by Kevin Hammonds

CRYSTALLIZING OPINION

Ultra-high-speed cameras are being used to study snowflake formation

Numerical weather models misdiagnose the huge variety of frozen hydrometeors that fall, but scientists from the University of Utah have developed a way to accurately predict where and how snow will fall

The report said, "The wrong type of snow…" covered the railroad tracks, and it was too powdery to be easily cleared. This was how British Rail famously excused a long week of disruptions to train service in February 1991. Angry commuters were unsympathetic: it smacked of the absurd to use snowflakes as a scapegoat.

Public opinion aside, accurately forecasting snowflake type is in fact a genuine meteorological challenge. Very often, numerical weather models fail to provide accurate forecasts of snowfall accumulation precisely because they misdiagnose the wide variety of frozen hydrometeors that fall from the sky. Slight adjustments to how snowflakes are created in the models make for large differences in where simulated snow lands, and whether it descends as gentle flurries or as a fully fledged blizzard.

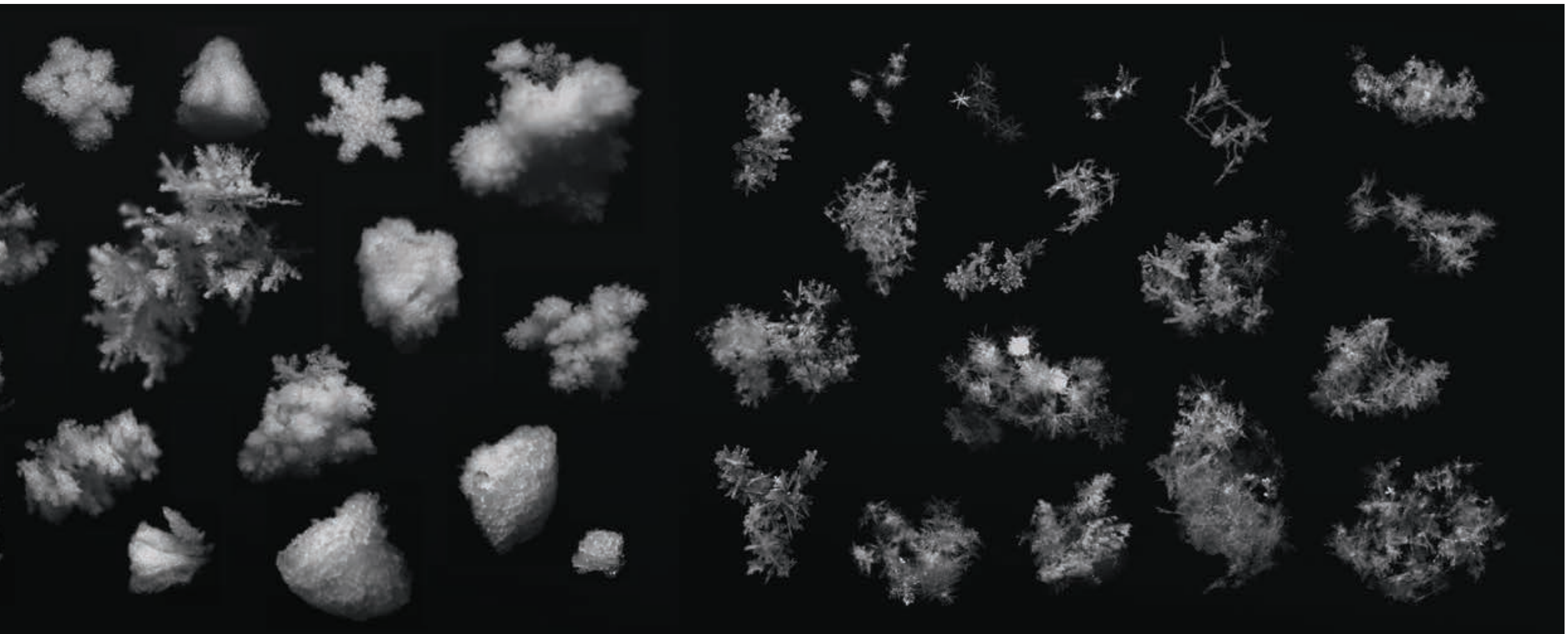
An added concern is that the type of snow can dramatically influence visibility in a storm. For an equivalent snowfall rate, driving conditions might be fairly clear and benign, or they could impose dangerous whiteout conditions, all dependent on hydrometeor shape and size. Incorrect assumptions equating high visibility to low precipitation rates have even contributed to past aviation accidents (see inset: USAir Flight 405, March 22, 1992).

Graupel and aggregates

Rarely, and only in very still conditions, do snowflakes arrive at the ground as the simple six-sided ice crystals that most people imagine. More often, frozen hydrometeors in winter storms consist of shapes and sizes that lie along a spectrum of snowflake possibilities.

At one end of the spectrum, a snowflake falls through a cloud layer of super-cooled liquid water droplets. The droplets freeze on impact with the snowflake in a process known as 'riming'. Very heavy snowflake riming leads to the formation of 'graupel' pellets, each having experienced a million such collisions during an increasingly rapid descent.

At the other extreme are aggregates, which are composed of many smallish dendritic ice crystals that have collided with each other repeatedly until becoming completely entangled. Not too dissimilar



The many types of snowflake, from large aggregate to rimed and graupel, photographed using the MASC

USAIR FLIGHT 405, MARCH 22, 1992

On the tarmac at New York's LaGuardia Airport, the First Officer of a USAir Fokker F28 described the snowfall as "not heavy, no large flakes". The airplane spent half an hour with no further de-icing. Then at take-off, with 51 passengers on board, the airplane failed to gain any more than a few meters of clearance from the ground. After striking several obstacles, the aircraft skidded off the runway into Flushing Bay. Twenty-seven died in the tragedy.

Failure to undergo proper de-icing procedures at LaGuardia was what doomed the aircraft. But a 1990s study led by Roy Rasmussen of the National Center for Atmospheric Research suggested that the root cause was a hazard termed 'high visibility, high snowfall rate conditions'. Wet and rimed snow falls very quickly. But even if the snowfall rate is high, the hydrometeors are compact and they do not impede visibility nearly as efficiently as would large and fluffy aggregated flakes. Under these conditions, high snowfall and rapid icing conditions can be missed where visibility alone is used to assess snowfall rates, as had happened at LaGuardia. The results highlighted the importance of determining hydrometeor form for helping to avoid aircraft icing in winter.

from feathers in a down pillow, fluffy aggregates present themselves as large and bulky, but are actually filled with pockets of air among intertwined tendrils of ice.

While large amounts of powdery, aggregated snow can make for terrific skiing or sledding, it is also the stuff of blizzards. For an equivalent hydrometeor mass, an aggregated snowflake blocks light much more efficiently than one that is more compact and heavily rimed. Rarely does heavily rimed snow lead to whiteout conditions, even if snow rates are heavy. This is because most of the mass is 'hidden' within the hydrometeor's densely coated shell. Conversely, the mass of large fluffy aggregated flakes is spread out over a large area and blocks light efficiently. Aggregates are the hallmark of whiteout conditions experienced in true blizzards.

Imaging frozen hydrometeors

How can we monitor frozen precipitation type? Current weather stations provide systematic measurements of wind, temperature, humidity and precipitation rates. Networks of these measurements enable us to diagnose current weather conditions and to evaluate and improve the accuracy of weather models.

But identifying hydrometeor size and riming extent is more challenging. Sometimes Present Weather Sensors are available. These can classify precipitation type, not by looking directly at the hydrometeors in freefall, but rather at how they scatter a beam of light. Unfortunately, correlating scattered light intensity with hydrometeor type is a difficult problem at best.

A few research instruments actually image snowflakes while they are in freefall, but only as very coarse resolution silhouettes. Collections of their pictures are often adequate for creating size distributions and for discriminating snow from rain. Nonetheless, they must be supplemented with manual observations in order to assess the extent of riming.

The Multi-Angle Snowflake Camera, or MASC, addresses these shortcomings. Developed by engineer Cale Fallgatter and atmospheric scientist Tim Garrett at the University of Utah in Salt Lake City, the MASC takes high-resolution triplet photographs of snowflakes in freefall, from three different angles, while simultaneously measuring their fallspeed. Snowflakes pass by two sets of infrared motion sensors, each sufficiently sensitive to pick up snowflakes as small as a grain of table salt. The sensors are vertically stacked so that the time between 'blips' indicates how fast the snowflake falls.

The bottom set of motion sensors triggers three high-speed industrial cameras with an exposure time of at most 1/25,000th of a second. Illumination of each hydrometeor is supplied by three high-power LEDs. The snowflake image resolution, depth-of-field and field-of-view depends on the type of camera body and lens that is chosen. For example, a 5MP camera with a 12mm lens has a 27µm resolution. With a 25mm lens the resolution is as fine as 14µm, although the depth of field is halved.

Currently, the MASC is snapping photos of hydrometeors in the Wasatch Mountains near Salt Lake City as part of the Wasatch Hydrometeor Aggregation and Riming Experiment. Funded by the National Science Foundation, project leads Tim Garrett and Sandra Yuter aim to use the data to help improve weather forecast models.

SECRETS OF THE SNOWPACK

A commonly heard saying among avalanche forecasters is, "The snowpack is just like us in many ways: it does not like rapid change." Dynamic mountain snowstorms and periods of rapid warming can have an immediate effect on the stability of what may already be a feebly structured snowpack.

But forecasters on the whole add the caveat that, "Ultimately, it is the strength of underlying layers in the snowpack that determine whether a slope will avalanche." The challenge is that it is difficult to obtain a keen sense for the strengths or weaknesses in the layering or stratigraphy of the snowpack. Stratigraphy is not as readily measured as the meteorology involved, as there are no satellite observations, temperature sounding profiles, or high-powered predictive models for the state of the snowpack interior.

Clues may come from knowledge of hydrometeor form. Since the 1960s, the size, shape and the extent of riming or aggregation of snowflakes have been thought to affect the density and distribution of weak layers within a snowpack. Post-doctoral research scientist and former Mammoth Mountain ski patroller, Ned Bair, has adapted the MASC for avalanche-related research on behalf of the US Army Corps of Engineers Cold Regions Research and Engineering Laboratory.

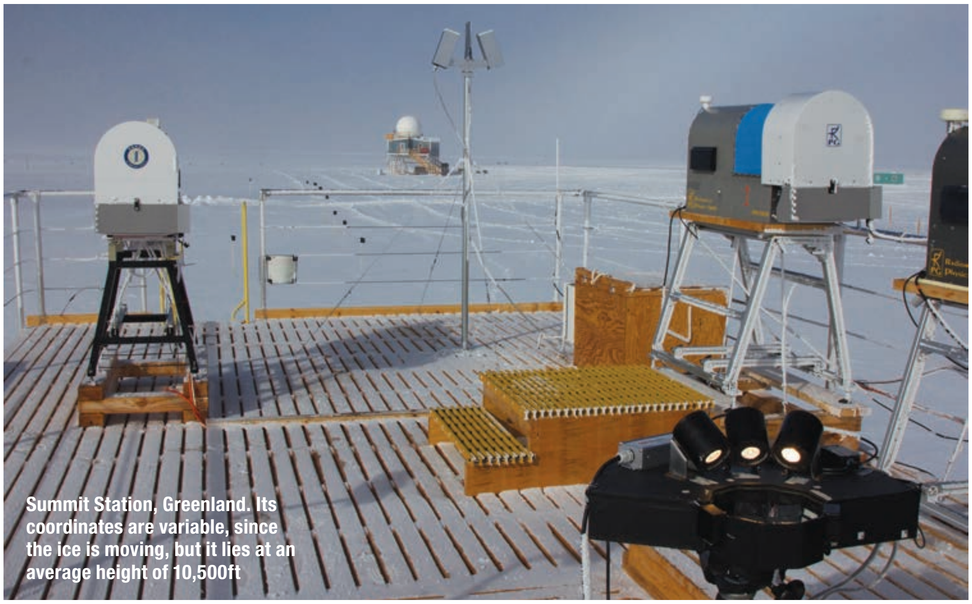
Because faceted crystals are typically the culprits of persistent weak layers within a snowpack, it is desirable to be able to link the properties of the original hydrometeor form to the rate at which its faceting may occur. Observations such as these can then be correlated with measurements of snow depth, snow water equivalent, and nearby avalanche occurrence records, in an effort to determine if a specific hydrometeor type is more susceptible than others in becoming the root cause of an avalanche.

The MASC installed at Alta in Greenland

Within the bounds of the Alta Ski Area, two MASCs have been deployed at different elevations on the same aspect of the mountainside. Other instruments are measuring fog droplets, typical weather station variables, and Doppler radar vertical profiles. Combined, this data is being used to assess the vertical development of aggregation and riming, how it affects hydrometeor fallspeed, and how it depends on local meteorology.

The effect on weather

The MASC can collect as many as tens of thousands of triplet images of snowflakes within a single day, each triplet having its own measured fallspeed. The range of hydrometeor forms that is observed is nothing short of extraordinary: simple stellar flakes or capped columns; graupel; powdery aggregates; and complex assemblages of everything in between. As each snowflake falls through the sky, subtle changes in temperature and humidity alternately favor columns, plates, dendrites or needles. Only rarely does a snowflake manage to reach the ground untouched by collisions with other snowflakes or with a cloud of liquid droplets.



Summit Station, Greenland. Its coordinates are variable, since the ice is moving, but it lies at an average height of 10,500ft

Certainly there are times when only rimed graupel particles fall, or when fluffy aggregates dominate. But transitions between the two sometimes happen over a space of minutes or even seconds. During many storms, the extent of snowflake riming by droplets lies along a continuum. And heavily rimed snowflakes might be mixed in with pristine snowflakes that have fallen to the ground largely unscathed. Often, there is no obvious way to neatly categorize a snow event as belonging to one species or another.

In post-analysis, computational routines are being used to automatically sift through the thousands of images that are collected, and to determine snowflake concentrations, sizes, fallspeeds and riming extent as a storm progresses. A continuum in riming is being characterized objectively in terms of a 'complexity' parameter. Complexity is defined as the ratio of the hydrometeor perimeter to the circumference of a circle that has the same cross-sectional area. Heavily rimed snowflakes tend to be more rounded and have a ratio closer to unity.

More qualitatively, changes in snowflake type are being monitored in real time. The Snowflake Showcase website hosted by Alta Ski Area displays MASC images of snowflakes in freefall. In addition to providing an immediate indication of the types of snowflakes flowing through the mountains, local skiing connoisseurs can use the pictures to anticipate deep powder or creamy graupel ahead of their excursions to the slopes.

A third MASC is currently in operation at Mammoth Mountain Ski Area in the Sierra Nevada through a purchase by the US Army Cold Regions Research and Engineering Laboratory (CRREL). Also, in summer 2012, a University of Utah MASC made a journey to the summit of the Greenland Ice Sheet (see left: MASC goes to Greenland). A comparison of images between the locations reveals marked

MASC GOES TO GREENLAND

Travelling abroad for the first time, the MASC visited the barren, icy and bitterly cold Summit Station of the Greenland Ice Sheet for a three-month deployment over the summer of 2012.

Located just north of the Arctic Circle at an elevation of 10,551ft above sea level, Summit Station is home to the Greenland Environmental Observatory and acts as host to numerous atmospheric and glaciological research experiments. Primarily deployed as a research and development opportunity for Fallgatter Technologies, the MASC was mounted alongside atmospheric remote sensing instrumentation that is part of the ICECAPS (the Integrated Characterization of Energy, Clouds, Atmospheric state, and Precipitation at Summit, Greenland) atmospheric research campaign sponsored by the National Science Foundation. Over the course of the summer season, the MASC was able to capture a wide variety of ice particle images, ranging from pristine hexagonal plates to heavily rimed dendritic aggregates, and even the elusive 'diamond dust'.

The MASC in Greenland fared remarkably well with the cold temperatures and riming conditions, but it was challenged by a lack of surrounding topography on the ice sheet. With no major barrier to atmospheric flow, winds tended to whip by. Without access to a wind shield, this made it difficult for the MASC to record images of 'falling' snowflakes that were instead being blown horizontally to destinations unknown. Fortunately, the MASC was mounted to a sturdy tripod with a full range of motion. Tilted vertically, the MASC's focal area could instead become a point for measurement of the flux of horizontally transported hydrometeors.

'Blowing snow' is believed to be a significant player in the spatial distribution of melt pond formation on the Arctic Ocean ice pack. Instruments such as the MASC may be well equipped to study such phenomenon in greater detail.

"A continuum in riming is being characterized objectively in terms of a 'complexity' parameter"

A MASC at Greenland Summit with a Greenland snowflake (inset)

differences in the types of hydrometeors that fall. Perhaps not surprisingly, riming is seen less often in hydrometeors sampled in the cold of Greenland Summit than in those seen in the Sierra Nevada.

In March 1992 a USAir Fokker F28 crashed, killing half the passengers. The accident was put down to not understanding the correct icing type

Looking ahead

The MASC is currently being distributed commercially through Fallgatter Technologies, a start-up company spun-off from the University of Utah in 2012. In addition to a sale to the US Army CRREL for avalanche research, external interest in the MASC technology has been focused on the MASC's ability to provide multi-angle views of frozen hydrometeors. Relating Doppler radar returns to a snowfall rate requires physical models of how hydrometeors interact with a beam of microwave radiation. As a first step, these models are based on some understanding of three-dimensional hydrometeor form.

The degree of riming can dramatically change how efficiently the mass of a snowflake turns an incoming microwave pulse into a back-scatter detectable such as a radar return. A lack of extensive observations of snowflake form has meant that estimates of typical hydrometeor shapes have been little more than educated guesswork. Scattering models have often assumed that snowflakes have six-sided symmetry, even though such flakes are in fact quite rare.

The MASC has the potential to improve this situation by providing extensive statistics for the true variability in hydrometeor form. In the longer term, the potential exists for strategically configured networks of MASCs to help remotely diagnose hydrometeor type along roads or at airports, as well as being able to validate weather prediction models. More comprehensive assessments of variations in frozen precipitation will be needed to alert the public to visibility hazards and to improve forecasts of snowfall from cold weather storms. ∎

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