RELATIONSHIP BETWEEN ICE FRAGMENTS IN CLOUDS AND PRECIPITATION PARTICLES DURING SNOW FALL EVENTS IN DEPENDENCY OF METEOROLOGICAL PARAMETERS – A CASE STUDY AT SONNBLICK OBSERVATORY, AUSTRIA

Veronika Krieger[1], Anna Heuberger[1], Julia Burkart[2], Elke Ludewig[2]

[1] *GeoSphere Austria – Avalanche Warning Service Salzburg, Salzburg, Austria*
[2] *GeoSphere Austria – Sonnblick Observatory, Salzburg, Austria*

ABSTRACT: The Sonnblick observatory is the highest observatory in Austria located on the peak of Rauriser Sonnblick at 3'106 m.s.l.. It is operated by Geosphere Austria, the national meteorological service of Austria. The observatory is equipped with a vast amount of measurement devices, related to meteorology, gases, aerosols and others. In addition to automated measurements, on-site observers deliver information about current snow and precipitation conditions on an hourly basis. Through this unique setup, we can explore possibilities in using long-term surveillance data from the observatory to forecast the type of precipitation particles reaching the snow surface and further test prospects to utilize the data in avalanche forecasting. As snow and ice is sensible to changes in temperature, humidity, evaporation and wind, the structure of the precipitation particles are expected to change within the cloud, in the atmosphere and from the moment they reach the snow surface. However, pictures of particles from the Observatory show that ice particles in clouds form distinct shapes such as dendrites, plates or needles, resembling new snow formations but at a smaller scale. Based on this observation, our research objective focuses on determining the extent to which ice formations in clouds provide structural information of precipitation particles reaching the snow surface. To investigate this objective, structural information of particles in a cloud are recorded using a measurement device (SwisensPoleno Jupiter) that provides holographic images. By comparing this information to standardized weather data and snow surface information from Sonnblick observers, we aim to test the predictability of precipitation particles from cloud particles. As a further step, the correlation between the well-accepted Nakaya snow crystal morphology diagram and cloud particles is assessed. In contrast to precipitation particles on the ground, particles in clouds are detected in a semi-automatic way at the Sonnblick Observatory. Therefore, knowledge about correlations between the original state of precipitation particles and their condition when they fall from the cloud can open up further research questions. A better understanding of new snow formations can be of benefit for avalanche forecasting as varying sizes and shapes of precipitation particles have a significant effect on the reactivity and duration of storm snow instabilities. With this case study we want to open up a discussion on further possible applications and analysis of the data in the field of snow metamorphism and avalanche forecasting.

KEYWORDS: snow crystals, crystal growth, holographic image, Nakaya diagram, in-cloud particles

1. INTRODUCTION

Crystal growth is a captivating and complex phenomenon that has been the subject of extensive investigation through both experimental studies (Nakaya, 1954; Libbrecht, 2005; Furukawa, 2015) and computational simulations (Reiter, 2005; Gravner and Griffeath, 2009; Barrett et. al., 2012; Demange, 2017). Over time, researchers have gained significant insights into the mechanisms and stages of crystal formation. It is therefore known that the process of crystal growth typically initiates with the formation of hexagonal prisms. These hexagonal prisms serve as the foundational structures from which diverse crystal shapes can develop, depending on the surrounding environmental conditions such as temperature, humidity, and supersaturation (Libbrecht, 2001).

The transition from simple hexagonal prisms to dendritic structures is of particular interest. Under atmospheric conditions, this transition generally occurs as the crystals increase in size. Specifically, it has been observed that up to a size of approximately 100 µm in diameter, the crystals predominantly remain in the form of hexagonal prisms (Libbrecht, 2005). Beyond this size threshold, the crystal growth can diverge into more complex morphologies, including dendritic patterns.

The final forms of snow crystals can be systematically categorized based on their distinct shapes, as outlined by Magono and Lee (1966). These shapes, which include plates, columns, needles, and dendrites, among others, result from the specific environmental conditions present during their formation. The well-known Nakaya morphology diagram, first introduced by Nakaya (1954) and further expanded upon by Kobayashi (1961) provides a detailed representation of how ambient atmospheric conditions—particularly temperature and supersaturation—directly influence the development of these different snow crystal shapes. This diagram not only highlights the sensitive connection between environmental variables and snow crystal morphology but also serves as a fundamental tool in the study of crystallography and meteorology, offering insights into the predictable patterns that govern snowflake formation.

In this study, we observe both the formation and precipitation of crystals, categorize crystal forms, and compare our observations with the monitored temperature, humidity, and supersaturation levels to determine whether the resulting crystal morphologies align with those described in the Nakaya diagram. Through this comparison, we aim to gain a deeper understanding of the relationship between atmospheric conditions and snow crystal formation, ultimately confirming or refining the accuracy of the Nakaya diagram.

2. MEASURING SITE AND METHOD

The Sonnblick Observatory (SBO), a premier climate and environmental research station operated by GeoSphere Austria, is positioned atop Rauriser Sonnblick at 3,106 meters above sea level. It hosts the ACTRIS European Center for Cloud Ambient Intercomparison (ECCINT), making it a critical hub for advanced atmospheric research. The SBO conducts extensive 24/7 monitoring in the atmosphere, cryosphere and biosphere which, in combination with ECCINT, now enables new analytical approaches in the field of precipitation and deposition linked to snow and avalanche conditions. Due to its high altitude location, the observatory is frequently enveloped in clouds. This setup provides a unique and invaluable opportunity to study the minute details of ice particle formation and growth within clouds, as well as the subsequent precipitation.

A key instrument used in this study is the SwisensPoleno Jupiter (Sauvageat et al., 2020), a sophisticated measurement device that is frequently deployed for the monitoring of pollen. The SwisensPoleno Jupiter instrument employs holographic imaging technology to capture detailed images of single particles that are drawn into its measuring chamber. For each particle two holographic images are obtained from perpendicular perspectives. The instrument samples air at 40 l/min and detects particles within the size range of 0.5 to 200 µm. It is protected within a weatherproof housing and installed outside at the Sonnblick measuring platform.

In our case study, images taken by the SwisensPoleno Jupiter were utilized to examine the smallest ice particles that were still in the process of growing within a cloud. At the same time, visual observations were made of snow freshly fallen from the cloud onto a crystal screen. The data collection spanned four days, with observations divided into eight distinct periods. The holographic images are classified according to the Magono-Lee classification, the visual observations are assigned to the standard crystal forms (needles, plates, dendrites). This methodical approach allowed for a comprehensive analysis of the ice particles and the environmental conditions under which they formed.

3. RESULTS

Examples of the holographic images captured by the SwisensPoleno Jupiter are presented in Figure 1. A significant portion of the automatically recorded data comprised fine water droplets (as expected for mixed-phase clouds typically occurring at Sonnblick outside of summer), which were easily filtered out due to their relative small size (typically less than 20 µm in diameter) and spherical shape. The remaining images contained a variety of ice crystal shapes,

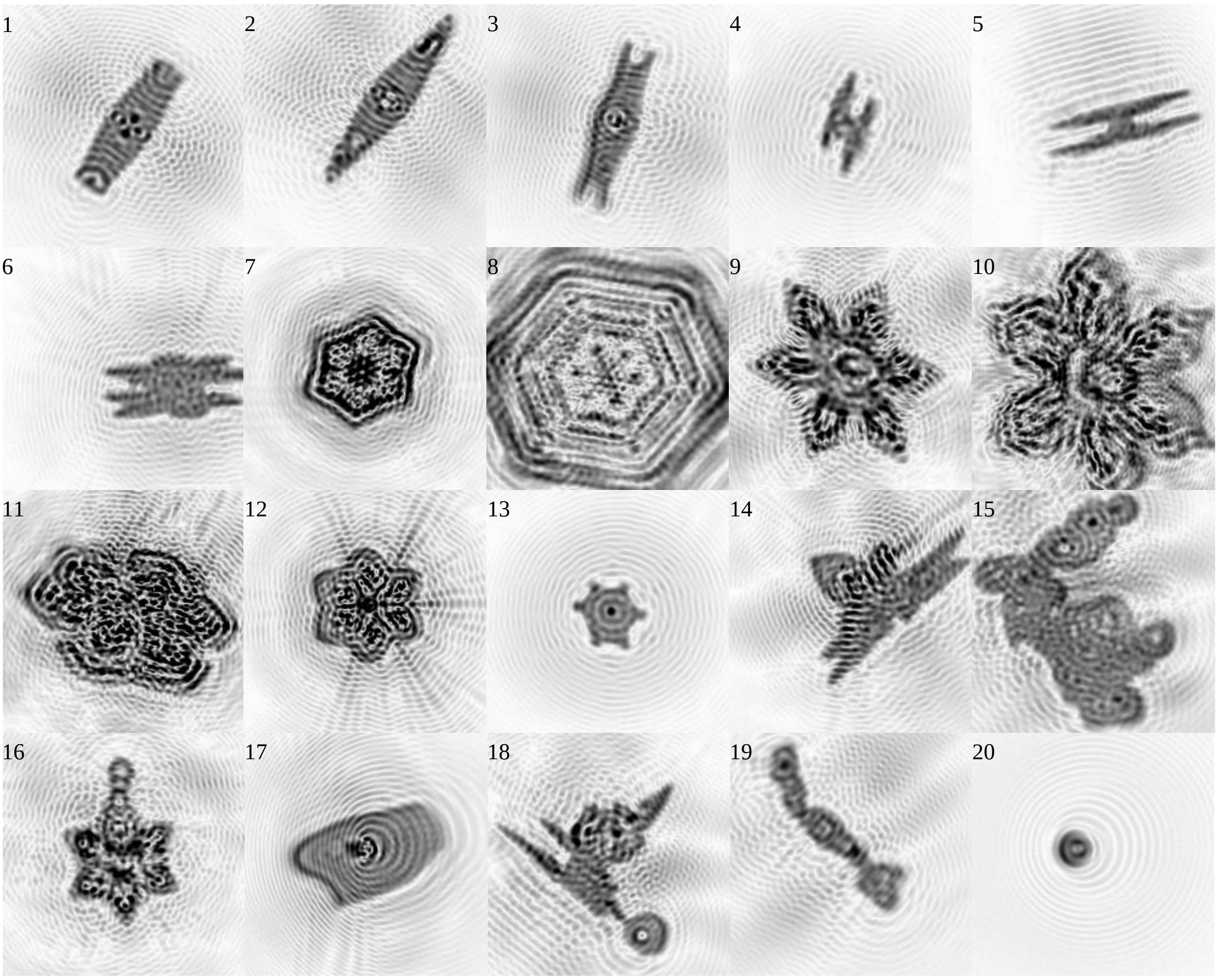


Figure 1: Examples of holographic images of ice crystals taken by SwisensPoleno Jupiter. 1-4: columns and needles, 4-6: column plates, 7-13: different forms of hexagonal plates, 14-19: mixed forms, 20: water droplet for comparison.

such as heavily sleeted crystals, different types of hexagonal plates needles and mixed forms (see Figure 1).

To analyze the distribution of crystal shapes, the photos were classified using the Magono-Lee classification (Magono and Lee, 1966). Most of the crystals shapes found were those with the names shown in Table 1.

Table 1: Most commonly observed crystal forms according to Magono and Lee (1966).

Nomenclature	*Characteristics*
N1a	Elementary needle
C1f	Hollow column
P1a	Hexagonal plate
P1b	Sector plate
P1c	Broad branch
CP1a	Column with plates

From the dataset, only those shapes that were clearly identifiable were selected for classification, ensuring accuracy and precision in the results. Thus, out of the initial pool of 3,507 pre-filtered holographic images, 967 were successfully classified into specific crystal categories. The details of this classification, broken down by time slot, are summarized in Table 2. The study revealed a notable distribution of crystal shapes across the different observation days. A particularly striking difference was observed between the days at the end of March and those in mid-April, both in terms of the types of crystals recorded and the percentage of holographic images that could be classified.

During the early days of March, the predominant snow crystal formations observed were needles and columns. In April, different meteorological conditions prevailed, and the crystal formations transitioned notably to columns and plates (see Figure 2). This change in crystal types reflects the natural response of crystal growth processes to the evolving environmental conditions.

Table 2: Timeslots with amount of observations and according classification.

No.	*Timeslot (UTC)*	*Total after automatic filtering*	*classifi-cations*	*pro-portion [%]*
0	27.03. 11:00-12:00	134	2	1.5
1	27.03. 12:00-16:30	358	5	1.4
2	29.03. 10:35-10:55	256	1	0.4
3	29.03. 14:55-15:15	78	1	1.3
4	20.04. 7:40-8:10	230	85	37.0
5	20.04. 12:10-12:40	682	290	42.5
6	25.04. 11:15-11:35	389	45	11.6
7	25.04. 12:10-12:30	1380	538	39.0
	total	3507	967	27.6

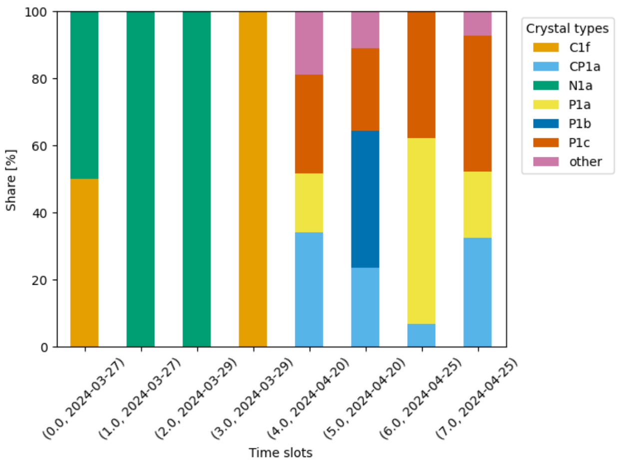


Figure 2: Distribution of snow crystal shapes during the observation time. For each time slot the three most common crystal shapes are shown, less frequent shapes are grouped under ‚other‘.

Figure 3 and Figure 4 illustrate the differences in the meteorological conditions, showing that temperatures were at least 2°C higher on the days in March compared to those in April, and the relative humidity was approximately 5% higher. According to the Nakaya snow crystal morphology diagram (Nakaya, 1954), which predicts crystal morphology based on temperature and supersaturation, these temperature and humidity ranges suggest that the precipitation particles observed in March were more likely to form as needles or columns. Conversely, in April, the cooler temperatures and lower humidity were more conducive to the formation of columns or solid prisms (see Figure 5). The agreement between SwisensPoleno Jupiter and the Nakaya diagram is good. For the time slots 4 to 7, however, the measurement tends to indicate plates, which according to theory tend to occur at lower temperatures.

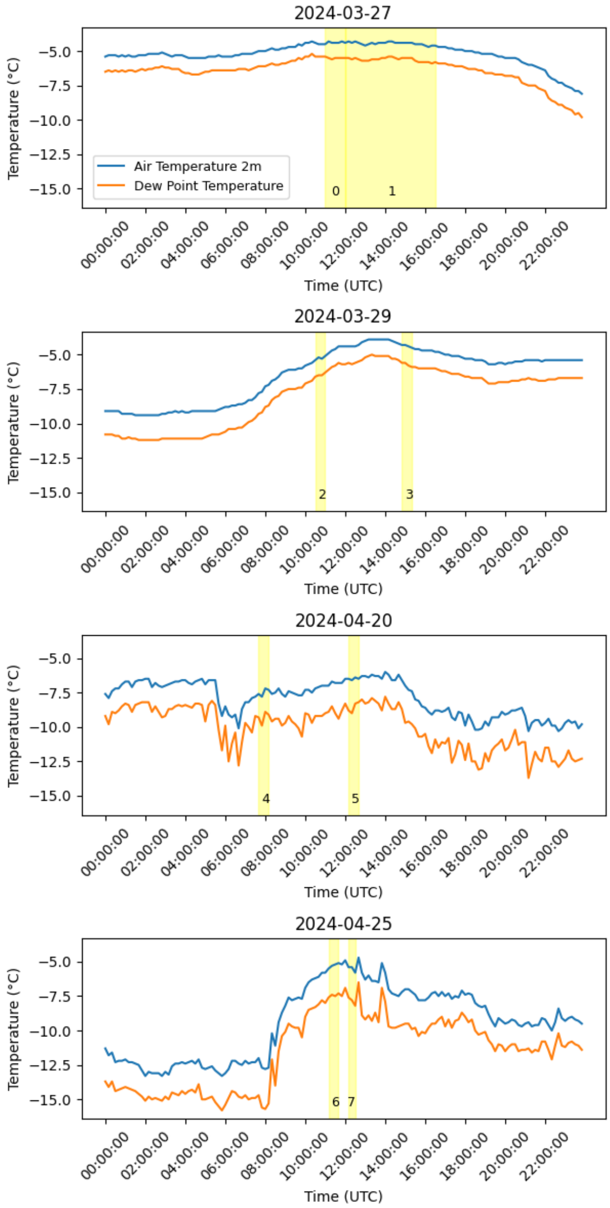
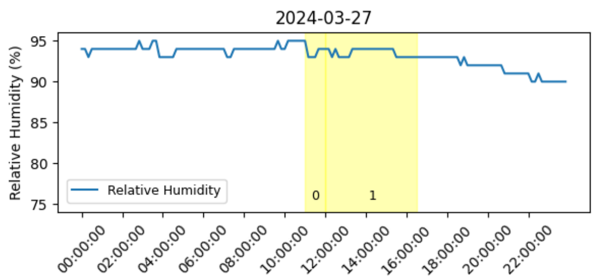


Figure 3: Temperature (2m) and dew point temperature measurement from automatic weather station at the Sonnblick Observatory. SwisensPoleno Jupiter observation time slots are highlighted in yellow.



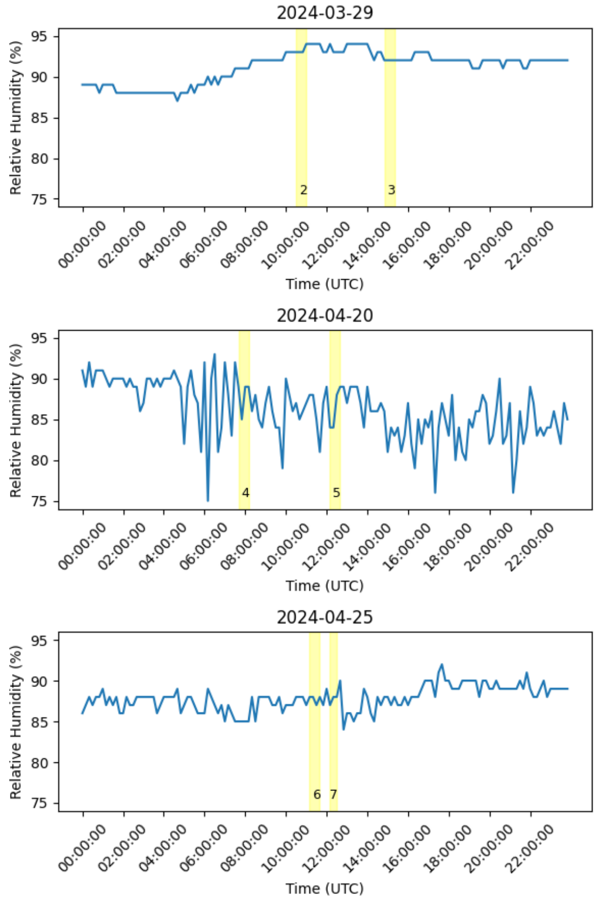


Figure 4: Relative humidity measurement from automatic weather station at the Sonnblick Observatory. Observation time slots are highlighted in yellow.

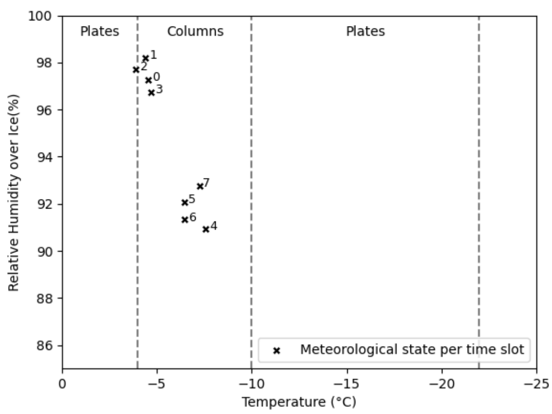


Figure 5: Meteorological states during the observed timeslots. Indicated transitions between plates and columns according to the Nakaya diagram (Nakaya, 1954).

Moreover, it is important to note that the holographic images captured by the SwisensPoleno Jupiter do not always correspond perfectly to the visually observed precipitation particles at first glance (see Table 3, more detailed comparison can be found in the appendix in Table 4). The visual observations of the precipitation particles were conducted using a crystal screen (see Figure 6). Therefore, the classification is coarser.

Table 3: Comparison of predictions according to Nakaya (1954), the SwisensPoleno Jupiter measurements and observations.

No.	*Prediction (Nakaya 1954)*	*Frequent crystal forms SwisensPoleno Jupiter*	*Frequent crystal forms observation*
0	needles, columns	C1f , N1a	needles
1	needles, columns	N1a	plates, needles, columns
2	needles, columns	N1a	needles, columns
3	needles, columns	C1f	sleet, needles
4	columns, prisms	CP1a, P1c, P1a	dendrites
5	columns, prisms	P1b, P1c, CP1a	dendrites
6	columns, prisms	P1a, P1c, CP1a	dendrites
7	columns, prisms	P1c, CP1a, P1a	dendrites

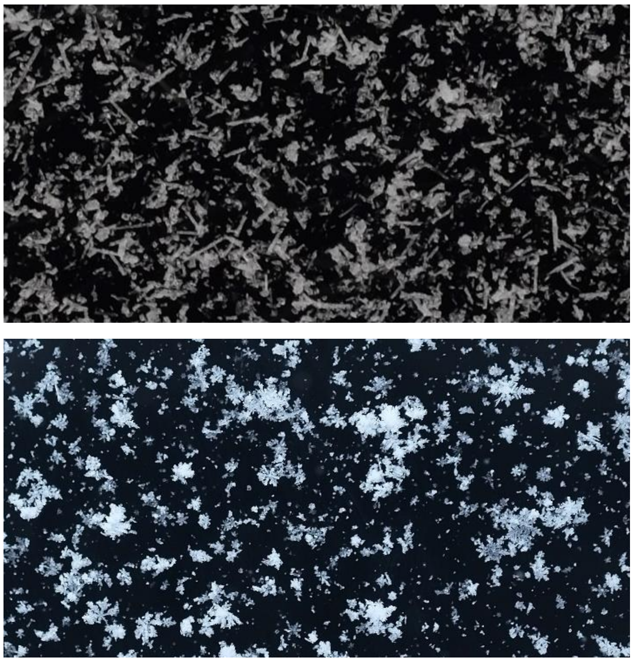


Figure 6: Examples of precipitation particles observations on March 27th (above) and April 20th (below).

Timeslots 0 and 2 align well with observations, showing a predominance of needles. Timeslots 1 and 3 show partial consistency, with some crystals matching expected forms. However, in Timeslots 4 to 7, a noticeable discrepancy arises: while visual observations clearly show dendrites, SwisensPoleno Jupiter measurements predominantly indicate plates or columns with plates. This discrepancy likely stems from the particle sizes measured; smaller particles are less likely to develop into fully formed dendrites, which typically require larger sizes to manifest. Additionally, the observed plates were often sector plates (P1b) or already showed broad branches (P1c), indicating that plate growth had already become unstable (see Figure 2). The corners of the plates accumulate more water molecules, ultimately leading to a dendritic shape (Libbrecht, 2001).

Nevertheless, the Nakaya diagram also does not match these observations, as dendrites typically form at temperatures above -4°C or below -10°C, necessitating further investigation. One possible explanation is that the dendrites originated from higher, colder air layers. Although the Sonnblick observatory was surrounded by clouds at the time, the crystals may not have to have formed near the meteorological measuring station itself.

4. DISCUSSION AND OUTLOOK

In conclusion, the measurements obtained in this study are valuable, as they provide simultaneous examination of ice crystals within clouds and the precipitation particles, which is crucial for understanding crystal morphology under varying atmospheric conditions. The observed mismatch, where the SwisensPoleno Jupiter identified plates while visual observations showed dendrites, can be attributed to the subtle transitions between crystal forms—such as sector plates evolving into dendrites as they grow in size—which may not be fully captured by the measurement device due to the inlet geometry. To overcome these discrepancies, future studies could combine the Poleno measurements with more refined visual analysis techniques or use additional imaging technologies that can capture a wider range of crystal sizes and forms.

The holographic images of in-cloud particles align well with the Nakaya morphology diagram, affirming its accuracy. Nevertheless, the discrepancy with visual observations calls for further investigation.

The crystal shapes identified by the Nakaya diagram are not only visually distinctive but have significant implications for snowpack properties. Despite the spatial variability of meteorological conditions, this information is crucial. Near weather stations, one can estimate the crystal shapes that are likely to form. This information can then be incorporated into avalanche forecasts. For example, if the environmental conditions suggest the formation of plate-like crystals, developing non-persistent weak layers are more prone to collapse compared to other conditions and snow crystals (Bair et al. 2012).

ACKNOWLEDGEMENT

We wish to express our sincere gratitude to the team at Sonnblick Observatory for their invaluable support in providing the photos of snowflakes and the associated data for this study. Their meticulous work and generous sharing of resources have greatly contributed to the depth and quality of our research.

REFERENCES

Bair, E. H., Simenhois, R., Birkeland, K., Dozier, J.: A field study on failure of storm snow slab avalanches, Cold Regions Science and Technology, 79–80, 20-28, https://doi.org/10.1016/j.coldregions.2012.02.007, 2012.

Barrett, J. W., Garcke, H., & Nürnberg, R.: Numerical computations of faceted pattern formation in snow crystal growth. Physical Review E—Statistical, Nonlinear, and Soft Matter Physics, 86(1), 011604, https://doi.org/10.1103/PhysRevE.86.011604, 2012.

Demange, G., Zapolsky, H., Patte, R., & Brunel, M.: A phase field model for snow crystal growth in three dimensions. npj Computational Materials, 3(1), 15, https://doi.org/10.1038/s41524-017-0015-1, 2017.

Furukawa, Y.: Snow and ice crystal growth. In Handbook of crystal growth (pp. 1061-1112). Elsevier, https://doi.org/10.1016/B978-0-444-56369-9.00025-3, 2015.

Gravner, J., & Griffeath, D.: Modeling snow-crystal growth: A three-dimensional mesoscopic approach. Physical Review E—Statistical, Nonlinear, and Soft Matter Physics, 79(1), 011601, https://doi.org/10.1103/PhysRevE.79.011601, 2009.

Kobayashi, T.: The growth of snow crystals at low supersaturations, Philosophical Magazine, 6:71, 1363-1370, https://doi.org/10.1080/14786436108241231, 1961.

Libbrecht, K. G.: Morphogenesis on ice: The physics of snow crystals. Engineering and Science, 64(1), 10-19, 2001.

Libbrecht, K. G.: The physics of snow crystals, Reports on progress in physics, 68(4), 855, http://dx.doi.org/10.1088/0034-4885/68/4/R03, 2005.

Magono, C., & Lee, C. W.: Meteorological classification of natural snow crystals, Journal of the Faculty of Science, Hokkaido University. Series 7, Geophysics, 2(4), 321-335, 1966.

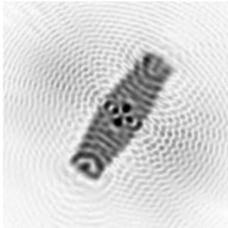
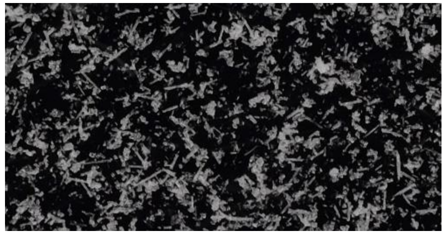
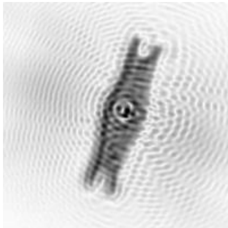
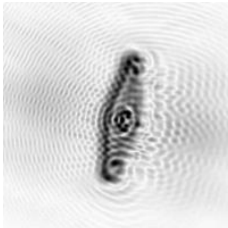
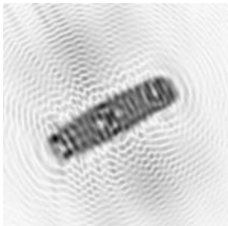
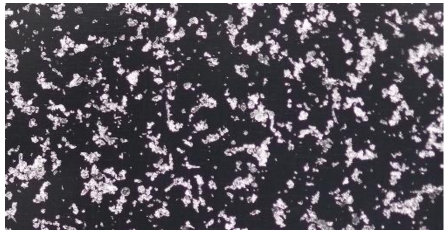
Nakaya, U.: Snow crystals: natural and artificial, Harvard University Press, https://doi.org/10.4159/harvard.9780674182769, 1954.

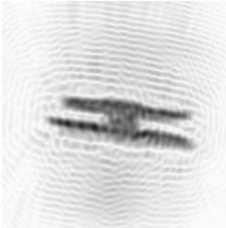
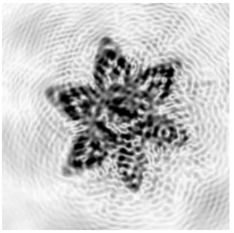
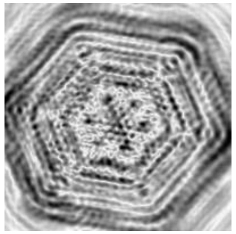
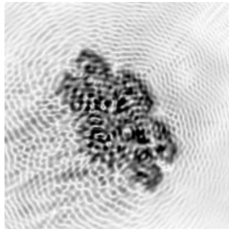
Reiter, C. A.: A local cellular model for snow crystal growth, Chaos, Solitons & Fractals, 23(4), 1111-1119, https://doi.org/10.1016/j.chaos.2004.06.071, 2005.

Sauvageat, E., Zeder, Y., Auderset, K., Calpini, B., Clot, B., Crouzy, B., Konzelmann, T., Lieberherr, G., Tummon, F., and Vasilatou, K.: Real-time pollen monitoring using digital holography, Atmos. Meas. Tech. 13, 1539–1550, https://doi.org/10.5194/amt-13-1539-2020, 2020.

APPENDIX

Table 4: Timeslots with corresponding crystal types, exemplary holographic image and visual observations.

No.	*Timeslot*	*Frequent crystal types SwisensPoleno*	*Exemplary holographic image*	*Frequent crystal typess observation*	*Visual observation*
0	27.03. 11-12 UTC	C1f , N1a		needles	
1	27.03. 12-16:30 UTC	N1a		plates, needles, columns	
2	29.03. 10:35-10:55 UTC	N1a		needles, columns	
3	29.03. 14:55-15:15 UTC	C1f		sleet, needles	

No.	*Timeslot*	*Frequent crystal forms SwisensPoleno*		*Frequent crystal forms observation*	
4	20.04. 7:40-8:10 UTC	CP1a, P1c, P1a		dendrites	
5	20.04. 12:10-12:40 UTC	P1b, P1c, CP1a		dendrites	
6	25.04. 11:15-11:35 UTC	P1a, P1c, CP1a		dendrites	
7	25.04. 12:10-12:30 UTC	P1c, CP1a, P1a		dendrites