THE MULTI-ANGLE SNOWFLAKE CAMERA

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ABSTRACT: We introduce a new instrument called the Multi-Angle Snowflake Camera (MASC). The MASC provides 10 to 40 μm resolution stereoscopic images of individual hydrometeors in freefall, while simultaneously measuring their fallspeed. Previously, manual photography of hydrometeors required collection on a flat surface, a process that is somewhat subjective and remarkably finicky due to the fragile nature of the particles. By contrast, the MASC is fully automated, and uses a sensitive IR trigger so that no physical contact is necessary. Field measurements at Alta and Mammoth are showing an extraordinary variety of hydrometeor forms. The MASC has many potential applications. We highlight three current projects: 1) improving understanding of the size-fallspeed relationships that are used to characterize precipitation in Doppler radar retrievals and numerical weather prediction models, 2) identifying weak crystals that form failure layers in avalanches during storms, and 3) using MASC measurements in conjunction with a scanning terrestrial LiDAR to estimate precipitation rates during storms.

KEYWORDS: precipitation, photography, fallspeed

1 INTRODUCTION

Despite dramatic progress in numerical weather prediction over the past several decades, a long-standing Achilles heel of mesoscale forecasting models is representation of precipitation microphysics. Microphysical processes are complicated to simulate, while modeled storm lifetime and precipitation rates are exquisitely sensitive to what types of hydrometeors form, and how fast they grow and fall.

Hydrometeor form is also relevant for making calculations of the hydrometeor electromagnetic scattering characteristics required for remote sensing applications and microwave communications. Radar measurement is based on the intensity of back-scattering by snowflakes, while radiometer measurement is based on the reduction of upwelling microwave energy that is initially emitted by surface and lower atmospheric gases, and then scattered by snowflakes in the atmosphere. Radio communications signals can be significantly depolarized by precipitation, and attenuation can range up to 3 dB per kilometer.

Normally, however, existing databases for calculating scattering by precipitation are based on calculations for idealized hydrometeor forms. Accurate characterization of hydrometeor shape appears to be essential for accurate representations of either of these two problems.

Constraining the problem with empirical data has proved challenging. Traditionally this has been done through the painstaking manual examination of individual hydrometeors (Locatelli and Hobbs 1974). Automated ground-based disdrometers have recently helped eliminate human subjectivity and allowed for greater statistical power (e.g. Kruger and Krajewski, 2002). Nonetheless, these newer instruments require imaging small, complex, fast-moving particles on a laser diode optical array, and this can lead to significant sizing errors (Yuter et al. 2006). Further, the images are normally silhouettes with a very coarse resolution of about 200 m, which makes it difficult to confidently discriminate particle habit (Barthazy and Schefold 2006). It is impossible to assess the extent of riming from 40 μm diameter droplets within silhouetted images at 200 μm resolution, or to easily discriminate them from tight clumps of aggregates. What is needed is a measurement technique that provides automated high resolution images of hydrometeors in freefall, while simultaneously measuring their fallspeed. This paper describes a new instrument with these capabilities, and summarizes a few of the

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statistical properties of hundreds of thousands of hydrometeors sampled during the winter of early 2012.

We suggest that images of hydrometeors and their fallspeeds can be used to 1) study storm snow avalanches and 2) for precipitation rate estimates. This paper describes two such projects underway at Mammoth Mountain, CA.

2 THE MULTI-ANGLE SNOWFLAKE CAMERA

The Multi-Angle Snowflake Camera, or MASC, was developed to address the need for high-resolution multi-angle imaging of hydrometeors in freefall, while simultaneously measuring their fallspeed. The instrument was developed out of the University of Utah and is now available through Fallgatter Technologies.

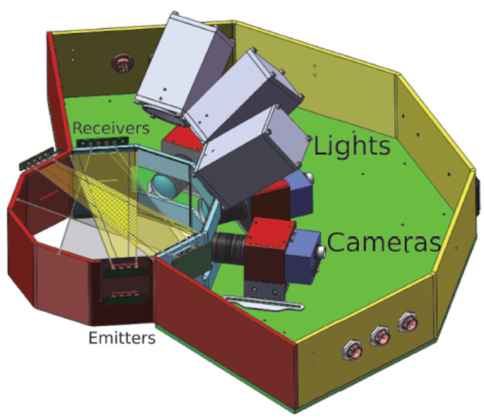

Figure 1 Schematic of the Multi-Angle Snowflake Camera

The MASC (Figure 1) consists of three cameras, separated by 36 degrees and each pointing at an identical focal point approximately 10 cm away. The focal point itself lies within a ring through which hydrometeors fall. The ring houses a system of near-infrared emitter-detector pairs, arranged in two arrays that are separated vertically by 32 mm. Hydrometeors passing through the lower array simultaneously trigger each of the three cameras as well as a bank of lights aimed at the center of the camera depth of field. Fallspeed is calculated from the time it takes to traverse the distance between the upper and lower triggering array.

The camera is sensitive to falling hydrometeors larger than about 0.1 mm. Depending on the choice of cameras and lenses, the image resolution ranges from 9 to 37 micrometers.

Analysis of MASC images has been performed using the MATLAB image processing toolbox. Images are analyzed for a range of properties, averaged over camera perspectives. These properties include the average maximum dimension along the major axis D_{max}, the aspect ratio relative to the minimum dimension along the minor axis, the hydrometeor orientation defined as the angle from the horizontal to the major axis, the hydrometeor cross-section allowing for internal holes, the equivalent radius r_{eq} defined as the radius of an equivalent cross-section circle, the hydrometeor perimeter P, and a dimensionless expression of the hydrometeor complexity defined as $\chi = P/2\pi r_{eq}$. While $\chi = 1$ for a spherical particle, it is close to unity for quasi-spherical particles such as graupel, and it is larger for more complex aggregate shapes.

3 MEASUREMENTS

All measurements described here were obtained between 10 Feb and 6 Apr 2012 at an altitude of 2600 m at the base of Collins Gulch, the uppermost side canyon in Little Cottonwood Canyon, located within the Wasatch Front about twenty miles south of Salt Lake City. The measurement site was outside the home of co-author DH, within the Alta Ski Area bounds. From the base of the ski area, Collins Gulch rises vertically through a depth of 760 m, to the summit of Mt. Baldy at 3350 m altitude. During storms, prevailing winds are normally up Little Cottonwood Canyon, but Collins Gulch is relatively sheltered compared to the Mt. Baldy ridgeline.

Approximately ten thousand images satisfied conservative rejection criteria. A small selection of images from the MASC were chosen (Figure 2) to highlight the extraordinary range and complexity of forms that characterize frozen hydrometeors. Hexagonally symmetric forms were observed only very rarely.

From this dataset, probability distributions were created (Figure 3) for maximum dimension, equivalent radius, aspect ratio, orientation, complexity, and fallspeed. In all regards, the range of possible characteristics is broad. The atmosphere seems to allow for most possibilities.

However, in general, the size and fallspeed measurements are broadly consistent with past measurements indicating typical linear

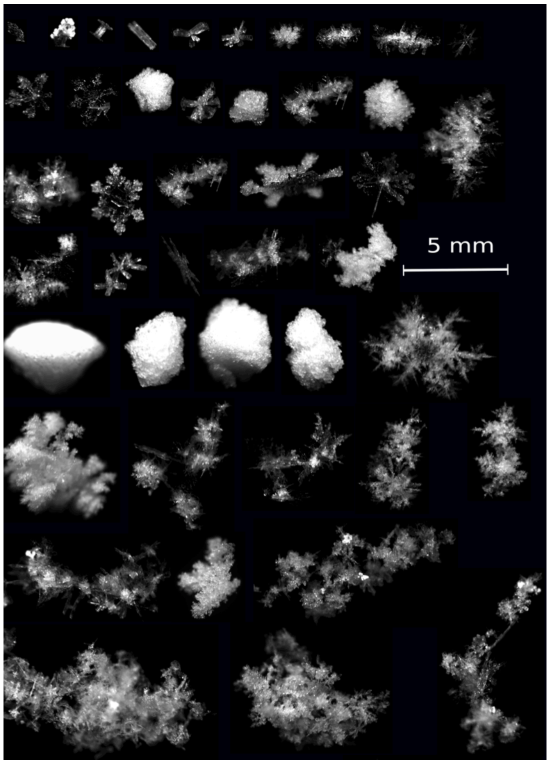

Figure 2 Hydrometeor images obtained at a photographic resolution of 9 micrometers.

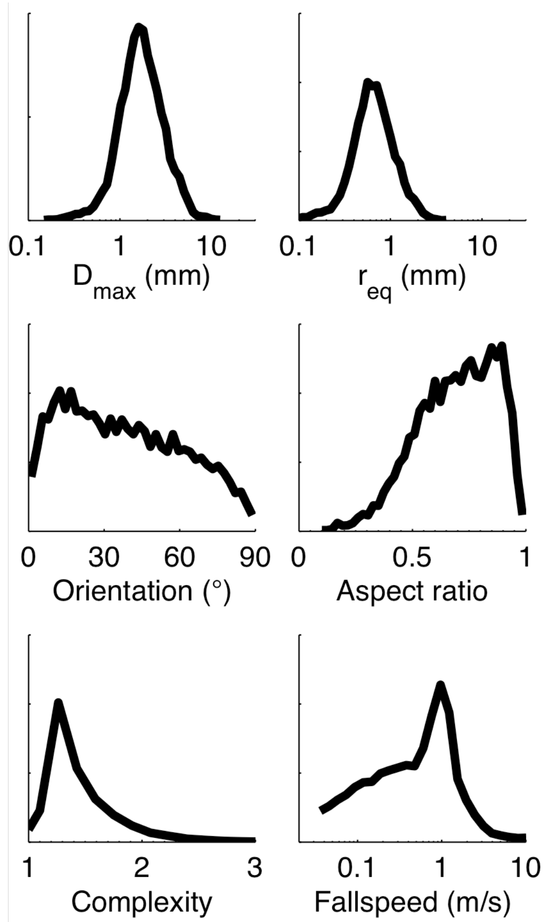

Figure 3 Statistics obtained with the MASC

dimensions of about 1 mm and fallspeeds of about 1 m/s (Locatelli and Hobbs 1974). The hydrometeors that were observed tended to have low complexity, with a clear preference for a near unity aspect ratio. The maximum dimension tends to lie nearer the horizontal than the vertical, although a wide variety of orientations are possible.

4 MASC AT MAMMOTH MOUNTAIN, CA

4.1 MASC measurements and avalanche activity

In 2011, a MASC was purchased and installed at the Cold Regions Research and Engineering Laboratory/UC-Santa Barbara Energy Balance Site (CUES, www.snow.ucsb.edu/cues) on Mammoth Mountain, CA. Because storm snow layering affects avalanche activity (Bair et al. 2012a), we suggest that failure layers can be identified as they fall using the MASC. To this end, we have installed at MASC at CUES, which sits above several explosively controlled avalanche paths that are permanently closed to skiers and riders. Nine of ten avalanches on these paths fail in the storm snow or at the storm/old snow interface, making them an ideal study area for storm snow avalanches. Using avalanche control records, we will examine how MASC measurements (e.g. Figure 3) affect avalanche activity. From this research, we aim for better prediction and monitoring of storm snow avalanches.

4.2 MASC measurements and LiDAR to estimate precipitation rate

Accurate measurement of snowfall in windy mountain areas is critical to understanding the global water cycle. Like many windy sub-alpine areas, the CUES site is an exceedingly difficult place to measure snowfall because of its exposure to wind. Precipitation gauges suffer severe undercatch in such windy conditions (Goodison et al. 1998). Alternatively, Radar, the most commonly used instrument to measure precipitation rate during snowfall, suffers from errors of up to 3X due to uncertainty in hydrometeor mass-diameter/mass-fallspeed relationships and low reflectivities in the microwave spectrum (Matrosov et al. 2009).

To examine a new approach, we have installed an automatic scanning terrestrial LiDAR at CUES that is capable of detecting millions of hydrometeors in the air as they fall, providing a snapshot of hydrometeor concentration. We will combine these LiDAR-derived concentration measurements along with mass-fallspeed measurements from the MASC to estimate precipitation rate during snowfall. For more information on this project see Bair et al. (2012b).

5 CONCLUSIONS

This paper described a new instrument for automated, high-resolution, stereoscopic photographs of hydrometeors in freefall while simultaneously measuring their fallspeed. The Multi-Angle Snowflake Camera (MASC) resolution is as fine as 9 μm, and the cameras are triggered by hydrometeors ranging from as small as 100 μm up to several centimeters. Three views of each hydrometeor from angles spanning 72 degrees help to constrain estimates of particle size, shape and orientation. Fallspeeds are determined from the time interval between triggers of two vertically separated arrays of infrared motion sensors.

The instrument has been designed to help improve representations of frozen hydrometeors in weather and remote sensing models. Weather model forecasts are sensitive to the details of bulk microphysical parameterizations for hydrometeor form and fallspeed. Remote sensing algorithms, particularly those using active and passive signals in the microwave, rest on assumed relationships between the mass of a hydrometeor and its scattering cross-section.

Between February and April 2012, continuous measurements were obtained with the MASC at an altitude of 2600 m, in the Wasatch Front near Salt Lake City, UT. This paper has shown statistical distributions collected during this period for such parameters as particle fallspeed, size, orientation, aspect ratio and a dimensionless measure of complexity. For each of these parameters, a very broad range of values was measured, although we observed a bias towards rounder shapes with an aspect ratio near unity, sizes of about 1 mm, and fallspeeds of approximately 1 m/s.

In 2011, a MASC was installed at the CUES site on Mammoth Mountain, CA. This MASC is being used for two ongoing projects: 1) monitoring snow crystals that form failure layers in storm snow avalanches and 2) estimating precipitation rate in conjunction with a scanning terrestrial LiDAR. These projects demonstrate the varied applications of the MASC and its potential to improve understanding of precipitation in mountain areas.

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