55.67	-73.83	Craven and Allison, 1998		yes	no	yes	no
MGA	core	60.27	-68.65	Craven and Allison, 1998		yes	no	yes	no
Dome C	core	123.35	-75.1	Cunde et al. 2008		yes	yes	yes	yes
Dome A	core	77.373	-80.367	Cunde et al. 2008	01/01/2005	yes	yes	yes	yes
SUMup-510	core	-161.567	-79.572	Dibb, 2017	01/01/1997	yes	no	no	no
SUMup-508	core	-160.323	-79.354	Dibb, 2017	01/01/1997	yes	no	no	no
SUMup-509	core	-161.065	-79.486	Dibb, 2017	01/01/1997	yes	no	no	no
B38	core	-6.7	-71.16	Fernandoy et al. 2017	15/01/2017	yes	no	no	no
B39	core	-9.9	-71.41	Fernandoy et al. 2017	15/01/2007	yes	no	no	no
FB0702	core	-6.67	-71.57	Fernandoy et al. 2017	15/01/2007	yes	no	no	no
FB0704	core	-9.56	-72.06	Fernandoy et al. 2017	15/01/2007	yes	no	no	no
WAIS divide	core	-112.083	-79.467	Fitzpatrick et al. 2014	01/02/2012	yes	yes	yes	yes
Lock-In	core	126.159	-74.134	Fourteau et al. 2019	15/01/2016	yes	yes	no	no
B32	core	0	-75	Freitag et al. 2003	01/01/1997	yes	yes	yes	yes
USITASE_99_1	core	-122.63	-80.62	Gow et al. 2004	01/01/1999	yes	yes	no	no
USITASE_01_2	core	-102.91	-77.84	Gow et al. 2004	01/01/2001	yes	yes	yes	no
USITASE_01_5	core	-89.14	-77.06	Gow et al. 2004	01/01/2001	yes	yes	yes	yes
D57	core	137.52	-68.18	Gow, 1968		no	no	yes	no
Little America	core	-162.22	-78.17	Gow, 1968		yes	yes	yes	no
Old Byrd	core	-120.02	-79.98	Gow, 1968		yes	yes	yes	no
SUMup-664	core	-55.936	-77.935	Graf and Oerter, 2006	28/01/1992	yes	yes	no	no
SUMup-669	core	-55.432	-78.606	Graf et al. 1988	01/02/1980	yes	yes	no	yes
SUMup-677	core	-59.635	-84.818	Graf et al. 1999	16/02/1995	yes	no	yes	no
Mizuho	core	44.37	-70.7	Kameda et al. 1994		yes	yes	yes	no
EDML	core	0.07	-75	Kipfstuhl et al. 2009	01/01/2006	yes	yes	yes	yes
SUMup-1654	core	162.5	-77.583	Mayewski et al. 1998	01/01/1998	yes	yes	yes	yes
SUMup-85	core	-95.962	-77.957	Medley et al. 2013	22/12/2010	yes	no	yes	no
SUMup-86	core	-121.22	-76.952	Medley et al. 2013	14/01/2011	yes	no	yes	no
SUMup-87	core	-101.738	-76.770	Medley et al. 2013	31/12/2010	yes	yes	no	yes
SUMup-86	core	-76.952	-121.22	Medley et al. 2013	01/01/2000	no	no	yes	no
SUMup-85	core	-77.957	-95.962	Medley et al. 2013	22/12/2010	no	no	yes	no
SUMup-1655	core	-71.714	-70.804	Montgomery et al. 2018	08/12/2018	yes	yes	no	yes
SUMup-766	NDP[a]	-75.804	-100.28	Morris et al. 2017	08/01/2014	no	no	yes	no

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SUMup-762	NDP[a]	-75.617	-99.073	Morris et al. 2017	31/12/2013	no	no	yes	no
SUMup-764	NDP[a]	-76.404	-99.828	Morris et al. 2017	04/01/2014	no	no	yes	no
SUMup-753	NDP[a]	-74.956	-94.630	Morris et al. 2017	14/12/2013	no	no	yes	no
SUMup-85	NDP[a]	-74.442	-93.445	Morris et al. 2017	04/12/2013	no	no	yes	no
SUMup-747	NDP[a]	-75.670	-94.69	Morris et al. 2017	20/12/2013	no	no	yes	no
SUMup-747	NDP[a]	-74.111	-89.224	Morris et al. 2017	28/11/2013	no	no	yes	no
SUMup-746	NDP[a]	-74.565	-86.913	Morris et al. 2017	24/11/2013	no	no	yes	no
Mizuho	core	44.33	-70.7	Narita and Maeno, 1978		yes	yes	yes	yes
H72	core	41.09	-69.2	Nishio et al. 2002	15/09/1998	yes	yes	yes	no
BAS depot	core	-10.5	-77.03	Nishimura and Maeno, 1985		no	no	no	no
V142	core	51.95	-72.53	Nishimura and Maeno, 1985		yes	no	yes	no
U234	core	47.48	-71.02	Nishimura and Maeno, 1985		yes	no	yes	no
W200	core	48.83	-69.58	Nishimura and Maeno, 1985		yes	no	yes	no
S18	core	40.12	-69.03	Nishimura and Maeno, 1985		yes	no	no	no
SUMup-683	core	-3.43	-75.581	Oerter et al. 2004	20/12/1997	yes	yes	no	yes
SUMup-628	core	0.069	-75.001	Oerter, 2002	28/01/2001	yes	yes	no	no
Concordia	core	123	-73.5	Olmi et al. 2019	15/12/2018	yes	no	no	yes
Dyer Plateau	core	-64.88	-70.67	Raymond et al. 1996	01/01/1990	yes	yes	yes	no
Km105	core	93.383	-67.433	Salamantin et al. 2009		yes	yes	yes	yes
Mount Johns	core	-94.383	-79.916	Schwank et al. 2016	01/01/2009	yes	yes	yes	yes
Maudheim	core	-10.93	-71.05	Schytt, 1958		yes	yes	yes	no
Siple Dome	core	-148.77	-81.66	Severinghaus and Battle, 2006		yes	yes	yes	no
South pole	core	0	-90	Severinghaus and Battle, 2006		yes	yes	yes	yes
Vostok	core	106.87	-78.45	Spencer et al. 2001		yes	yes	no	yes
SUMup-79	core	-102.910	-77.844	US ITASE, 2013	01/01/2001	yes	no	no	no
SUMup-96	core	-104.97	-79.16	US ITASE, 2013		yes	yes	no	no
SUMup-69	core	-104.967	-79.160	US ITASE, 2013	01/01/2001	yes	no	no	no
SUMup-75	core	-95.646	-78.120	US ITASE, 2013	01/01/2001	yes	no	no	no
SUMup-82	core	-92.25	-77.61	US ITASE, 2013		yes	yes	no	no
SUMup-83	core	-89.138	-77.060	US ITASE, 2013	01/01/2001	yes	yes	no	no
SUMup-53	core	178.531	-88.509	US ITASE, 2013	01/01/2007	yes	no	no	yes
SUMup-54	core	-107.983	-88.002	US ITASE, 2013	01/01/2002	yes	no	no	no
SUMup-55	core	95.310	-86.840	US ITASE, 2013	01/01/2003	yes	no	no	no
SUMup-56	core	-107.990	-86.503	US ITASE, 2013	01/01/2002	yes	no	no	no
SUMup-57	core	145.719	-85.782	US ITASE, 2013	01/01/2007	yes	no	no	no
SUMup-58	core	-104.995	-85.000	US ITASE, 2013	01/01/2002	yes	no	no	no
SUMup-59	core	140.631	-84.395	US ITASE, 2013	01/01/2007	yes	no	no	no
SUMup-60	core	-104.987	-83.501	US ITASE, 2013	01/01/2002	yes	no	no	no
SUMup-62	core	-110.008	-82.001	US ITASE, 2013	01/01/2002	yes	no	no	no
SUMup-63	core	136.084	-81.658	US ITASE, 2013	01/01/2007	yes	no	no	no
SUMup-65	core	-126.17	-81.200	US ITASE, 2013	01/01/1999	yes	yes	no	yes
SUMup-66	core	-122.63	-80.620	US ITASE, 2013	01/01/1999	yes	no	no	no
SUMup-68	core	-111.239	-79.383	US ITASE, 2013	01/01/2000	yes	yes	no	yes
SUMup-70	core	-122.267	-79.133	US ITASE, 2013	01/01/2000	yes	yes	no	yes
SUMup-71	core	149.680	-79.036	US ITASE, 2013	01/01/2006	yes	no	no	no
SUMup-72	core	-111.497	-78.733	US ITASE, 2013	01/01/2000	yes	no	no	no
SUMup-73	core	-115.917	-78.433	US ITASE, 2013	01/01/2000	yes	no	no	no
SUMup-74	core	-124.484	-78.332	US ITASE, 2013	01/01/2000	yes	no	no	yes
SUMup-76	core	-120.076	-78.083	US ITASE, 2013	01/01/2000	yes	no	no	no
SUMup-80	core	153.381	-77.762	US ITASE, 2013	01/01/2006	yes	yes	no	yes
SUMup-81	core	-123.995	-77.683	US ITASE, 2013	01/01/2000	yes	no	no	no
SUMup-82	core	-92.248	-77.612	US ITASE, 2013	01/01/2001	yes	no	no	no
SUMup-84	core	-89.018	-76.097	US ITASE, 2013	01/01/2001	yes	no	no	no
D9_10	core	139.8	-66.7	Van den Broeke, 2008		yes	no	yes	no
D41	core	139.37	-66.97	Van den Broeke, 2008		yes	no	yes	no
D45	core	138.88	-67.28	Van den Broeke, 2008		yes	no	yes	no
D50	core	138.33	-67.62	Van den Broeke, 2008		yes	no	yes	no
D59	core	137.32	-68.35	Van den Broeke, 2008		yes	no	yes	no
D72	core	135.8	-69.33	Van den Broeke, 2008		yes	no	yes	no
D80	core	134.72	-70.02	Van den Broeke, 2008		yes	no	yes	no
D100	core	133.98	-71.57	Van den Broeke, 2008		yes	no	yes	no
Law Dome	core	112.94	-66.73	Van den Broeke, 2008		no	no	no	no
DSS	core	112.8	-66.77	Van den Broeke, 2008		yes	yes	yes	no

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Berkner S(B24)	core	-45.72	-79.61	Van den Broeke, 2008		yes	yes	yes	no
Berkner N	core	-46.27	-78.31	Van den Broeke, 2008		yes	no	yes	no
Dome Fuji	core	39.67	-77.32	Van den Broeke, 2008		yes	yes	yes	no
Kohnen	core	0.07	-75	Van den Broeke, 2008		yes	yes	yes	no
Asuka	core	24.13	-71.52	Van den Broeke, 2008		yes	yes	yes	no
G6	core	39.76	-73.11	Watanabe, 1999		yes	yes	yes	no
G15	core	45.98	-71.2	Watanabe, 1999		yes	no	yes	no
G2	core	39.86	-71.04	Watanabe, 1999	01/12/1995	yes	yes	yes	no
H15	core	40.78	-69.08	Watanabe, 1999		yes	yes	yes	no
S25	core	40.46	-69.03	Watanabe, 1999		yes	yes	yes	no
summup-1532	core	-9.917	-71.408	Wilhelsm, 2007	26/01/2007	yes	yes	no	yes
RICE-12-13-B	core	-161.7	-79.362	Winstrup et al. 2019	15/01/2013	yes	yes	yes	yes
RID-75	core	-161.667	-79.366	Winstrup et al. 2019	01/01/1975	yes	no	no	no

[a]neutron density probe.

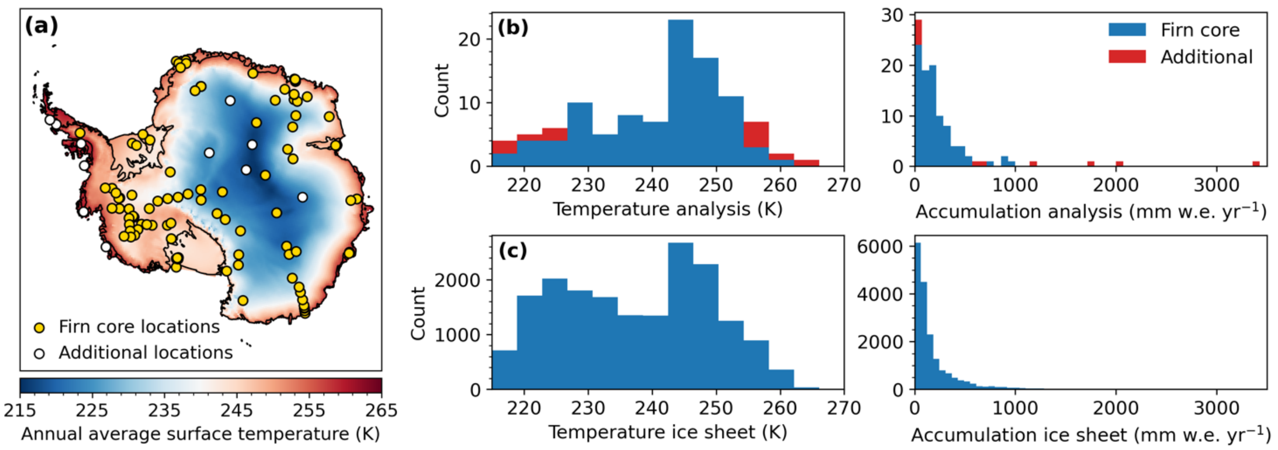

Figure S1. (a) Map of the locations used in the sensitivity analysis, including 95 firn core locations and 11 additional locations. Histograms of the temperature and accumulation distribution for **(b)** the sensitivity analysis locations, and **(c)** for the entire ice sheet.

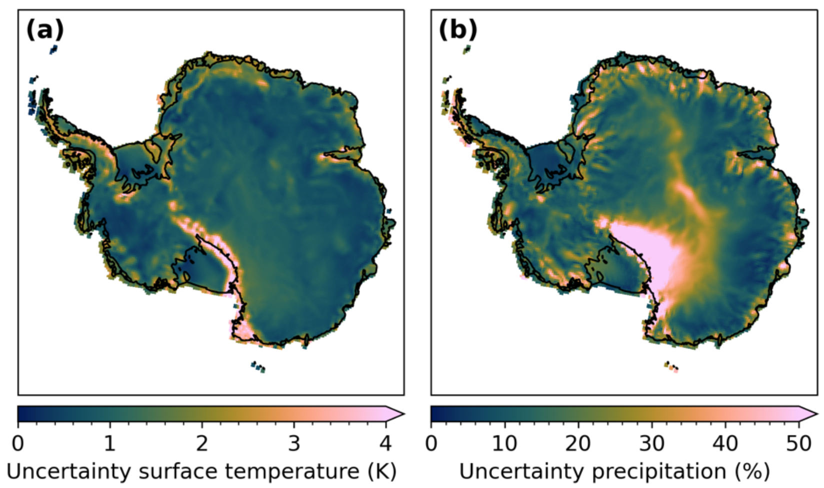

Figure S2. Prescribed uncertainty in **(a)** surface temperature and **(b)** precipitation based on the standard deviation among regional climate models and reanalysis products obtained from Carter et al. (2022).

Figure S3. Empirical relations used to expand the uncertainty analysis over the full ice sheet.

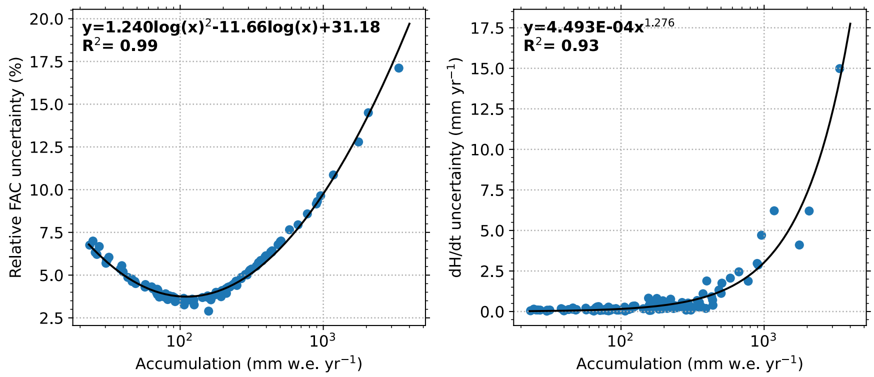

Figure S3a. Empirical relations of the MO fit experiments for relative firn air content (FAC) and surface elevation change (dH/dt) uncertainties against annual average accumulation.

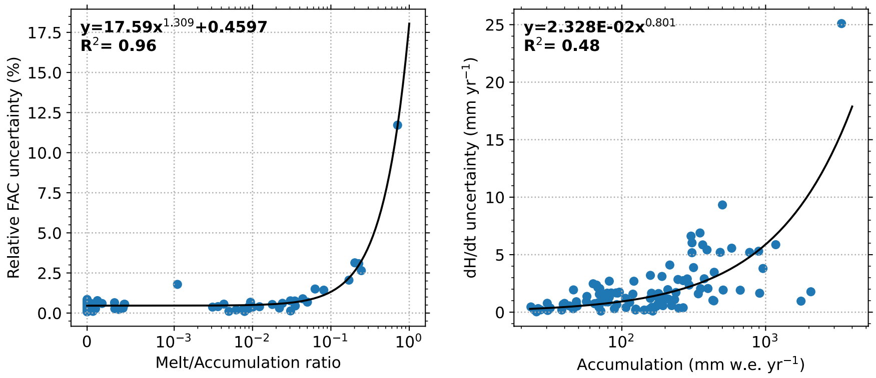

Figure S3b. Empirical relations of the fresh snow density experiments for relative firn air content (FAC) and surface elevation change (dH/dt) uncertainties against melt/accumulation rate and annual average accumulation.

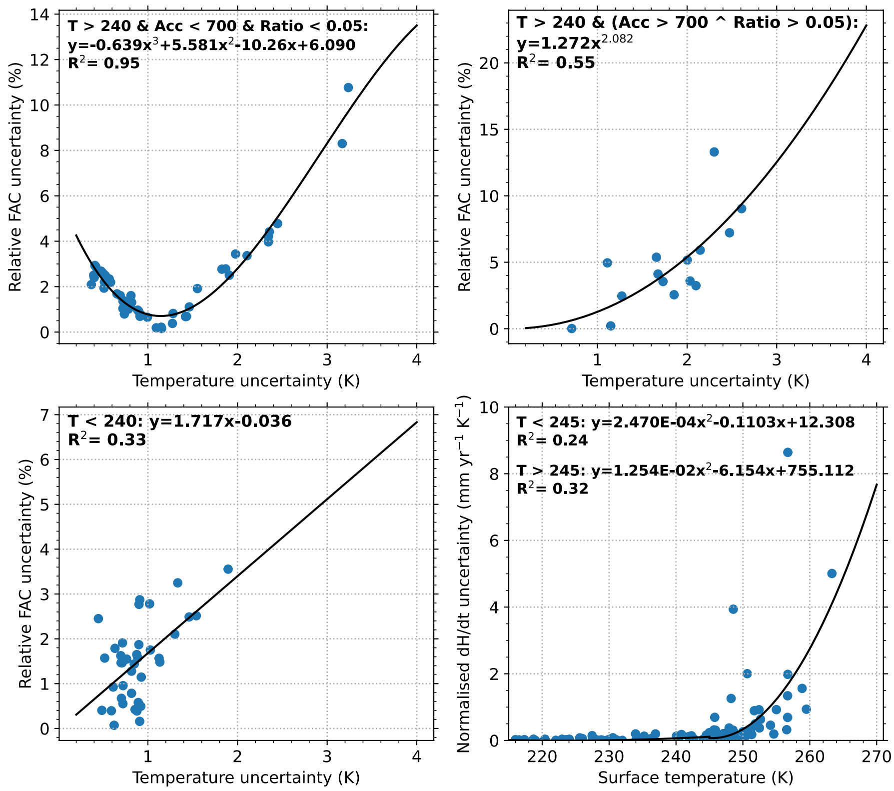

Fig. S3c. Empirical relations of the temperature forcing experiments for relative firn air content (FAC) and normalized surface elevation change (dH/dt) uncertainties against the prescribed temperature uncertainty and annual average surface temperature. The data is grouped based on annual average temperature (T), accumulation (Acc) and melt/accumulation ratio (Ratio).

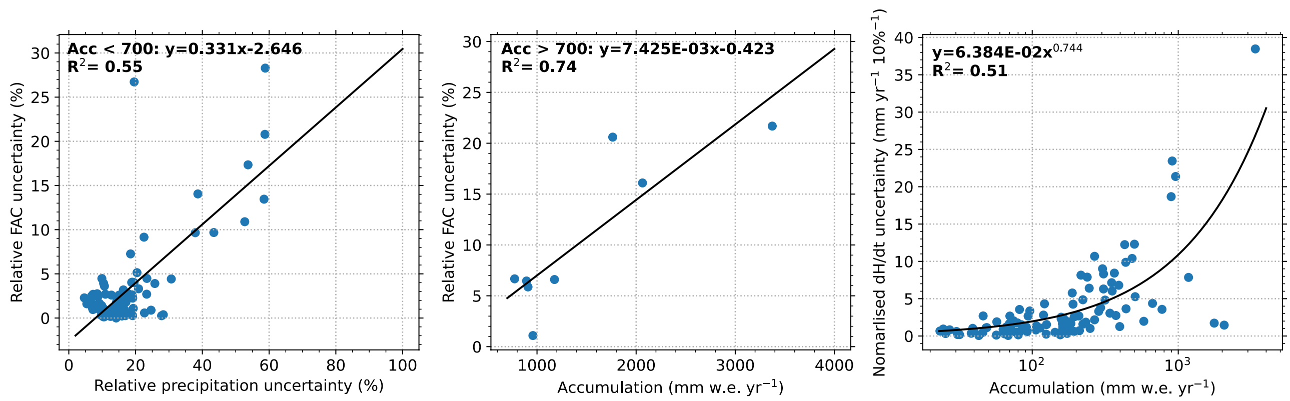

Figure S3d. Empirical relations of the precipitation forcing experiments for relative firn air content (FAC) and normalized surface elevation change (dH/dt) uncertainties against the prescribed precipitation uncertainty and annual average accumulation. For the relative FAC empirical relations the data is grouped based on annual average accumulation (Acc).

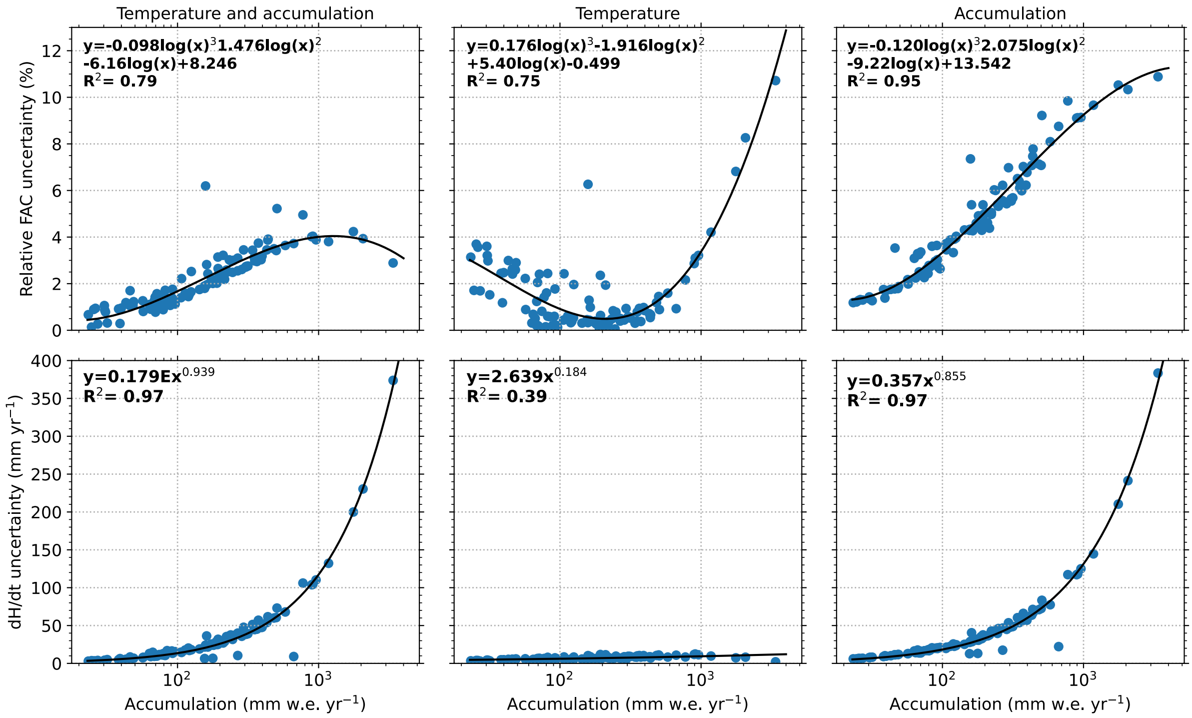

Figure S3e. Empirical relations of the spin-up forcing experiments for the Antarctic Peninsula and Ellsworth Land, including the combined temperature and accumulation, the temperature and accumulation experiments, for relative firn air content (FAC) and surface elevation change (dH/dt) uncertainties against annual average accumulation. The boundary of the Antarctic Peninsula and Ellsworth Land regions are selected based on the patterns found by Thomas et al. (2017) and Medley and Thomas (2019).

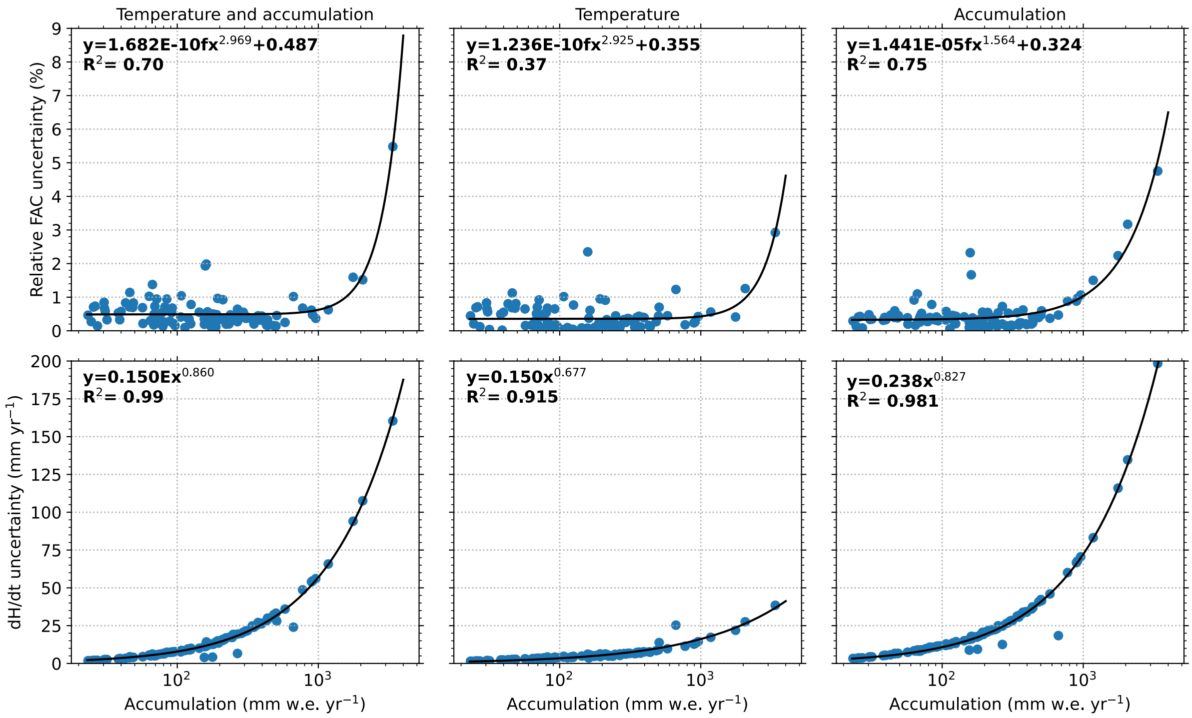

Figure S3f. Empirical relations of the spin-up forcing experiments for the remainder of the AIS (apart from the Antarctic Peninsula and Ellsworth Land), including the combined temperature and accumulation, the temperature and accumulation experiments, for relative firn air content (FAC) and surface elevation change (dH/dt) uncertainties against annual average accumulation.

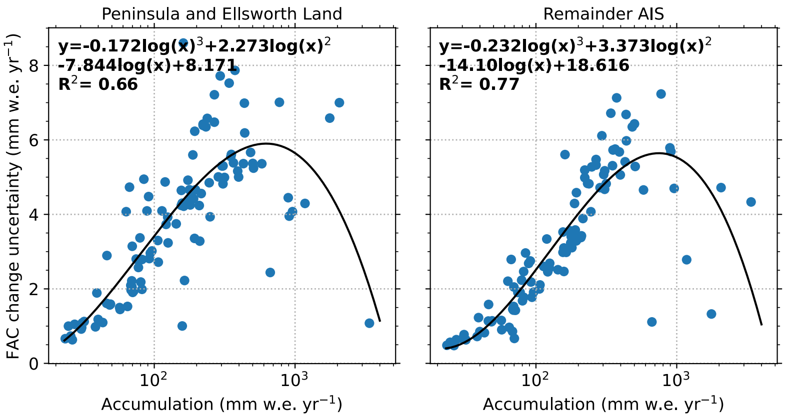

Fig. S3g. Empirical relations of the combined temperature and accumulation spin-up forcing experiments for the Antarctic Peninsula and Ellsworth Land for firn air content (FAC) change uncertainties against annual average accumulation.

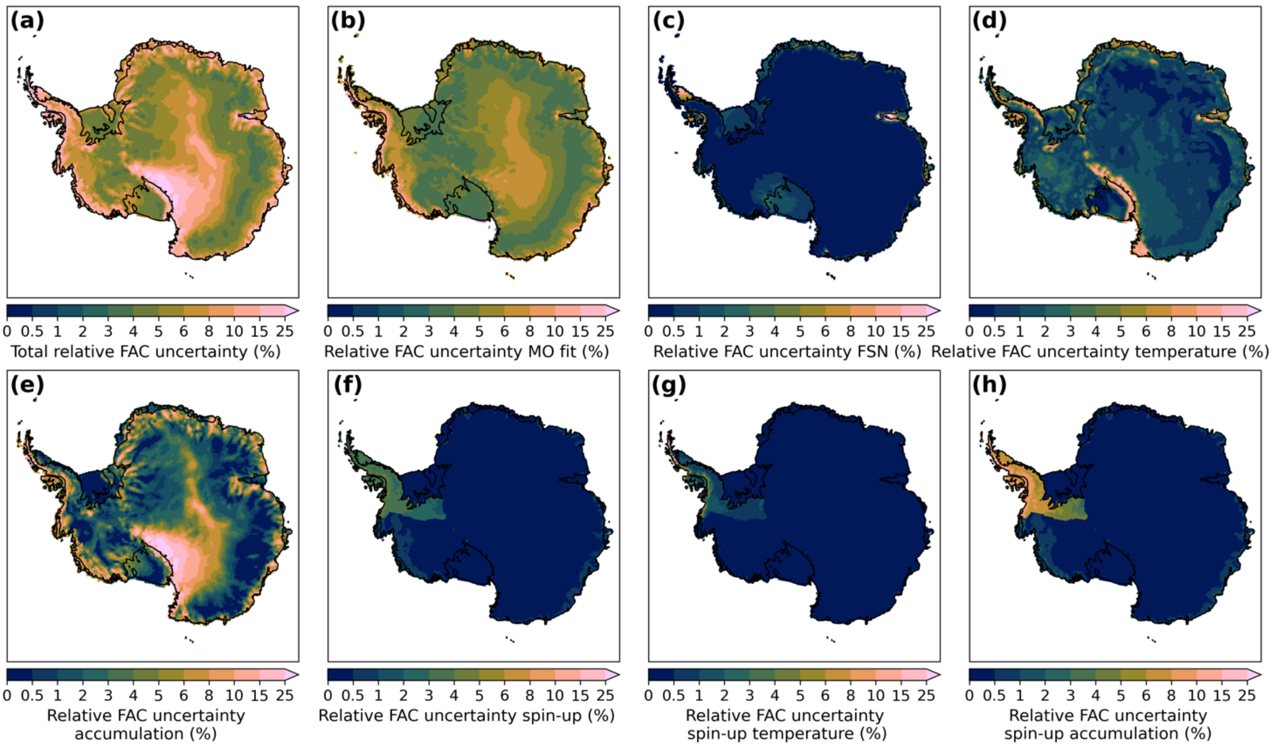

Figure S4. Maps from FDM v1.2A of the estimated relative firn air content (FAC) uncertainty from the sensitivity analysis for **(a)** the total of all experiments from panels b to f, **(b)** the MO fit experiments, **(c)** the fresh snow density experiments, **(d)** the temperature forcing experiments, **(e)** the accumulation forcing experiments, **(f)** the combined temperature and accumulation spin-up experiments, **(g)** the temperature spin-up experiments and **(h)** the accumulation spin-up experiments. The uncertainties are expanded over the ice sheet using the empirical relations from Figure S3.

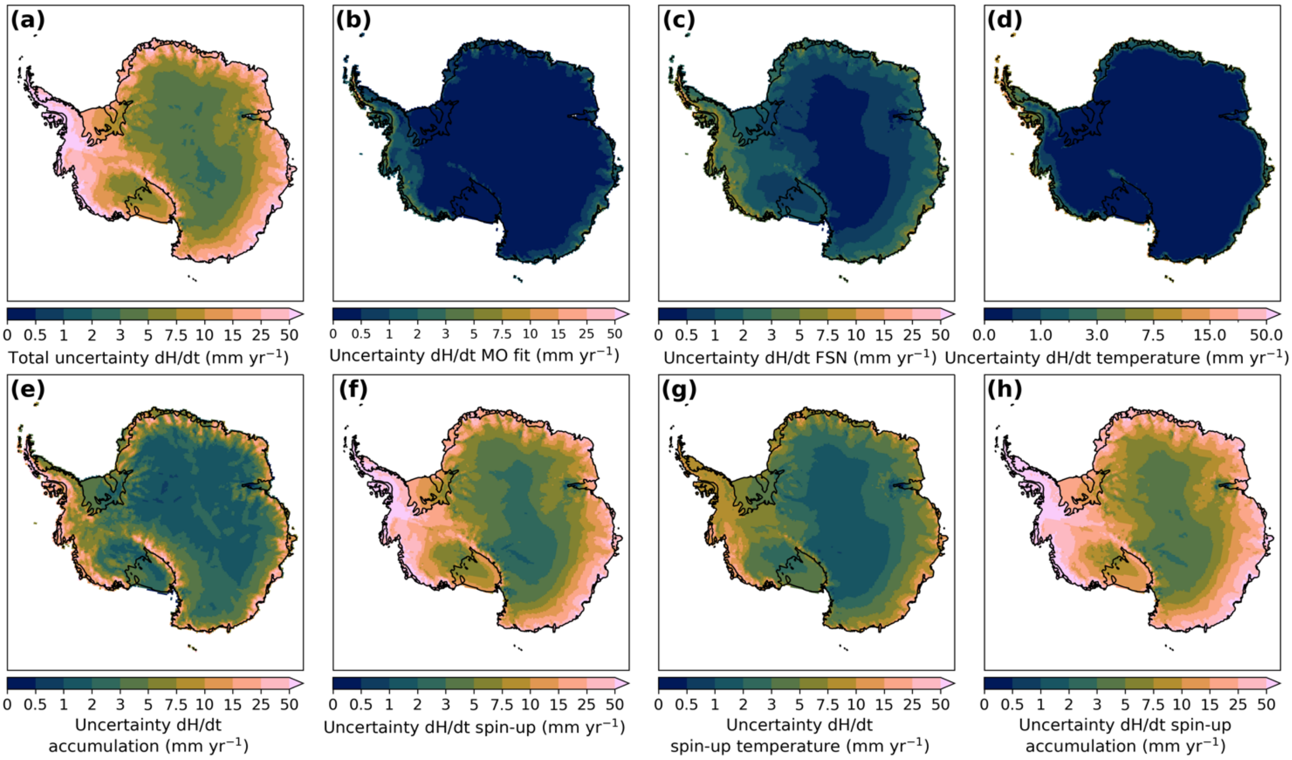

Figure S5. Maps from FDM v1.2A of the estimated surface elevation change (dH/dt) uncertainty from the sensitivity analysis for **(a)** the total of all experiments from panels b to f, **(b)** the MO fit experiments, **(c)** the fresh snow density experiments, **(d)** the temperature forcing experiments, **(e)** the accumulation forcing experiments, **(f)** the combined temperature and accumulation spin-up experiments, **(g)** the temperature spin-up experiments and **(h)** the accumulation spin-up experiments. The uncertainties are expanded over the ice sheet using the empirical relations from Figure S3.

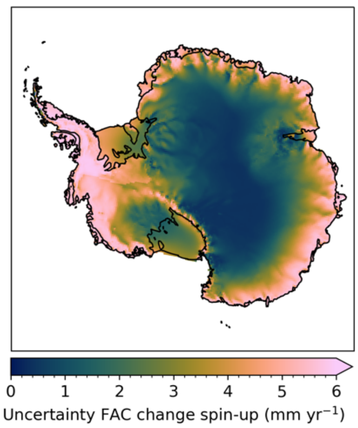

Figure S6. Map from FDM v1.2A of the estimated firn air content (FAC) uncertainty from the sensitivity analysis for the combined temperature and accumulation spin-up experiments.

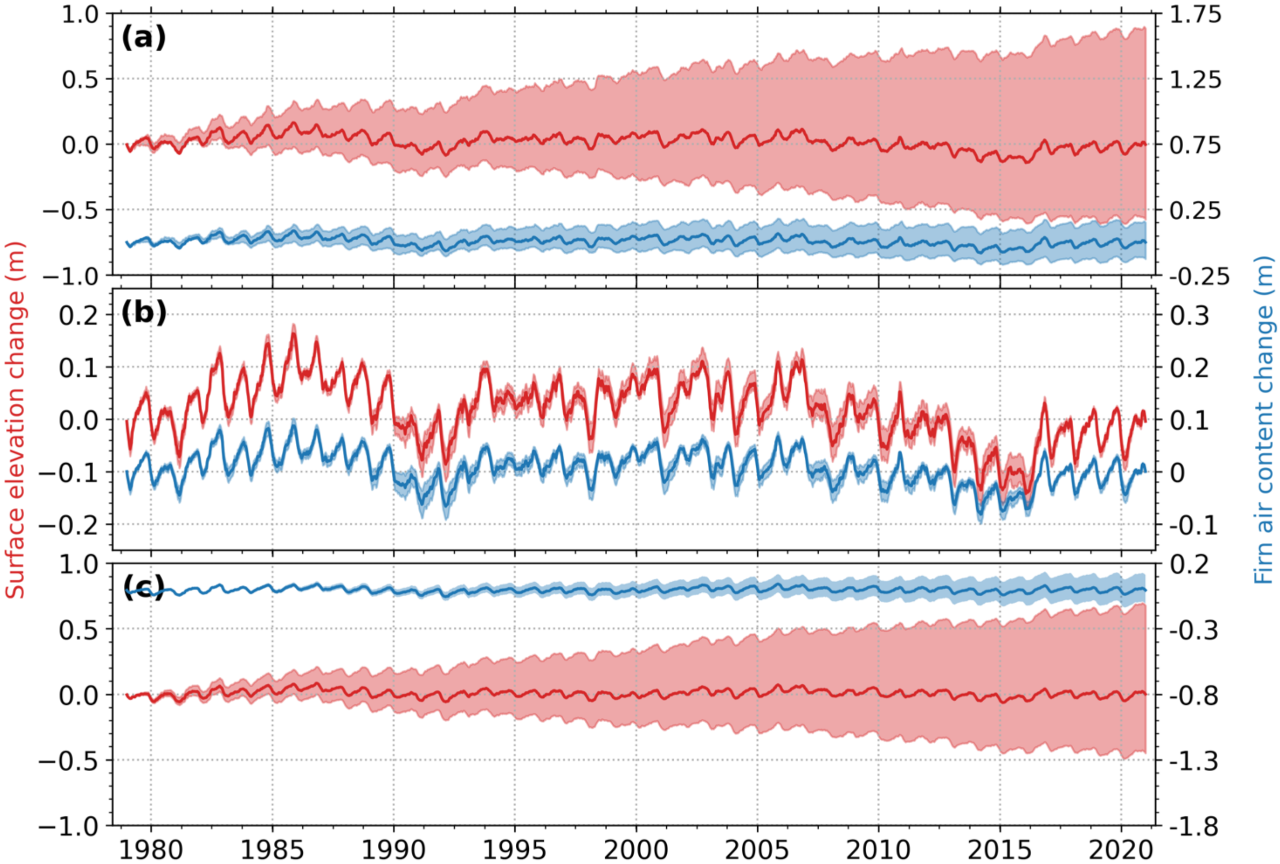

Figure S7. Time series from FDM v1.2A of the surface elevation change and firn air content averaged over the 106 sample locations including **(a)** the total uncertainty of all sensitivity experiments and **(b)** the uncertainty of all experiments except for the spin-up experiments. **(c)** Time series from FDM v1.2A of the ice-sheet-wide averaged surface elevation change and firn air content including the estimated ice-sheet-wide averaged uncertainties of the combined temperature and accumulation spin-up experiments. The uncertainties of the surface elevation change and firn air content are indicated by the red and blue shaded areas, respectively.

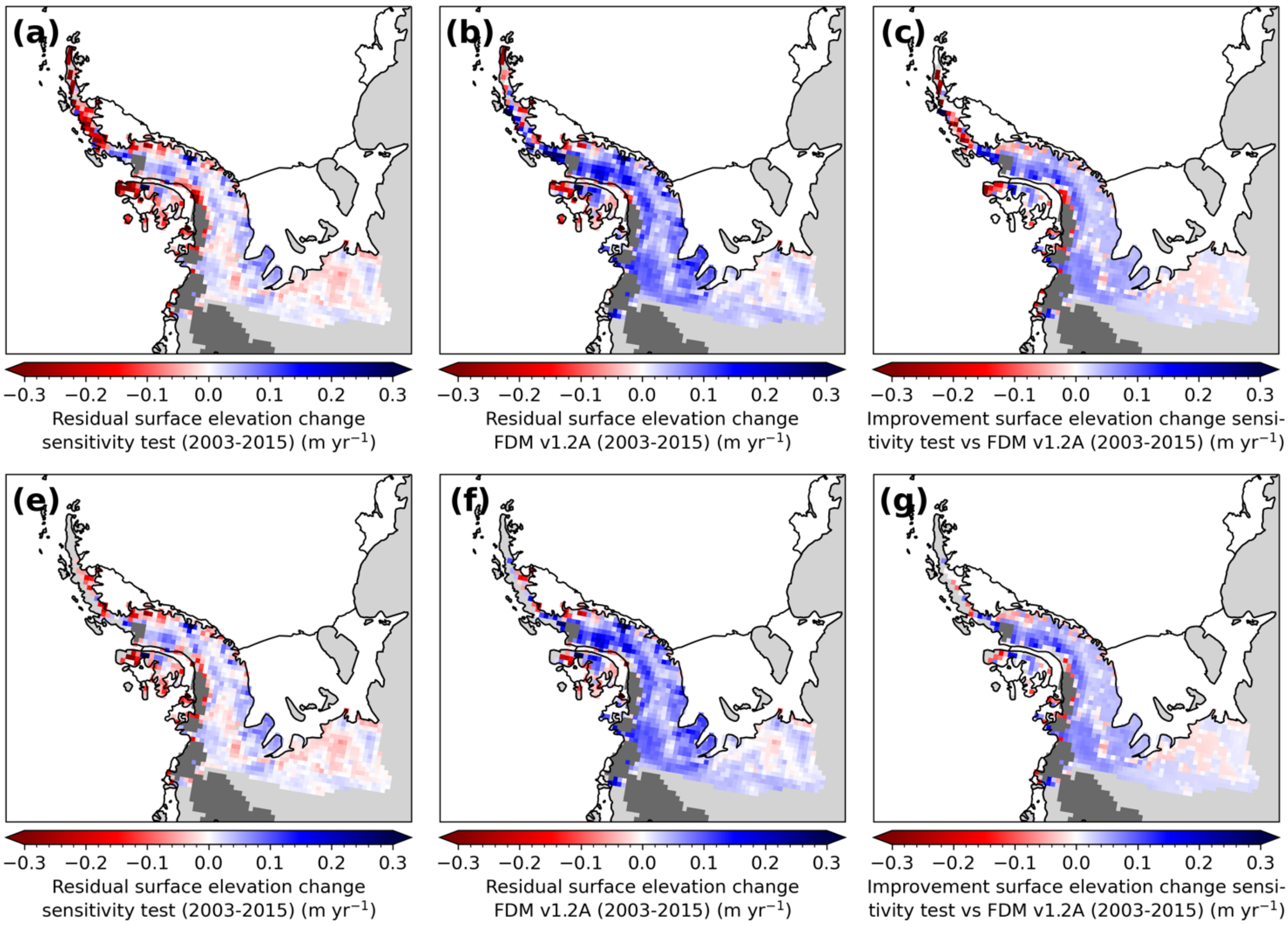

Figure S8. Maps of the residual trend of **(a)** altimetry minus the combined temperature and precipitation spin-up sensitivity experiments and **(b)** altimetry minus FDM v1.2A. **(c)** Difference in altimetry agreement between the combined temperature and precipitation spin-up experiment and FDM v1.2A (absolute residual of FDM v1.2A compared to altimetry minus absolute residual of the combined temperature and precipitation spin-up experiment compared to altimetry). **(e,f,g)** are similar as (a,b,c) except that regions where the age of the criticial density level of ρ = 830 kg m^{-3} is lower than 42 year are masked out.

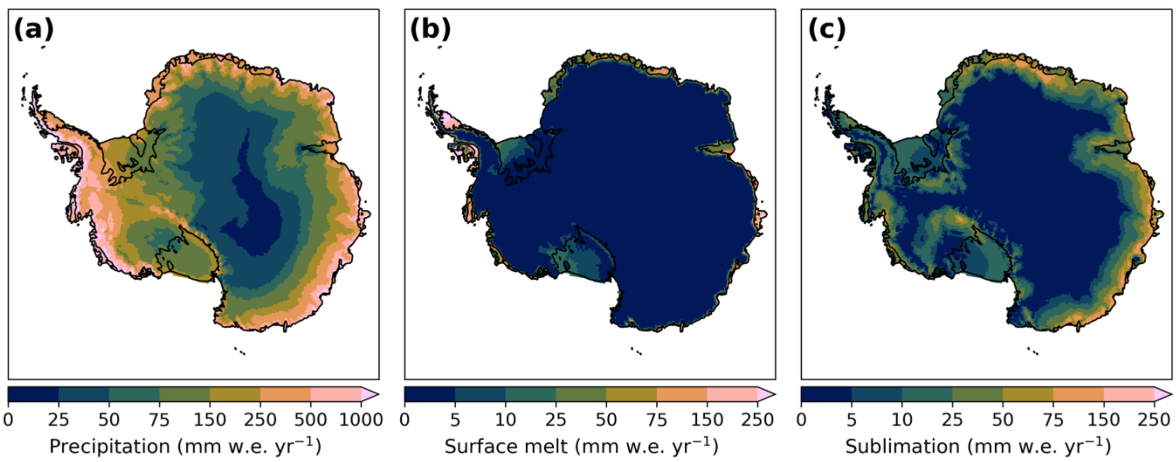

Figure S9. Maps of the mean annual **(a)** accumulation, **(b)** surface melt and **(d)** sublimation over the period 1979-2020 from RACMO2.3p2.

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