Analysis of spatial and temporal distribution of wet snow events in Germany

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***Abstract* – The last severe wet snow event in Germany, which caused serious damages on the electric power network in Münsterland, was in November 2005. It led to a reconsideration of the previous knowledge of wet snow events in Germany. The objective of the investigation was to determine the spatial and temporal distribution of wet snow events for the whole country. Data of 70 meteorological stations evenly distributed over the territory of Germany were analyzed for this purpose for the period 1980-1999.**

A criterion proposed by Makkonen (1989) was used in order to determine the occurrence of wet snow accretion. The results of applying the wet snow criterion show that the process of wet snowfall consists of several short living processes embedded in longer snowfall events.

In order to have a general picture of wet snow conditions over the country we calculated the ratio of wet snow observation hours to all synoptic messages reporting snowfall. Results for wet snow ratios (WSR) show that the west part of Germany is more affected (WSR between 0,34 and 0,38) by wet snow events with the highest WSR of 0,44 in the northwest coastal region (Bremerhaven). Surprisingly high values of WSR have been determined for the south part of Germany, especially in pre-Alps regions, as well. Nevertheless the wet snow ratio decreases with the altitude in general.

The analysis of temporal distribution shows that wet snow events occur from November till April in the lowlands and from October till May in mountainous regions. Most often the maximum of the wet snow hours is in March. Some regions show two maxima or an almost equal distribution of wet snow events during the winter season. The maximum of wet snow events for mountain stations occurs in April.

Keywords: atmospheric icing, wet snow occurrence and distribution

I. INTRODUCTION

Knowledge about the appearance frequency of wet snow events and the maximum possible wet snow loads are of great importance for the design of different technical equipments and their proper function and security. The first investigations in this field started in Japan in the beginning of the 1950s and continue until nowadays [1] – [11]. The last important wet snow event in Germany, which caused serious damages on the electric power network in Münsterland, was in November 2005 ([14], [15]). This event led to a reconsideration of the previous knowledge of wet snow events in Germany and its verification.

Wet snow depositions are defined as one of the possible types of ice depositions, despite that it shows differences to all of them. Wet snow depositions usually occur, when snowfall is observed and the air temperature is positive (0-3°C). Wet snow is formed initially as dry snow in upper layers of the atmosphere, where low temperatures predominate. The metamorphosis to wet snow takes place during the fall through the lower and warmer air layers.

The objective of this investigation was to determine some of the characteristics of the process – the frequency of occurrence of wet snow events and their duration, the seasonal number of wet snow hours as well as their spatial and temporal distribution for Germany.

II. DATA AND METHODOLOGY

Data of 70 meteorological stations evenly distributed over the territory of Germany were analyzed for the period 1980-1999. The meteorological data set includes hourly values of air temperature, dew point temperature, wind direction and wind velocity, horizontal visibility and information about the current weather events. From this data we have chosen only cases when any snowfall was reported. We used a criterion proposed by Makkonen, see [12], to select wet snow events from all observations of snowfall:

$$t_a > \frac{1.75 \cdot 10^3}{p}\left(6.11 - \mathrm{R}e_s(t_a)\right) \qquad (1)$$

where t_a is the air temperature in °C, R is the relative humidity and $e_s(t_a)$ is the saturation water vapour pressure in air at temperature t_a and p is the atmospheric air pressure. In this way the wet snow cases were selected on the basis of the available meteorological information.

Relative humidity was not available directly from the meteorological data set. It was recalculated from dew point temperature using formulas published in [13], assuming a standard atmospheric pressure of 1013.25 hPa.

Fig. 1 shows an example of the application of criterion (1) for all wet snow cases that have been selected from all meteorological observations at station Bremerhaven. The theoretical curve that is defined by criterion (1) is displayed in Fig. 1, too.

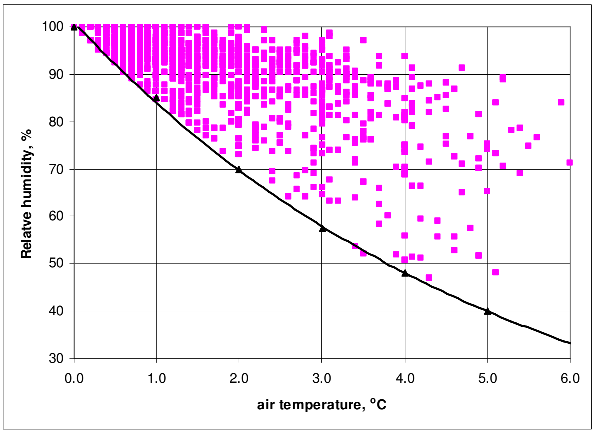


Fig. 1. The critical curve after eq.1 separating wet and dry snow events and the determined wet snow cases for station Bremerhaven

III. RESULTS

A. The Wet Snow Ratio (WSR)

The results of applying the criterion of Makkonen to the meteorological time series showed in general that wet snowfall events consist of several short living processes embedded in longer snowfall events. Therefore it was a challenge to determine the "real" number of wet snow events out of all snow events. In order to have a general picture of the wet snow conditions over the country we calculated the ratio of wet snow observation hours to all synoptic messages that reported snowfall.

It was ascertained that the west part of the country is more affected (WSR between 0,34 and 0,38) by wet snow events with highest WSR's (up to 0,44) in the northwest coastal region. Surprisingly high values of this ratio have been determined as well for the south part of Germany especially in the for-Alps regions – for stations as Bamberg, Konstanz, Kempten, Oberstdorf etc.. This could be explained by the influence of the mountains in enhancing the lifting process of warm air masses and the increased general number of snowfall events, see Fig. 2.

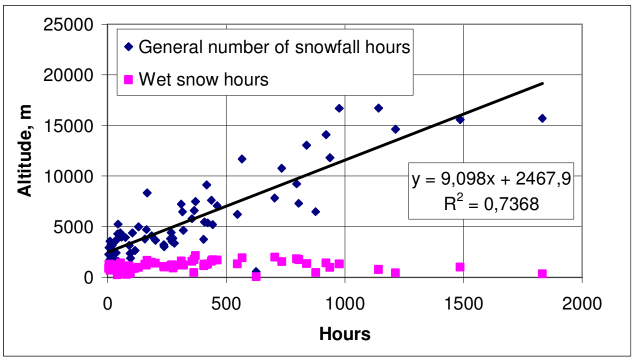


Fig. 2. General snowfall and wet snow hours for the whole period of the investigation

The dependency of wet snow ratios on the altitude is presented for all stations under consideration in Fig. 3. The altitudes are presented on a logarithmic scale for a better illustration. It can be seen that the wet snow ratio decreases with the altitude in general.

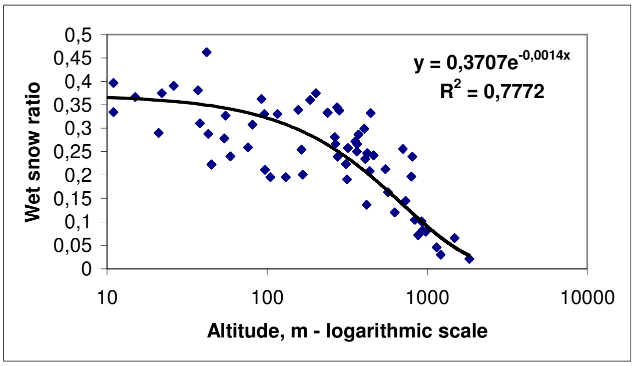


Fig. 3. Change in the wet snow ratio (WSR) with altitude

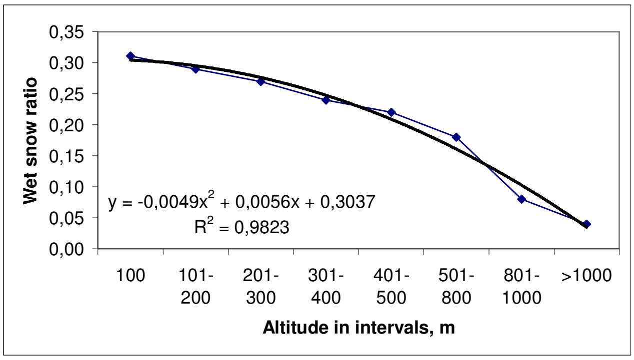


Fig. 4. Averaged wet snow ratios (WSR) in altitude intervals

Averaged values for the WSR for the whole country are presented in Fig. 4, together with a polynomial trend function with a very high correlation coefficient of R^2=0,98. Fig. 5 depicts results of similar analysis, but with two separate curves for the west and the east part of Germany. It shows remarkable differences between these two regions, which is an indicator that wet snow events are more common in the west part of the country.

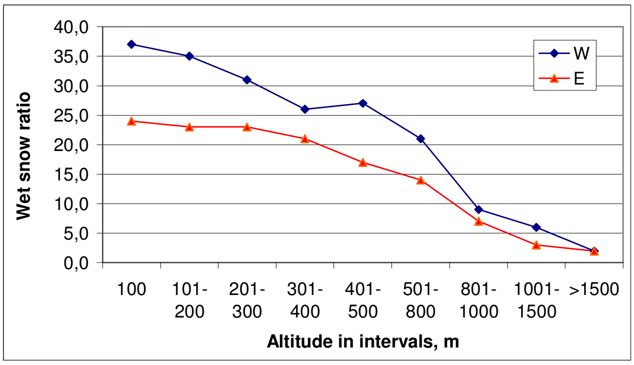


Fig. 5. Separated WSR for the west and east part

Results of WRS's for all meteorological stations under consideration are summarized in Table 1 together with supplementary meteorological characteristics that have been analyzed for the wet snow events.

The results of analysis of WSR for 70 stations in Germany are presented in Fig. 6.

Table 1. Results of statistical analysis of wet snow events in Germany, on the basis of data from 70 meteorological stations in Germany for the period 1980-1999. N_{All} is the number of all synoptic messages that reported snowfall. $N_{Wet\ snow}$ is the number of all wet snow observations.

Station	Altitude, m	N_{All}	$N_{Wet\ snow}$	**Wet Snow Ratio**	Mean wind direction, °	Mean wind velocity, m/s	Air temperature, °C
Aachen	202	3662	1371	**0,37**	242	4,1	1,6
Angermünde	54	4383	1221	**0,28**	210	4,9	1,4
Arkona	42	3953	841	**0,21**	191	10,2	1,5
Artern	164	4708	1198	**0,25**	219	5,6	1,6
Augsburg	462	7069	1714	**0,24**	245	4,6	1,4
Bamberg	239	3019	1006	**0,33**	234	3	1,6
Berlin-Schönefeld)	45	5249	1169	**0,22**	230	5,8	1,6
Berus	363	1918	477	**0,25**	242	5,7	1,5
Boizenburg	45	1573	349	**0,22**	243	5,8	1,5
Boltenhagen	15	3179	1165	**0,37**	208	8,6	1,7
Bremerhaven	7	2926	1301	**0,44**	228	6,7	1,7
Brocken	1142	16710	765	**0,05**	251	15,2	0,6
Chemnitz	418	9131	1248	**0,14**	246	7,1	1,4
Cuxhaven	5	2245	875	**0,39**	227	7,1	1,7
Doberlug-Kirchhain	97	1887	398	**0,21**	227	5,8	1,5
Düsseldorf	37	2408	918	**0,38**	233	5	1,6
Erfurt-Bindersleben	316	6470	1234	**0,19**	238	5,5	1,5
Feldberg/Schw.	1486	15566	1013	**0,07**	238	10,9	0,7
Fichtelberg	1213	14630	441	**0,03**	257	11,2	0,7
Freudenstadt	796,5	9240	1820	**0,20**	250	4,1	1,1
Gera-Leumnitz	311	7235	1616	**0,22**	249	5,3	1,4
Giessen	186	4106	1480	**0,36**	219	3,8	1,5
Görlitz	238	3217	1072	**0,33**	239	3,5	1,7
Göttingen	167	8346	1681	**0,20**	250	6,4	1,5
Greifswald	2	4104	958	**0,23**	208	5,3	1,4
Grossenkneten-Ahlhorn	42	551	255	**0,46**	234	5,4	1,6
Hamburg-Fuhlsbüttel	11	3565	1194	**0,33**	223	5,1	1,5
Hannover-Langenhagen	55	4315	1409	**0,33**	240	5,5	1,5
Hersfeld, Bad	272,2	3516	1213	**0,34**	227	3,2	1,7
Hof-Hohensaas	567	11700	1916	**0,16**	239	5,4	1,2
Hohenpeißenberg	977	16694	1318	**0,08**	237	6,1	1
Kahler Asten	839	13027	1362	**0,10**	248	8	0,9
Karlsruhe	111,6	2642	873	**0,33**	208	4,6	1,5
Kempten	705	7813	1997	**0,26**	228	2,5	1,2
Kissingen, Bad	282	3362	1136	**0,34**	211	2,8	1,8
Köln-Wahn	92	3164	1148	**0,36**	261	4,3	1,7
Konstanz	442,5	5216	1735	**0,33**	225	3	1,6
Leinefelde	356	5783	1575	**0,27**	245	4,9	1,4
Leipzig-Schkeuditz	131	4981	976	**0,20**	247	6,5	1,6
Lingen	22	1904	714	**0,38**	236	4,3	1,8
Lippspringe, Bad	157	3794	1287	**0,34**	238	4	1,4
List Auf Sylt	26	2560	1000	**0,39**	222	9,4	1,8
Magdeburg	76	3929	1018	**0,26**	236	5,1	1,7
Mannheim	96,1	2364	780	**0,33**	241	3,5	1,6
Marienberg, Bad	547	6214	1321	**0,21**	254	4,2	1,2
Marnitz	81	865	266	**0,31**	234	5,3	1,5
Mühldorf/Inn	405	3753	1121	**0,30**	252	3,8	1,4
Neuruppin	38	3702	1149	**0,31**	220	4,8	1,6
Norderney	11	1770	702	**0,40**	231	8,3	2
Oberstdorf	806	7296	1747	**0,24**	157	1	1,3
Öhringen	275,9	3845	921	**0,24**	239	3,6	1,5
Passau-Oberhaus	409	5457	1282	**0,23**	247	2,5	1
Regensburg	366	6597	1756	**0,27**	249	3,7	1,4
Rostock-Warnemünde	4	3333	844	**0,25**	202	6,9	1,5
Saarbrücken	320	4623	1191	**0,26**	240	4,3	1,5
Schleswig	43	4298	1237	**0,29**	212	5,2	1,4
Schmuecke	937	11795	967	**0,08**	229	6,5	0,8
Schwerin	59	3964	950	**0,24**	210	6,1	1,5
Seehausen	21	3182	923	**0,29**	228	5,5	1,4
Sonneberg-Neufang	626	565	68	**0,12**	198	5,5	1,3
Stötten	734	10774	1560	**0,14**	238	7	1,2
Stuttgart-Echterdingen	371	7480	2147	**0,29**	247	4,6	1,8
Trier-Petrisberg	265	3829	1078	**0,28**	229	4,2	1,6
Wasserkuppe	921	14086	1428	**0,10**	236	7,7	0,7
Weiden/Opf.	439,6	7601	1585	**0,21**	237	3,3	1,2
Weißenburg/Bayern	422	5383	1328	**0,25**	236	4,2	1,5
Wendelstein	1832	15697	335	**0,02**	246	8,6	0,8
Wittenberg	105	4393	858	**0,20**	237	4,8	1,5
Würzburg	268	4421	1181	**0,27**	244	4,8	1,5
Zinnwald-Georgenfeld	877	6475	463	**0,07**	258	7,1	1,2

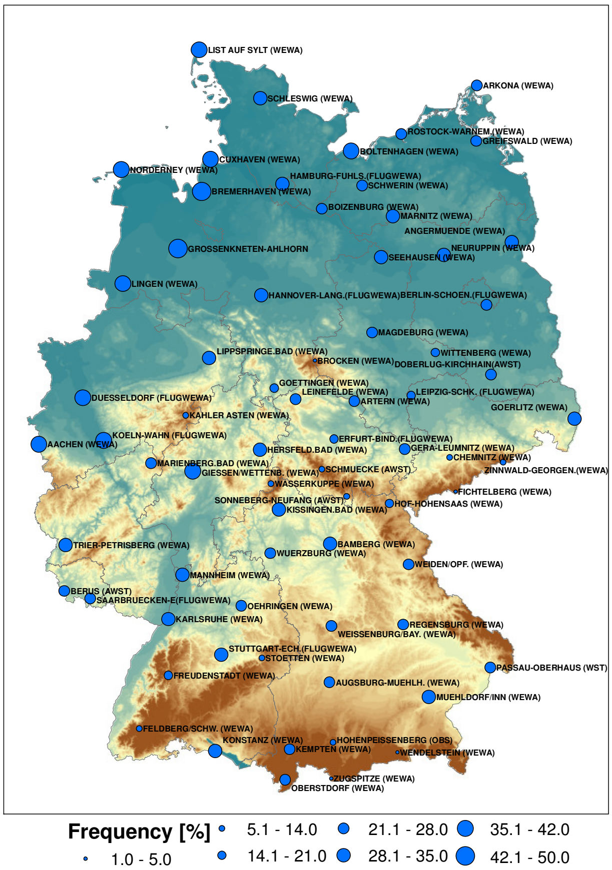


Fig. 6. Spatial distribution of wet snow ratio in Germany during the observation period 1980-1999. Background colour varies with altitude from blue (lowlands) to brown (mountainous areas).

B. Duration of Wet Snow Events and Seasonal, Monthly and Spatial Distribution of Wet Snow Hours

Wet snowfall events consist of several short living processes embedded in longer snowfall events. Different assessments of the duration of wet snow events are presented in Table 2.

Table 2. Maximum (Max.) and Mean consecutive (Con.) and cumulative (Cum.) duration (hours) of wet snow events

	Mean Con.	Max Con.	Mean Cum.	Max Cum.
Aachen	4	10	17	40
Bremerhaven	3	10	20	45
Freudenstadt	4	10	20	34
Grossenkneten-Ahlhorn	1	3	5	19
Hamburg	3	9	16	32
Hannover	3	10	19	39
Hersfeld	3	8	15	29
Kempten	4	11	18	45
Lingen	2	6	11	22
Lipsringe	4	11	20	72
Neuruppin	3	9	16	35
Schleswig	3	9	15	37
Stuttgart	4	12	22	45
Stötten	3	10	18	41
Weißenburg	3	8	13	22
Wittenberg	3	8	14	32

The first two columns are based on duration, counting only consecutive wet snow reports, and the other two columns are based on reports which are not consecutive but are still in snowfall conditions and/or the temperature remains below 0°C – i.e. a cumulative duration of a wet snow event. It can be seen that the last two durations exceed the first ones with up to 4 times of magnitude. This illustrates how difficult the estimation of the real duration of a wet snow event is.

It seams reasonable to expect that the seasonal wet snow hours should correlate in neighbor stations. On next four figures (Fig. 7 - Fig. 10) are presented the correlation graphs for three couple of neighbor stations: Giessen–Aachen, Hannover–Bremerhaven, Hannover–Hersfeld and Bamberg-Hersfeld. All these relations have high correlation coefficients – R of 0,8 or above.

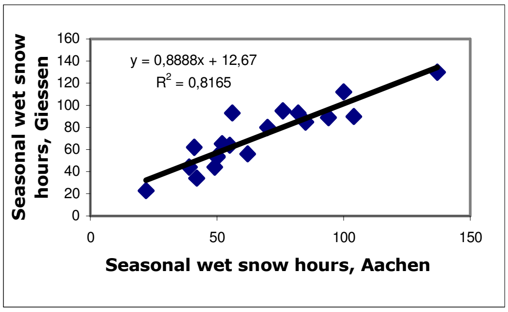


Fig. 7. Correlation of the seasonal wet snow hours Aachen–Giessen

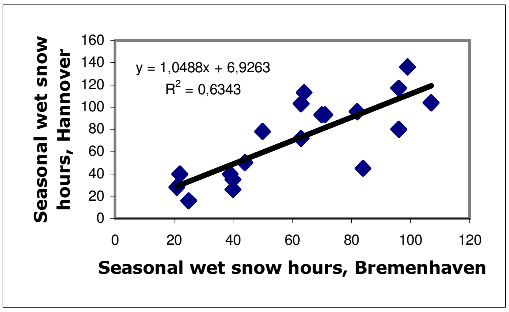


Fig. 8. Correlation of the seasonal wet snow hours Bremerhaven–Hannover

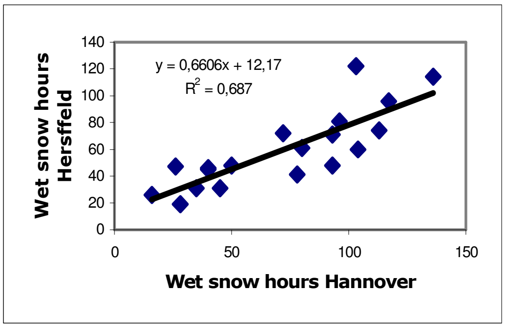


Fig. 9. Correlation of the seasonal wet snow hours Hannover–Hersfeld

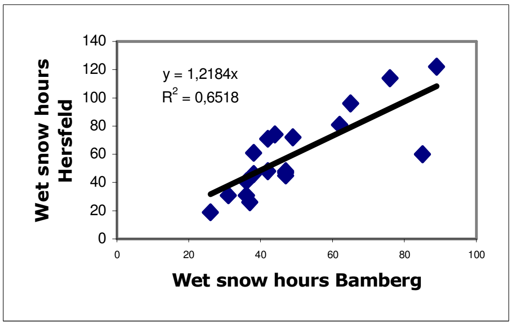
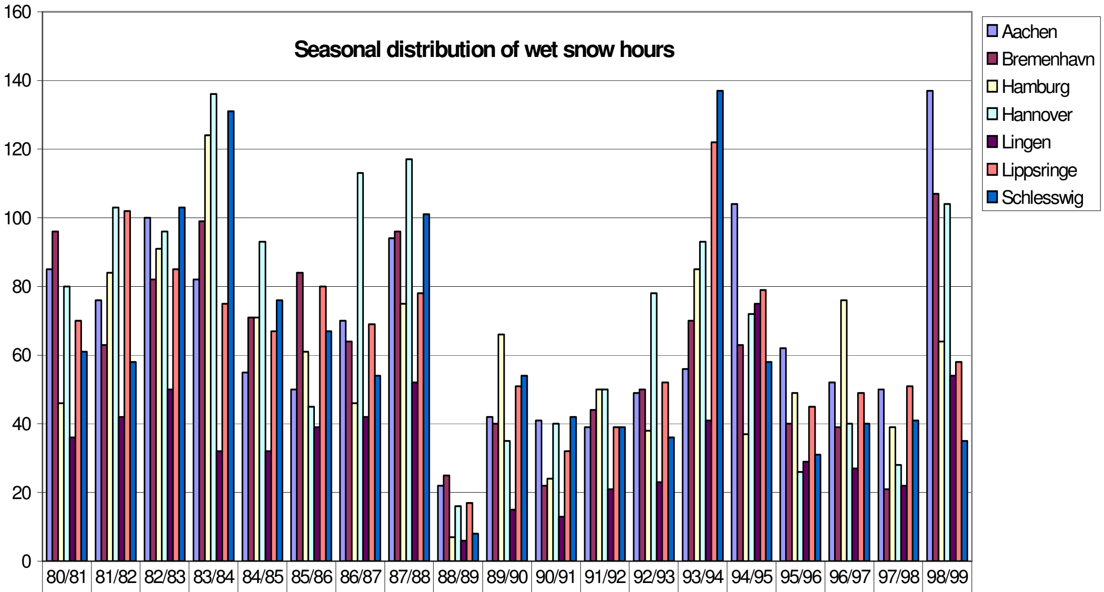


Fig. 10. Correlation of the seasonal wet snow hours Bamberg–Hersfeld



	80/81	81/82	82/83	83/84	84/85	85/86	86/87	87/88	88/89	89/90	90/91	91/92	92/93	93/94	94/95	95/96	96/97	97/98	98/99
Aachen	85	76	100	82	55	50	70	94	22	42	41	39	49	56	104	62	52	50	137
Bremenhavn	96	63	82	99	71	84	64	96	25	40	22	44	50	70	63	40	39	21	107
Hamburg	46	84	91	124	71	61	46	75	7	66	24	50	38	85	37	49	76	39	64
Hannover	80	103	96	136	93	45	113	117	16	35	40	50	78	93	72	26	40	28	104
Lingen	36	42	50	32	32	39	42	52	6	15	13	21	23	41	75	29	27	22	54
Lippsringe	70	102	85	75	67	80	69	78	17	51	32	39	52	122	79	45	49	51	58
Schlesswig	61	58	103	131	76	67	54	101	8	54	42	39	36	137	58	31	40	41	35

Fig. 11. Seasonal distribution of wet snow hours for the investigated period for some stations in north and northwest parts of Germany

Table 3 Relative frequency (%) of the wet snow hours and their possible period of appearance.

	Altitude, m	I	II	III	IV	V	X	XI	XII	S
Aachen	202,0	16,8	19,2	26,3	10,5	0,1	0,1	9,8	17,3	100,0
Augsburg	462,0	16,9	16,6	20,9	16,1	0,4	0,5	11,5	17,1	100,0
Bamberg	239,0	21,4	19,5	21,2	9,2	0,0	0,0	8,8	20,0	100,0
Bremenhav	7,0	22,6	20,2	23,1	6,4	0,2	0,0	9,0	18,6	100,0
Freudensta	797,0	11,8	10,7	22,3	22,3	4,2	4,7	12,2	11,7	100,0
Hamburg	11,0	20,4	17,7	21,3	11,6	0,3	0,2	12,7	15,9	100,0
Hannover	55,0	22,6	21,5	23,6	9,4	0,0	0,1	9,6	13,3	100,0
Hersfeld	272,0	18,7	16,6	22,2	12,2	0,0	0,0	10,2	20,1	100,0
Kempten	705,0	13,1	14,0	18,1	20,7	1,8	2,8	14,9	14,6	100,0
Lingen	22,0	20,9	18,2	26,5	9,8	0,0	0,0	10,8	13,8	100,0
Lipsringen	157,0	19,1	16,0	22,0	15,1	0,0	0,1	10,2	17,5	100,0
Muehlendo	405,0	15,1	18,4	21,5	15,1	0,0	0,8	10,6	18,5	100,0
Neurupin	38,0	16,5	19,8	21,2	11,1	0,0	0,1	12,2	19,1	100,0
Norderney	11,0	23,2	18,9	18,1	4,8	0,3	0,0	10,0	24,6	100,0
Obersfdorf	806,0	10,8	12,1	21,8	24,5	3,9	4,3	12,0	10,6	99,9
Schlesswig	43,0	20,7	14,2	25,5	11,4	0,1	0,0	9,8	18,2	100,0
Stotten	734,0	11,3	10,3	20,4	27,8	2,6	3,5	12,5	11,6	100,0
Stuttgart	371,0	19,6	18,4	19,1	11,4	0,2	0,5	8,7	22,0	100,0
Weissenbu	422,0	21,2	15,5	22,8	13,6	0,0	0,2	9,0	17,8	100,0
Wittenberg	105,0	15,5	18,9	21,5	14,6	0,0	0,0	9,8	19,6	100,0
Boltenhage	15,0	24,3	20,2	20,7	9,2	0,0	0,5	10,5	14,7	100,0
Boizenburg	45,0	19,8	18,1	26,6	14,6	0,3	0,0	5,7	14,9	100,0
Seehausen	21,0	20,7	22,5	24,2	9,2	0,0	0,2	7,8	15,4	100,0
Schwerin	59,0	18,5	19,9	22,5	12,1	0,2	0,5	10,5	15,7	100,0
Magdeburg	59,0	15,6	20,4	23,1	11,3	0,0	0,0	9,5	20,0	100,0
Goettingen	167,0	18,8	18,5	19,0	13,0	0,4	0,1	10,9	19,3	100,0
Duesseldo	37,0	23,4	21,8	23,1	5,3	0,0	0,0	8,9	17,4	100,0
Koeln	92,0	25,1	19,7	22,5	7,3	0,0	0,1	9,1	16,2	100,0
Cuxhavn	5,0	18,9	18,5	29,9	6,1	0,0	0,1	9,5	17,0	100,0
List	26,0	17,7	18,2	28,6	7,6	0,2	0,1	8,7	18,9	100,0
Arkona	42,0	21,5	18,8	21,1	11,6	0,2	0,7	10,6	15,6	100,0

The correlations of the seasonal wet snow hours for each station with all other stations were calculated. In general there is a good agreement in the seasonal regime and the correlations for seasonal wet snow hours. It could be found a good relation between close located stations showing high correlation coefficients – above 0,80. Nevertheless, some values for stations that are far away from each other are high only by chance.

Fig. 11 shows the seasonal distribution of wet snow hours for some stations in north and northwest parts of Germany with a good agreement between neighboring stations.

The possible wet snow periods spread from November till April for the low part of the country and from October till May for the some mountain regions (see Table 3). Most often the maximum of the wet snow occurs in March. Some regions show two maxima or an almost equal distribution of wet snow events during the winter. The maximum number of wet snow events at mountain stations occurs in April.

IV. SUMMARY

This study shows that the criterion proposed by Makkonen (1989) can be used for the analysis of wet snow conditions when no other information except standard meteorological data are available. The criterion has been used to analyze data of 70 meteorological stations evenly distributed over the territory of Germany. The results of analysis showed in general that wet snowfall events consist of several short living processes embedded in longer snowfall events. Wet snow ratios, the duration of the wet snow events and their spatial and temporal distributions were studied.

V. ACKNOWLEDGMENT

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VI. REFERENCES

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