SUPPLEMENTARY MATERIAL

For

Isotopic Evidence for the Riming Growth of Ice in Precipitation

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Table S1 (A-F). Dates/times for which concurrent radar and isotope data were available. Daily averages of MDV were calculated for Summit and Dumont d'Urville. Averaging times were daily or sub-daily at Ny-Ålesund and Andenes, and 25- or 30-min at Cazadero and Rio Claro.

A. SUMMIT, Greenland

Date	Date	Date	Date	Date	Date	Date	Date
20130117	20140226	20120514	20120723	20120803	20140821	20130915	20131012
20140101	20140228	20120516	20120724	20120804	20140823	20130919	20131013
20140104	20130318	20120525	20120725	20120806	20110901	20130920	20131015
20140106	20130322	20120526	20120726	20120807	20110905	20130922	20131016
20140107	20130327	20120527	20120728	20120808	20110906	20130924	20111103
20140108	20140307	20120528	20120729	20120809	20110914	20130925	20111105
20140109	20140311	20120529	20120730	20120810	20110915	20130926	20111106
20140110	20140312	20120530	20130709	20120811	20110916	20130929	20121127
20140111	20140324	20140502	20130710	20120814	20110917	20111001	20131104
20140112	20140326	20140503	20130711	20120815	20110918	20111002	20131107
20140118	20140330	20140508	20130716	20120822	20110919	20111003	20131108
20140119	20120409	20140519	20130721	20120823	20110920	20111004	20131110
20140120	20120410	20140521	20130726	20120824	20110921	20111005	20131111
20140121	20120411	20140522	20130727	20120825	20110922	20111009	20131112
20140122	20120412	20120606	20130728	20120827	20110923	20111010	20131119
20140123	20120413	20120615	20130730	20120831	20110924	20111012	20131120
20140124	20120414	20120616	20140726	20130801	20120906	20111013	20131125
20140125	20120415	20120617	20140727	20130802	20120907	20111014	20131126
20140127	20120416	20120618	20140729	20130803	20120912	20111015	20131127
20140128	20120425	20120619	20140730	20130805	20120913	20111016	20131129
20140129	20120426	20120620	20140731	20130806	20120914	20111018	20131130
20140130	20120428	20120621	20110811	20130807	20120915	20111019	20121213
20140131	20120430	20120625	20110812	20130809	20120920	20111020	20131209
20130201	20140403	20120626	20110814	20130814	20120922	20111021	20131210
20130208	20140406	20120627	20110815	20130815	20120925	20111022	20131214
20140203	20140413	20120628	20110817	20130816	20130901	20111027	20131216
20140205	20140425	20120630	20110818	20130817	20130902	20111029	20131217
20140206	20120501	20110726	20110822	20130818	20130903	20121001	20131221
20140213	20120503	20110727	20110826	20130819	20130904	20121004	20131223
20140214	20120504	20110728	20110827	20130820	20130905	20121005	20131225

A. (continued)

Date	Date	Date	Date	Date	Date	Date	Date
20140216	20120505	20120701	20110828	20130822	20130906	20121026	20131227
20140218	20120506	20120702	20110829	20130824	20130907	20121027	
20140219	20120507	20120703	20110830	20130825	20130908	20131001	
20140221	20120510	20120704	20110831	20130826	20130909	20131008	
20140222	20120511	20120707	20120801	20140811	20130913	20131009	
20140223	20120512	20120708	20120802	20140819	20130914	20131010	

B. Dumont d'Urville

Date	Date	Date	Date
1/27/19	5/29/19	1/13/20	4/14/20
2/6/19	6/2/19	1/18/20	5/12/20
3/12/19	7/19/19	2/16/20	5/14/20
4/18/19	7/23/19	3/2/20	8/28/20
5/6/19	1/7/20	3/17/20	9/10/20

C. Ny-Ålesund, Svalbard (Norway)

Date	Type	Date	Type	Date	Type	Averaging Time
4/28/17	Rain	5/16/18	Rain	2/2/18	Snow	
6/27/17	Rain	5/23/18	Rain	5/19/17	Snow	
6/28/17	Rain	5/24/18	Rain	5/21/17	Snow	
6/29/17	Rain	7/8/18	Rain	5/26/17	Snow	
7/5/17	Rain	7/9/18	Rain	3/1/20	Snow	07:00 - 20:00
7/6/17	Rain	7/10/18	Rain	3/3/20	Snow	19:00 (3/2) - 09:00 (3/3)
7/7/17	Rain	7/12/18	Rain	3/5/20	Snow	19:00 (3/4) - 08:00 (3/5)
7/8/17	Rain	7/21/18	Rain	3/8/20	Snow	all of 3/07
9/22/17	Rain	7/27/18	Rain	3/8/20	Snow	11:00 - 6:00
10/9/17	Rain	8/20/18	Rain	3/13/20	Snow	18:00 (3/12) - 09:00 (3/13)
10/10/17	Rain	8/28/18	Rain	3/14/20	Snow	20:00 (3/8) - 11:00 (3/14)
1/10/18	Rain	8/29/18	Rain	3/14/20	Snow	11:00 - 18:00
1/15/18	Rain	9/3/18	Rain	3/15/20	Snow	17:00 (3/14) -13:00 (3/15)
5/5/18	Rain	9/5/18	Rain			
		4/16/18	Rain			

D. Andenes, Norway

Date	Averaging (start-end)	Type	Date	Averaging (start-end)	Type
2/25/20	daily	snow	3/1/20	2/29_16:00 - 3/1_8:00	snow
2/26/20	daily	snow	3/1/20	8:00 - 12:00	snow
3/8/20	daily	rain	3/2/20	3/1_16:00 - 3/ 2_10:00	snow
3/9/20	daily	rain	3/12/20	10:00 - 16:00	snow
2/29/20	2/28_16:00 - 2/29_8:00	snow	3/13/20	8:00 - 12:00	snow
2/29/20	8:00-16:00	rain	3/13/20	12:00 - 16:00	snow

E. Cazadero, California

Date	Start time	End time	Date	Start time	End time
3/1/09	5:45	6:15	2/8/07	20:45	21:15
	6:15	6:45		21:15	21:45
	6:45	7:15		21:45	22:15
	7:15	7:45		22:15	22:45
	7:45	8:15		22:45	23:15
	10:15	10:45		23:15	23:45
	10:45	11:15	2/9/07	0:15	0:45
	11:15	11:45		0:45	1:15
	11:45	12:15		1:15	1:45
	12:45	13:15		1:45	2:15
	13:15	13:45		2:15	2:45
	13:45	14:15	2/10/07	5:45	6:45
	14:15	14:45		9:45	10:45
	14:45	15:15		13:15	13:45
	15:15	15:45		13:45	14:15
3/21/05	22:00	22:30		14:15	14:45
	22:30	23		14:45	15:45
	23:00	23:30	1/25/10	0:15	0:45
	23:30	0:00:00		1:15	1:45

E. (continued)

Date	Start time	End time	Date	Start time	End time
3/22/05	0:00	0:30		1:45	2:15
	0:30	1:00		3:15	3:45
	1:00	1:30		4:15	4:45
	1:30	2:00		14:45	15:15
	2:00	2:30		16:15	16:45
	2:30	3:00		16:45	17:15
	4:00	4:30		17:15	17:45
2/8/07	19:15	19:45		19:45	20:15
	19:45	20:15		20:45	21:15
	20:15	20:45		22:45	23:15

F. Rio Claro, Brazil

Date	Start	End	Date	Start	End	Date	Start	End
10/8/19	14:30	15:05	12/10/19	20:43	21:18	1/5/20	17:37	18:09
	15:05	15:45		21:18	21:53		18:09	18:49
	15:45	16:15		21:53	22:28			
	17:05	17:55		23:08	23:28			

Table S2. Mode of precipitating cloud types (0=IC; 1=CLW; 2=indeterminate) at Summit for two sub-daily intervals (0-12 hr; 12-24 hr) based on 1-min resolution classification of Pettersen et al. (2018).

Date	d-ex	mode 0-12 hr	mode 12-24 hr	Date	d-ex	mode 0-12 hr	mode 12-24 hr	Date (Summer)	d-ex	mode 0-12 hr	mode 12-24 hr
2/14/14	-6.86	2	2	6/6/12	13.15	2	2	8/22/11	14.57	1	1
2/3/14	-6.79	2	2	6/15/12	16.59	1	1	8/26/11	19.1	1	1
1/30/14	-6.04	2	2	6/16/12	17.12	1	1	8/27/11	19.06	1	1
2/16/14	-3.72	2	2	6/17/12	18.28	1	1	8/28/11	14.25	1	1
2/23/14	-3.64	2	2	6/18/12	18.82	1	1	8/29/11	13.34	1	1
1/20/14	-3.43	1	2	6/19/12	16.71	2	2	8/30/11	11.1	1	1
2/26/14	-3.28	2	2	6/20/12	16.53	1	2	8/31/11	15.26	1	1
2/28/14	-2.49	1	1	6/21/12	15.06	2	2	8/1/12	13.61	1	1
2/19/14	-2.46	1	2	6/25/12	21.44	2	2	8/2/12	13.01	1	1
2/8/13	-2.26	2	2	6/26/12	17.85	2	2	8/3/12	14.52	1	1
1/29/14	-1.96	2	2	6/27/12	18.13	2	2	8/4/12	16.55	1	1
2/22/14	-1.92	2	2	6/28/12	23.94	2	2	8/6/12	13.81	1	1
2/1/13	-0.94	2	2	6/30/12	21.17	1	1	8/7/12	11.69	1	1
2/13/14	-0.71	2	2	7/26/11	17.72	2	2	8/8/12	10.71	1	1
1/19/14	-0.53	2	1	7/27/11	14.9	1	1	8/9/12	14.18	1	1
12/25/13	-0.29	2	2	7/28/11	13.4	1	1	8/10/12	27.67	2	0
2/18/14	0	2	2	7/1/12	13.58	1	1	8/11/12	13.22	1	2
1/28/14	0.26	2	2	7/2/12	23.55	2	2	8/14/12	11.84	1	1
1/12/14	0.27	2	2	7/3/12	22.4	2	2	8/15/12	13.25	1	2
12/19/13	0.59	2	2	7/4/12	34.92	2	2	8/22/12	16.94	1	1
12/23/13	1.43	2	2	7/7/12	17.48	1	1	8/23/12	17.52	1	1
1/31/14	1.79	2	2	7/8/12	21.25	1	1	8/24/12	17	1	2
1/27/14	1.81	2	1	7/23/12	22.63	2	2	8/25/12	13.93	1	1
2/6/14	1.84	2	2	7/24/12	16.92	2	2	8/27/12	17.21	1	2

Table S-2 (continued)

Date	d-ex	mode 0-12 hr	mode 12-24 hr	Date	d-ex	mode 0-12 hr	mode 12-24 hr	Date (Summer)	d-ex	mode 0-12 hr	mode 12-24 hr
2/21/14	1.86	2	2	7/25/12	21.93	2	2	8/31/12	17.57	1	2
1/25/14	2.26	2	2	7/26/12	16.92	2	2	8/1/13	12.9	1	1
2/5/14	3	2	2	7/28/12	11.31	1	1	8/2/13	17.62	1	1
12/13/12	3.46	2	1	7/29/12	8.43	1	1	8/3/13	18.93	1	1
1/22/14	3.48	2	1	7/30/12	10.44	1	1	8/5/13	17.54	0	2
12/27/13	3.6	2	2	7/9/13	13.7	1	1	8/6/13	19.38	2	2
1/21/14	3.76	2	2	7/10/13	11.81	1	1	8/7/13	15.6	2	2
1/6/14	3.77	2	2	7/11/13	14.11	1	1	8/9/13	9.28	1	2
1/24/14	3.9	2	2	7/16/13	16.91	1	2	8/14/13	14.86	1	1
1/18/14	4.1	2	2	7/21/13	15.86	1	1	8/15/13	13.64	1	2
1/4/14	4.34	1	2	7/26/13	14.66	1	1	8/16/13	18.87	1	2
1/23/14	4.55	1	2	7/27/13	14.87	1	1	8/17/13	19.79	2	2
1/11/14	5.3	2	2	7/28/13	18.91	1	1	8/18/13	23.6	2	2
12/9/13	5.63	2	2	7/30/13	16.67	1	1	8/19/13	21.78	1	2
12/14/13	5.64	2	2	7/26/14	12.29	2	2	8/20/13	11.16	2	1
1/17/13	5.88	2	2	7/27/14	12.27	2	2	8/22/13	17.92	2	2
1/7/14	6.1	2	1	7/29/14	13.63	2	2	8/24/13	12.58	0	2
1/1/14	6.21	1	1	7/30/14	18.45	2	2	8/25/13	13.27	1	2
12/21/13	6.62	2	2	7/31/14	17.03	2	2	8/26/13	14.78	1	2
12/10/13	7.8	2	2	8/11/11	20.6	1	1	8/28/13	16.85	2	2
12/17/13	8.22	2	2	8/12/11	19.32	1	1	8/30/13	20.43	2	2
1/9/14	8.61	0	1	8/14/11	29.06	1	2	8/11/14	11.32	2	2
1/10/14	10.26	2	2	8/15/11	18.07	1	2	8/19/14	15.93	2	2
1/8/14	13.17	2	2	8/17/11	19.75	1	2	8/21/14	14.39	1	1
12/16/13	13.77	2	2	8/18/11	18.36	1	1	8/23/14	12.67	1	1

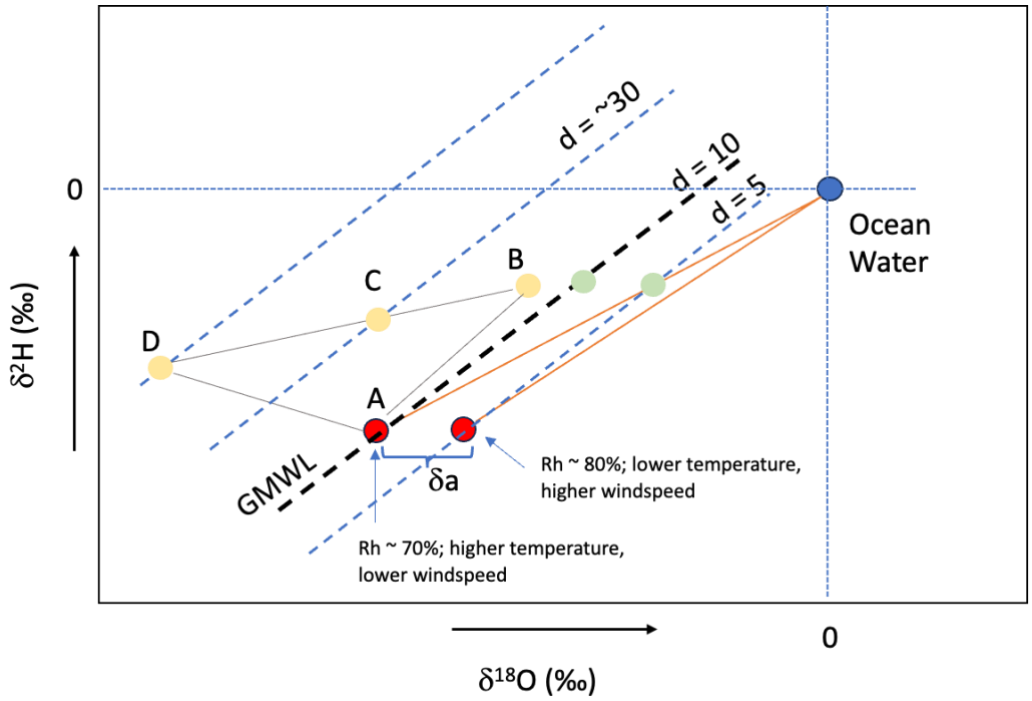


Fig. S1. Schematic diagram showing isotopic fractionation and d-excess change in evaporation and condensation (after Merlivat and Jouzel, 1979; Jouzel and Merlivat, 1984). The global meteoric water line (GMWL) is the global average isotopic composition of precipitation ($\delta^2H = 8\delta^{18}O + 10$) with a d-excess (d) of 10. The isotopic composition of water vapor (δa) from the evaporation of ocean water (blue circle) would have different d-excess values (red circles) depending upon the relative humidity, temperature and wind speed during evaporation. Condensation of water vapor in isotopic equilibrium would result in liquid water with the same d-excess as the vapor (green circles). Ice growth by deposition from a starting vapor at A would produce the solid phase (yellow circles) along the line B-D where the level of supersaturation with respect to ice increases towards D. Ice supersaturation is the ratio of ambient water pressure to vapor pressure at ice saturation. At B, the vapor pressure could be ~20% and at C ~200% greater than that at ice saturation. D represents pure diffusion where air flow is unaffected in the vicinity of ice crystals.

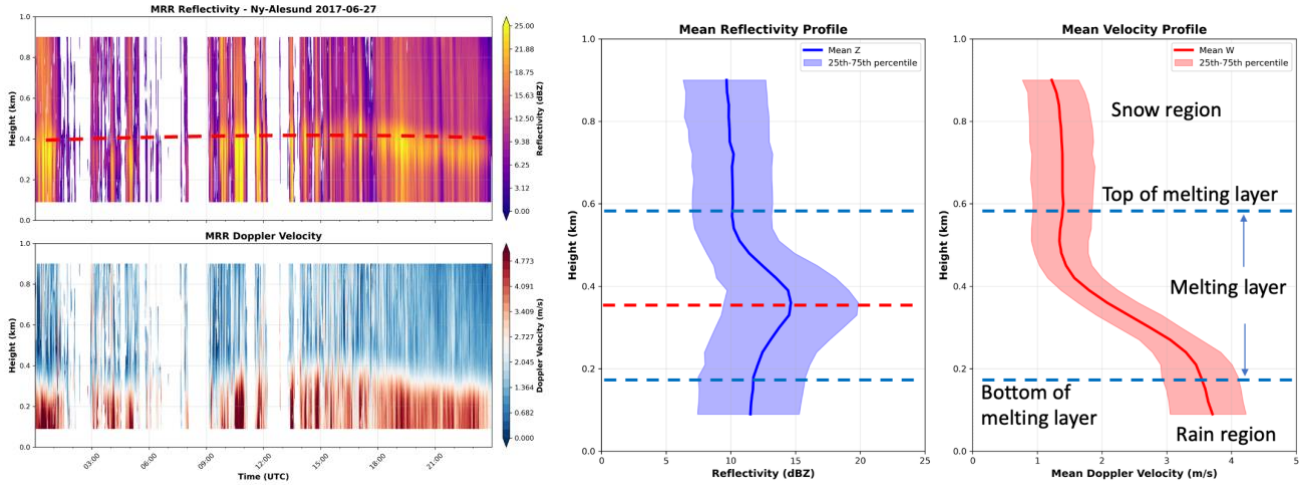


Fig. S2 Vertical profiles of reflectivity (Ze) and mean Doppler velocity (MDV) for 2017-06-27 at Ny-Ålesund from a micro-rain radar. The left panel shows the variations with time. The right panel shows the daily average values with the shaded areas showing the variability as 25th and 75th percentiles. The dashed red line shows the bright band, marked by a peak in reflectivity, and the dashed blue lines show the top and bottom of the melting layer. See text for explanations.

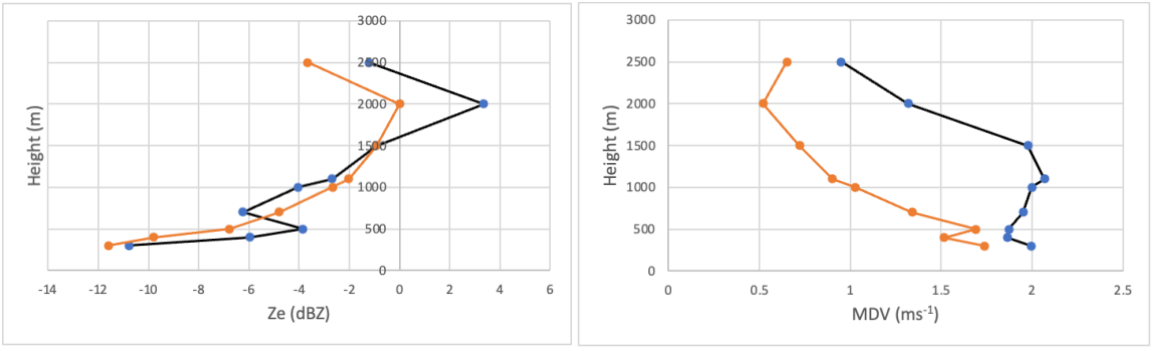


Fig. S3 – Typical profiles of reflectivity and MDV at Dumont d'Urville for 1/28/2019 (blue) and 3/3/2019 (brown) when snowfall may have been sublimated at lower altitudes.

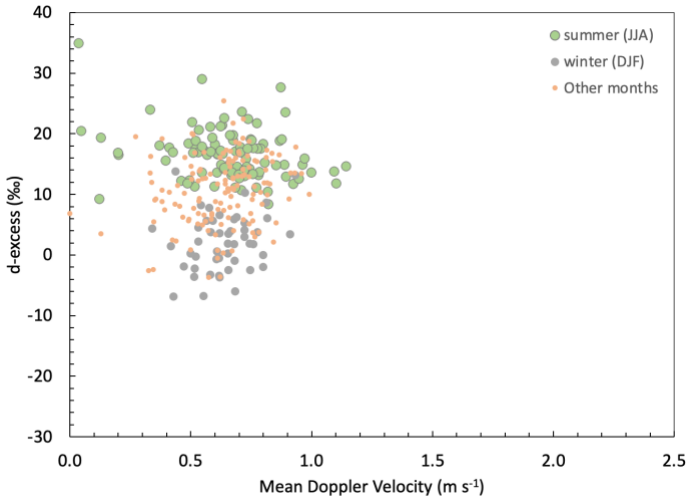


Fig. S4 – Summit d-ex and MDV data for all months showing that the summer (JJA) and winter (DJF) encompass the range of values in the other months.

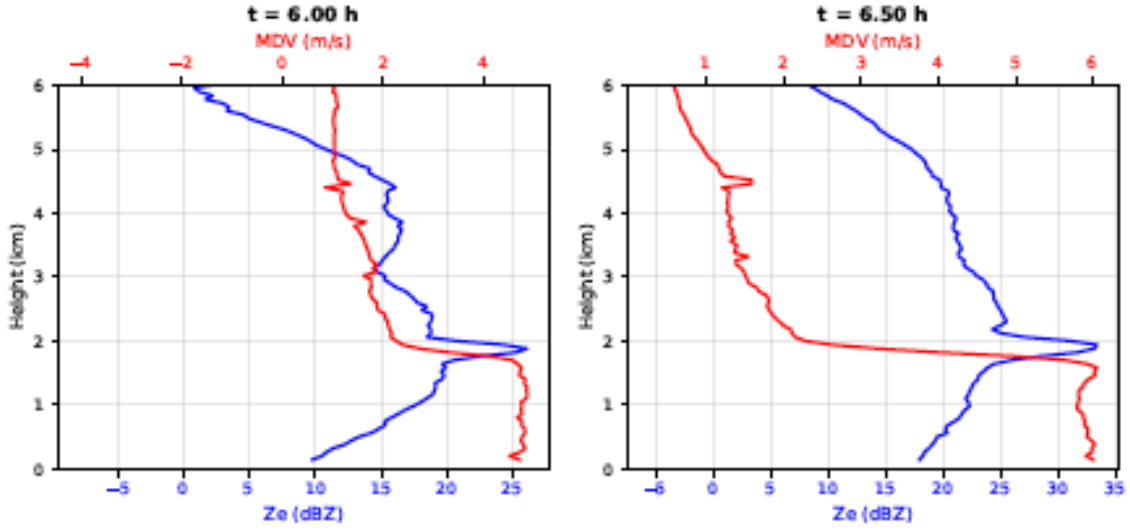
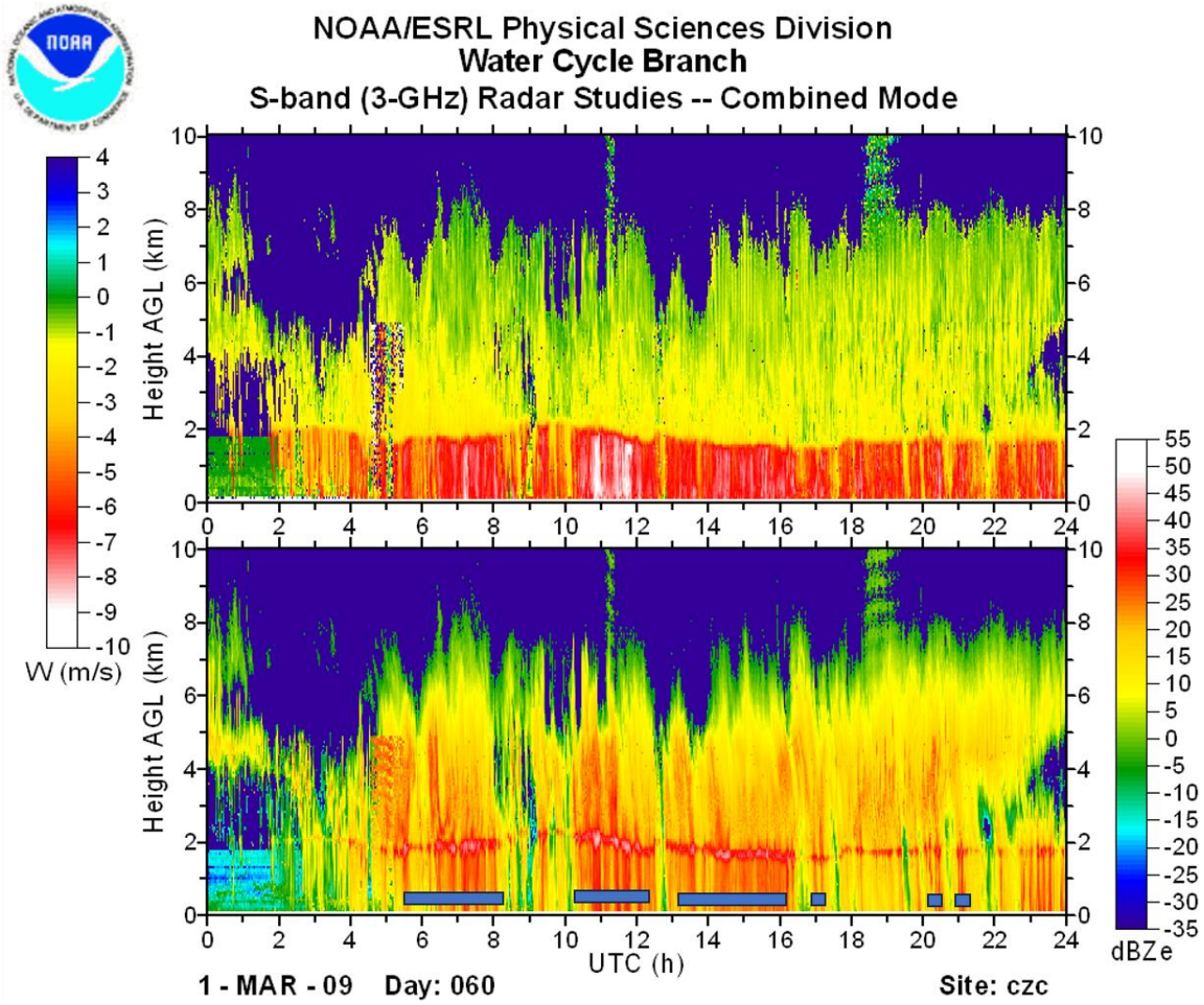


Figure S5 – Typical vertical profiles of reflectivity (Ze) and MDV at Cazadero, California indicating potential sub-cloud evaporation (decreasing Ze below ~1.5 km) on 1 March 2009. Time intervals: left panel: 05:45 to 06:15 hr; right panel: 06:15 to 06:45 hr



95 Fig. S6 – Time-height profiles of MDV (top) and reflectivity (bottom) for the 1 March 2009 event at Cazadero. The horizontal blue rectangles in the lower panel show the time where MDV was averaged for 30 min intervals corresponding to isotope samples.

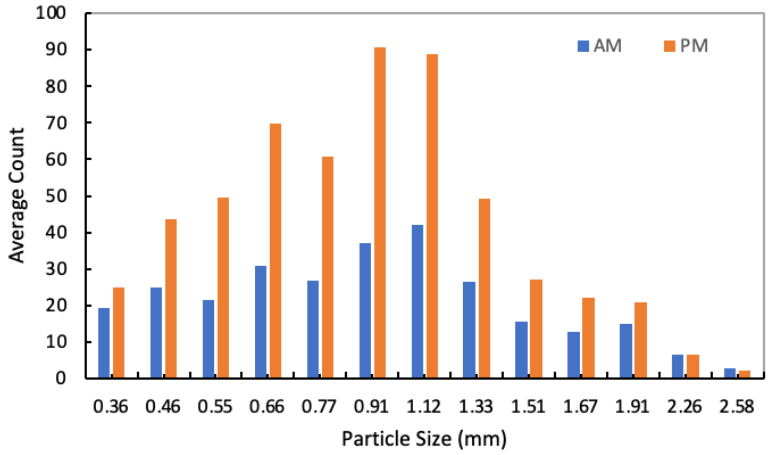


Figure S7 – Particle size distribution in Cazadero precipitation on 1 March 2009. Note the smaller size in the morning that may indicate sub-cloud evaporation. (Data provided by A. White, email communication, 13 August 2023).

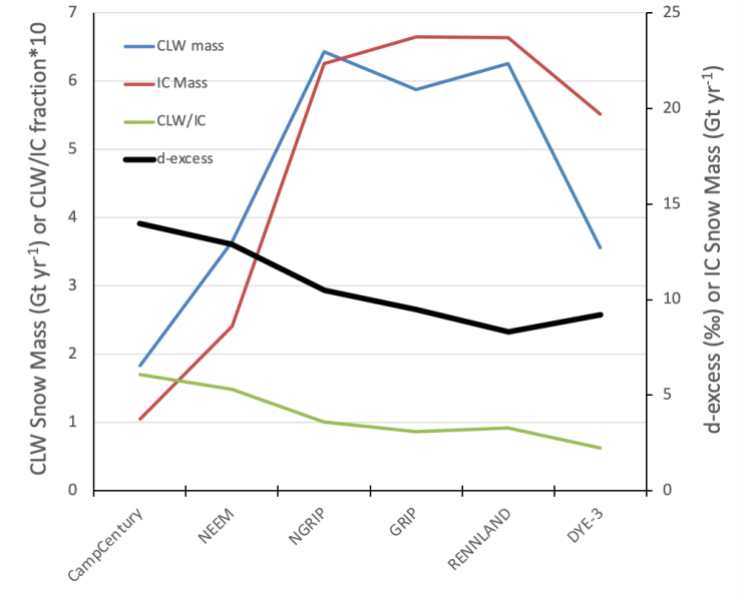


Figure S8 – Spatial (northwest to southeast) variations of d-excess and snow mass resulting from different cloud types (IC=ice clouds; CLW=liquid-bearing clouds) across Greenland. Cloud type data from McIlhattan et al. (2020).