Meteorological Characteristics of Heavy Snowfall in the Cordillera Vilcanota, Peru

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ABSTRACT

We examined the meteorological characteristics associated with heavy snowfall in the Cordillera Vilcanota, Peru (~14°S, 71°W) using data from meteorological stations installed by Appalachian State University on the Osjollo Anante Icecap (5,540 m) and at a nearby alpine wetland (5,050 m). Approximately 55% of all precipitation hours occurred during the daytime, peaking around 1600 LST. A secondary maximum at 0300 LST is associated with a higher proportion of heavy snow hours, with 57% occurring at night. The heavier nighttime snowfall events are typically characterized by longer durations, higher radar reflectivity, and lower overall lapse rates (calculated using temperatures at each station). Precipitation was predominantly solid throughout the year, constituting 94% of all precipitation hours. Prevailing winds are from the west on the Osjollo Icecap, but are from the northwest during most precipitation hours. Graupel (*phati* in the local Quechua language) was observed frequently, sometimes accounting for as much as half of all precipitation hours in a single month, particularly during austral winter. These findings help to better characterize glacier-precipitation interactions by analyzing amounts, phase, and timing of precipitation in a heavily glacierized tropical cordillera.

Keywords: Heavy snowfall, precipitation type, Cordillera Vilcanota, Peru

INTRODUCTION

Tropical high mountains experience a great amount of precipitation variability that is an important aspect of local climatology and can have a major impact on glacier behavior (Francou et al. 2003, Kaser et al. 2004, Barry 2008, Vuille, 2011). Glacier shrinkage is occurring throughout the tropics around the world, including Kilimanjaro in east Africa (Molg et al. 2009), where one of the most important factors is a decrease in frozen precipitation (Kaser et al. 2004; Kaser et al. 2010). Other studies have focused on Andean glaciers and have concluded that the timing and phase of precipitation are fundamental influences on glacier mass balance (Francou et al. 2003; Garreaud et al. 2003). Overall, the tropical Andes exhibit a trend of negative mass balance consistent with global trends of deglaciation (Vuille et al. 2008, Mark et al. 2010). These negative trends are expected to continue and further decrease glacier volume (Jones et al. 2014). The Cordillera Vilcanota of Peru is a tropical Andean range where significant deglaciation has been documented (Mark et al. 2002) and is projected to continue in the future (Seimon et al. 2007).

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Salzmann et al. (2013) showed noticeable ice cover area change from 1962 to 2006, decreasing from 440 km² to 297 km². Over the past decade, the rate of decline seen in these glaciers has increased 13% (Hanshaw and Bookhagen 2014).

Precipitation variability in the Cordillera Vilcanota, particularly of frozen precipitation, plays a vital role in understanding the effects of recent deglaciation on regional water supply in the form of runoff (Chevallier et al. 2011). Understanding precipitation phase, timing, and frequency can also help to improve knowledge on how these factors influence water isotopes ($\delta^{18}O$, HDO) measured in ice cores from these regions (Thompson 1980, Goodman et al. 2001, Vimeux et al. 2009). It is vital to establish current climatology and circulation patterns to be able to properly interpret these proxy data as reconstructions of past climate. Improved interpretations will lead to better paleoclimate reconstructions to show what climate of the past was like and how it is currently changing. Precipitation variability is closely linked to interpretations of ice core records. The Cordillera Vilcanota contains the Quelccaya icecap, the largest glacier in the tropics and site of ice core drilling programs for paleoclimate reconstruction in 1983 and 2003 (Thompson et al. 1985, Thompson et al. 2013). Without a full understanding of hydrometeorology, any interpretation of these proxy data is extremely difficult.

Studies on precipitation timing in the central Andean region have identified that post-noon convective precipitation following diurnal heating is favored (Garreaud and Wallace 1997, Garreaud 1999, Vuille and Kemig 2004, Romatschke and Houze 2010, Mohr et al. 2014). However, for Cusco and stations immediately adjacent to the Cordillera Vilcanota, Perry et al. (2014) identified markedly different patterns with the major fraction occurring close to midnight from systems hypothesized to be stratiform in character. Over a seven year period comprising 847 individual events, wind trajectories were from the north-northwest in the majority of precipitation events (58%), with 95 % originating over the Amazonian basin within 72 hours of precipitation occurrence. Inter-annual variability in seasonal precipitation totals is modulated by the El Niño-Southern Oscillation (ENSO), with La Niña events promoting drier conditions and El Niño events being significantly wetter. This is the inverse of the patterns recognized elsewhere across the central Andes (e.g., Vuille 1999, Vuille and Keimig 2004, Francou et al. 2003, Garreaud et al. 2003).

Although the determination of precipitation phase and intensity is a considerable challenge in tropical high mountains (e.g., L'hôte et al. 2005), automated present weather sensors can provide high temporal resolution while classifying precipitation by type and intensity to help better assess precipitation characteristics (e.g., Yuter et al. 2006). In this study, we utilize automated meteorological instrumentation along with manual observations from a citizen science precipitation observer to investigate snowfall characteristics in the Cordillera Vilcanota of Peru. Specifically, this paper is guided by the following research questions: (1) What is the timing (e.g., day vs. night) and phase (e.g., rain, snow, graupel) of precipitation in the region from 2012-2014? (2) What are the meteorological characteristics of heavy snow hours in the region and how do they compare to light snow hours? The results presented here, while particular to Cordillera Vilcanota, contribute more broadly to understanding of deglaciation, interpretation of ice cores, and the meteorological factors that control the type and intensity of precipitation in tropical high mountains worldwide.

DATA AND METHODS

Data for this study were obtained from manual daily precipitation observations and two automated meteorological stations installed by Appalachian State University in April 2012 in the Cordillera Vilcanota (Fig. 1). The site at Murmurani Alto is located at 5,050 m above sea level (asl) in a small wetland (*bofedale*). The second site at 5,540 m asl is located on the southeastern margin of the Osjollo Anante Icecap, approximately 120 m lower and 1.25 km southeast of the summit (Fig. 2). Table 1 provides a list of parameters observed at the two sites. The manual measurements were taken each morning by a trained observer as part of a citizen science initiative developed by Appalachian State University using established protocols developed for measuring snowfall (Doesken and Judson 1998) and for citizen scientist precipitation observers as part of the Collaborative Rain, Hail, and Snow (CoCoRaHS) network in the U.S. and Canada (Cifelli et al. 2005). The data from the two automatic stations, along with the manually observed data, were recovered during annual visits in July of each year. Parsivel present weather codes were used to discriminate heavy snow (73) from light snow (71) observations, and for hours characterized by graupel (87-88) and snow (71-73).

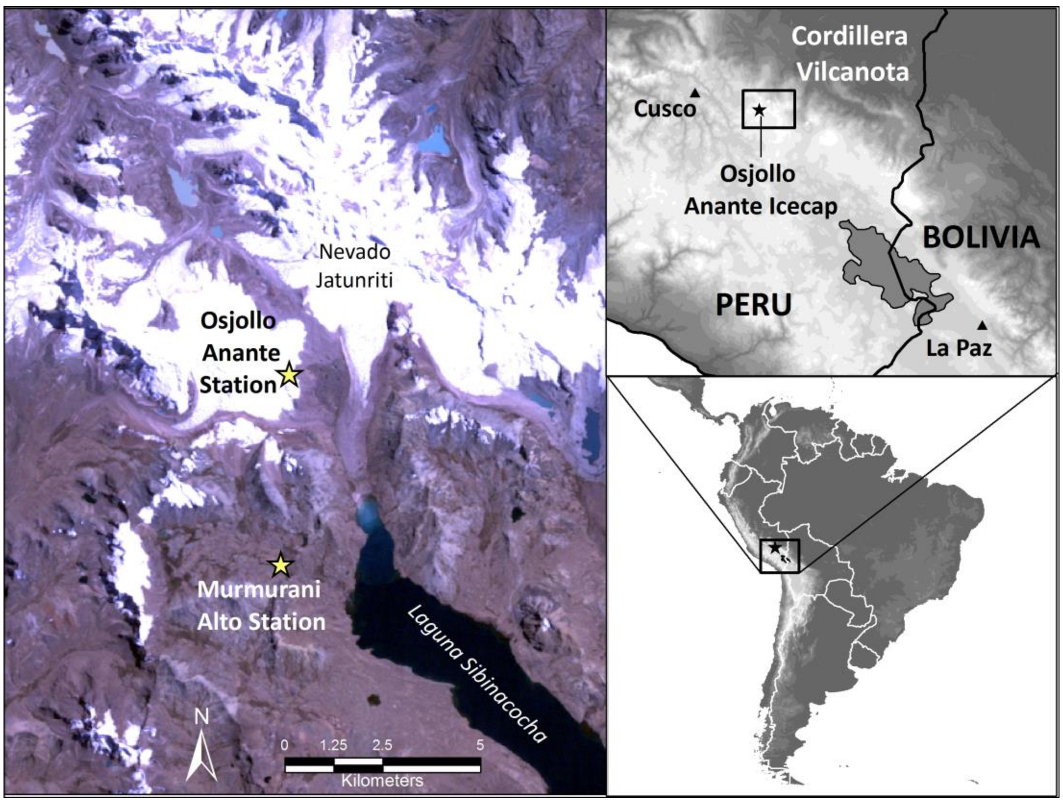


Figure 1. Location of Cordillera Vilcanota and meteorological stations used in this study. Landsat 8 true color visible satellite image acquired on 22 July 2013.

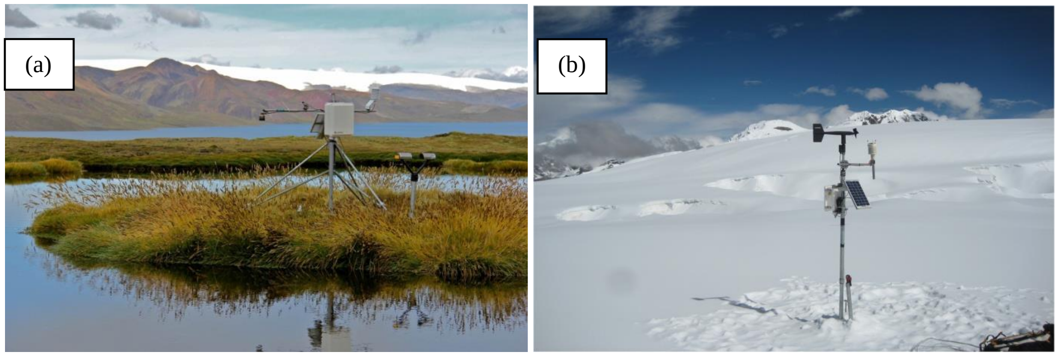


Figure 2. Murmurani Alto Station (a) at 5,050 m looking SE with Quelccaya icecap in background and Osjollo Anante Station (b) at 5,540 m looking WNW (Photo Credits: Tracie Seimon and Baker Perry).

Table 1. Summary of variables measured at Murmurani Alto and Osjollo Anante meteorological stations in the Cordillera Vilcanota.

Variable	Temporal Resolution	Sensor/Source
Murmurani Alto (5,050 m asl)		
Temperature and Relative Humidity	1-hr / 24-hr	H2CS3 Rotronics
SYNOP Present Weather Code	1-hr / 24-hr	Parsivel Present Weather
Radar Reflectivity	1-hr / 24-hr	Parsivel Present Weather
Pressure	1-hr / 24-hr	CS 106 Pressure
Snowfall	1-hr / 24-hr	CS SR50A Sonic Depth
Liquid Equivalent Precipitation	24-hr	Manual Observation
Snowfall	24-hr	Manual Observation
Osjollo Anante (5,540 m asl)		
Temperature and Relative Humidity	1-hr / 24-hr	Vaisala WXT 510
Pressure	1-hr / 24-hr	Vaisala WXT 510
Wind Speed and Direction	1-hr / 24-hr	Vaisala WXT 510
Wind Speed and Direction	1-hr / 24-hr	RM Young 05103 Alpine

RESULTS AND DISCUSSION

In the two years between 1 July 2012 and 30 June 2014, snowfall at Murmurani Alto averaged 467 cm (431 cm in 2012-2013 and 502 cm in 2013-2014) as recorded by an acoustic snow depth sensor, and liquid equivalent precipitation averaged 686 mm (623 mm in 2012-2013 and 749 mm in 2013-2014), recorded by the observer (Table 2). Most of the precipitation occurred during the peak months of the austral wet season (DJF, Fig. 3). Snowfall exceeding 80 cm occurred during several months during the wet seasons, with nearly 120 cm accumulating in January 2014. New snowfall density averaged 147 kg m^{-3}, with very little variation between the two years. Snowfall events were typically light (2.1 cm per event over the period of study), but frequent, with precipitation a near daily occurrence during the wet season. Even though precipitation is nearly exclusively solid at Murmurani Alto, snowfall is highly ephemeral and typically ablates quickly during daylight hours with the high solar elevation of the tropical sun. The maximum snow depth recorded during the period was 17 cm.

Snow was the primary precipitation type, but graupel (*phati* in the native Quechua language) also constituted a significant number of precipitation hours. In some months graupel accounted for over half of the precipitating hours, particularly during the dry season (Fig. 4). Although liquid precipitation (rain) was infrequent (5% of precipitation hours; Table 3), its presence is noteworthy at 5,050 m, as many glacier termini in the Cordillera Vilcanota are found below this level (Salzmann et al., 2013). Our observations suggest that rain does fall on occasion in the ablation zone, promoting melting of the glacier surface and reducing surface albedo that may influence glacier mass balance in the region (e.g., Francou et al. 2003). Unfortunately, our dataset covering a rather short temporal period does not allow for the identification of inter-annual trends or relationships with ENSO.

Table 2. Summary of snowfall and precipitation for 2012-13, 2013-14, and entire period of record. These totals do not include April to June 2012.

Variable	2012 - 2013	2013 - 2014	Mean
Snowfall (cm)	431	502	467
Precipitation (mm)	623	749	686
New Snowfall Density (kg m^{-3})	145	149	147
Number of Snowfall Events	159	197	178
Mean Snowfall per Event (cm)	2.7	2.5	2.6
Max Snow Depth (cm)	17	17	17

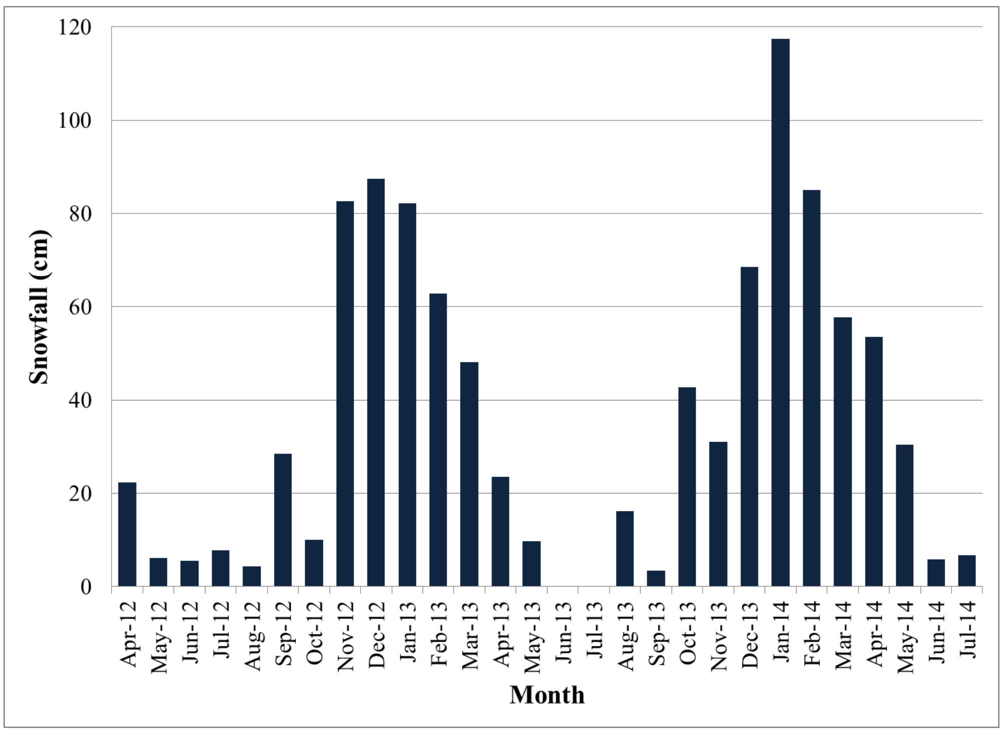
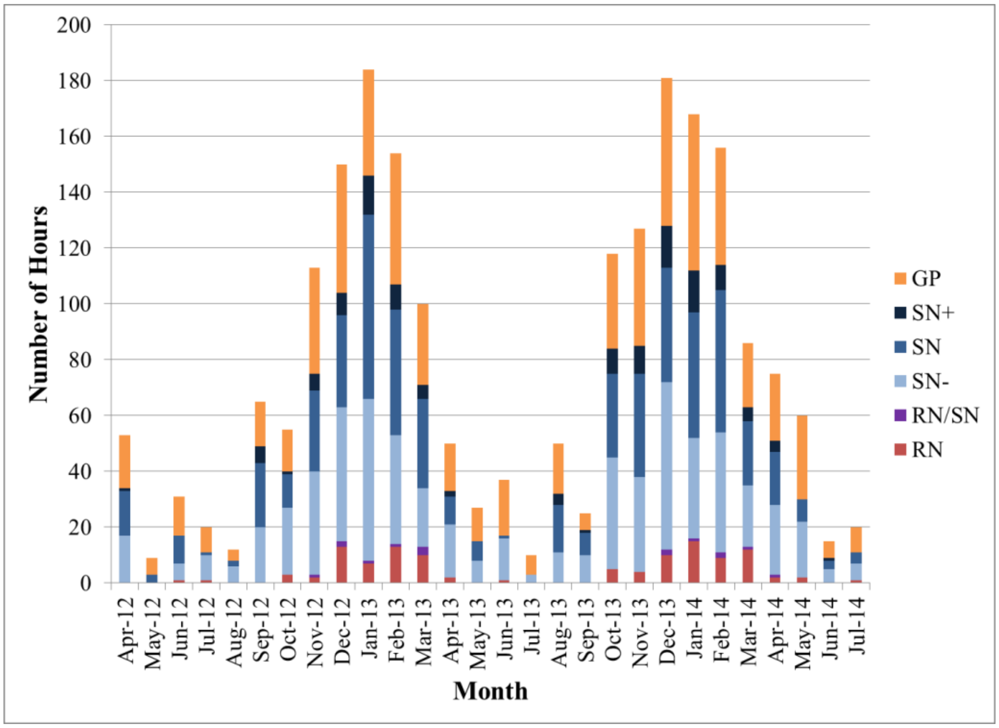


Figure 3. Monthly snowfall totals from automated acoustic snow depth sensor from Murmurani Alto.



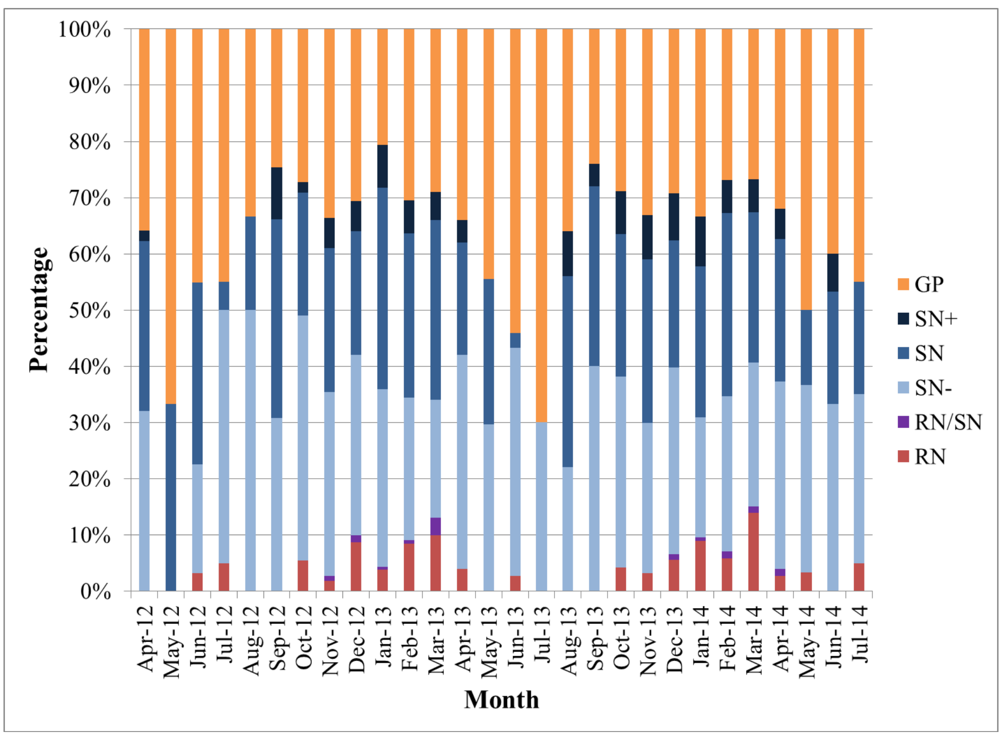


Figure 4. All precipitating hours from April 2012 to July 2014 by total number of hours (top) and total percentage (bottom) of each precipitation type by month. GP graupel; SN+ heavy snow; SN moderate snow; SN- light snow; RN/SN rain/snow mix; RN rain.

Table 3. Summary of precipitation hours for 2012-13, 2013-14, and entire period of record.

Precipitation Type	2012 - 2013 Hours	%	2013 - 2014 Hours	%	Total Hours	%
Rain (61 - 63)	52	5	59	6	111	5
Rain/Snow (67 - 68)	8	1	7	1	15	1
Light Snow (71)	304	31	309	29	613	30
Snow (72)	261	27	282	26	543	27
Heavy Snow (73)	51	6	73	7	124	6
Graupel (87-88)	291	30	341	31	632	31
Total	*967*		*1071*		*2038*	

Precipitation is most common in the afternoon and at night (Fig. 5), with highest frequencies around 1500 LST and 0300 LST, respectively. Heavy snow hours and longer duration heavy snowfall events occur with a higher frequency at night, with 57% of heavy snow hours occurring between 7 PM and 7 AM LST (Fig. 6). While the peak in the afternoon was greater than the one at night, the afternoon peak was more strongly associated with rain/mix, light snow, and graupel hours (Fig. 6). This suggests that diurnal convection may contribute more to annual precipitation in the higher elevations of the Cordillera Vilcanota than at Cusco, about 150 km to the west. However, an important difference between the studies is the method used to identify precipitating hours. Perry at al. (2014) used hourly precipitation totals, whereas we used a Parsivel present weather sensor that may be more sensitive, since hourly precipitation totals were not available to identify precipitation events.

Heavy snow hours were characterized by higher relative humidity at both Osjollo Anante and Murmurani, higher temperatures on Osjollo Anante, and lower temperature lapse rates (Table 4). In particular, temperature lapse rates between Murmurani Alto and Osjollo Anante were 2°C km^{-1} lower during the hours of heavy snow. Wind direction during heavy snow hours was variable, but light snow hours were associated with winds primarily from the northwest (Fig. 7). Graupel was associated with higher surface temperatures, lower relative humidity, and higher lapse rates between Murmurani Alto and Osjollo Anante (Table 4). Graupel hours occurred with primarily northwest flow, whereas snow hours also have a northwest component but wind direction was more variable. Higher lapse rates during hours of graupel mean that near surface conditions were generally more unstable than seen in snowfall. Graupel is formed by riming of ice particles as they pass through supercooled cloud liquid water and more unstable air should support this process because of increased turbulence and longer suspension of ice particles in clouds before precipitating out.

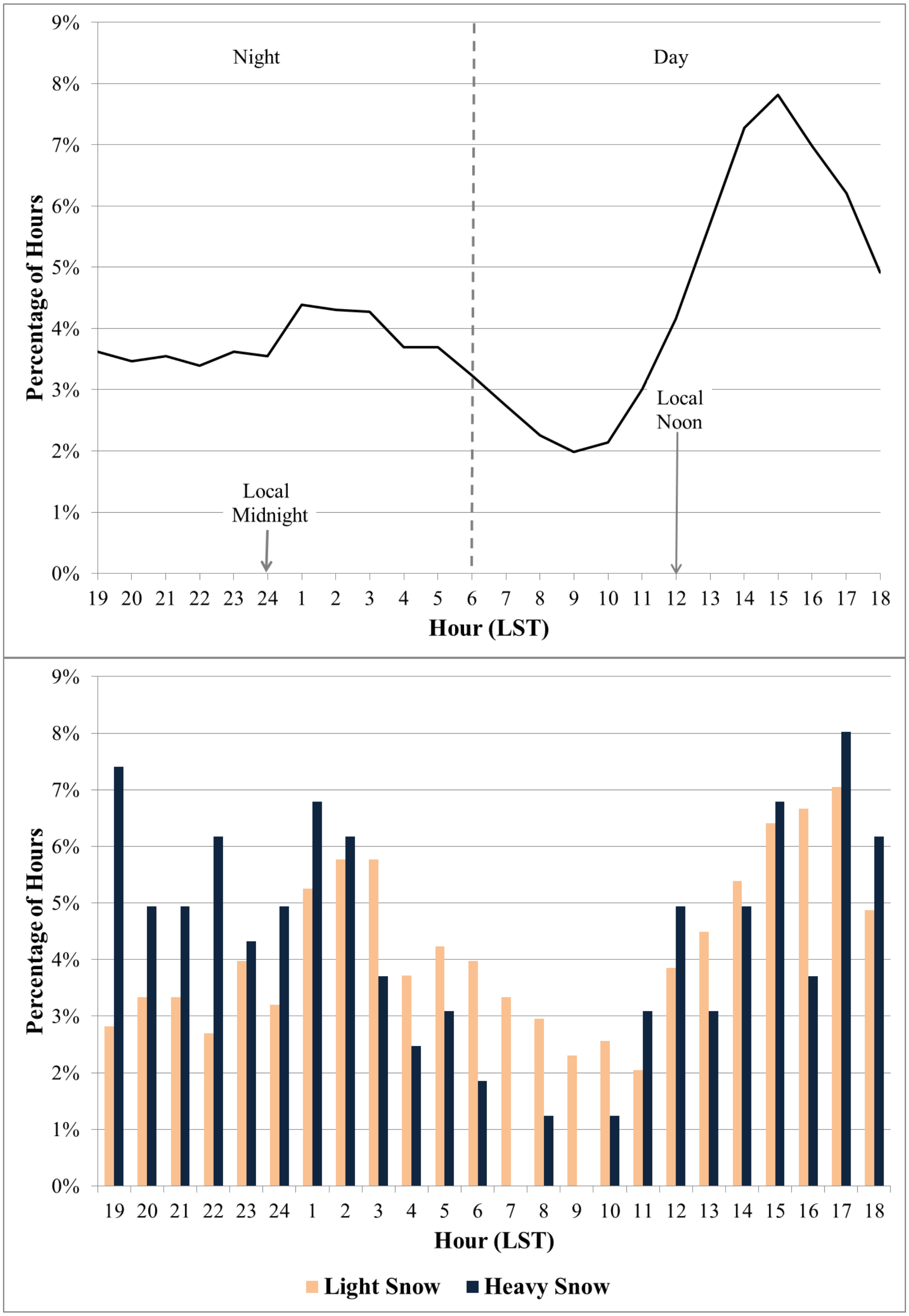


Figure 5. Frequency of all precipitating hours (top) and hours of light vs. heavy snow (bottom).

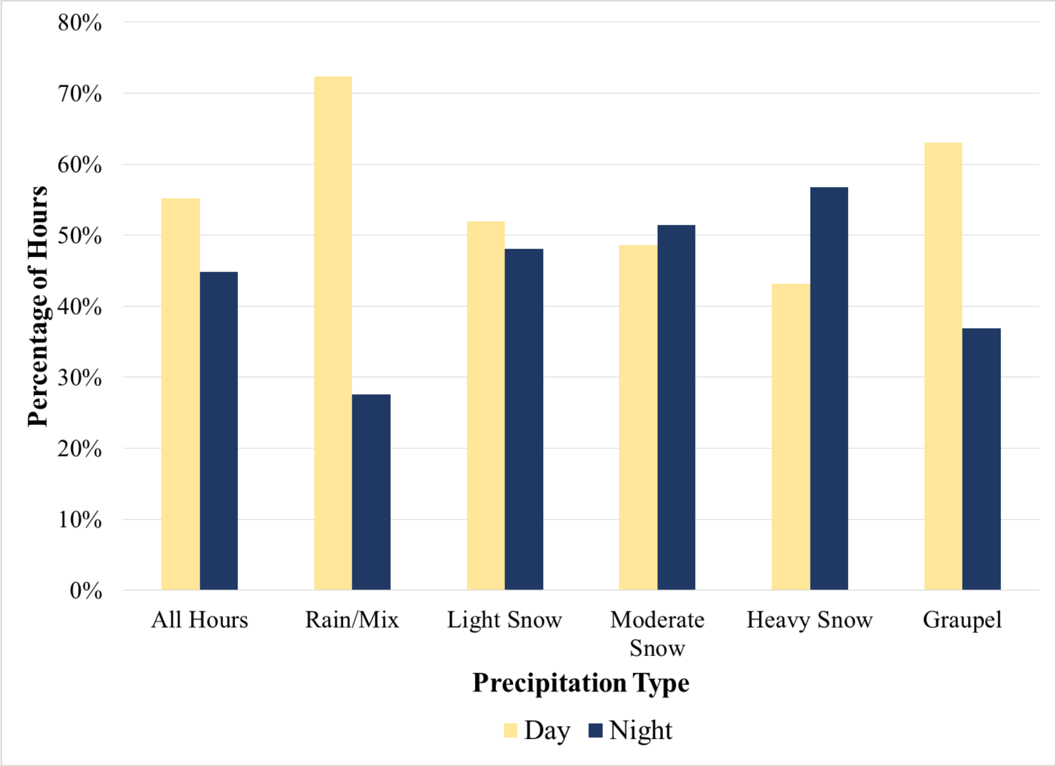


Figure 6. Frequency of precipitation type during day (7 AM – 7 PM LST) and night (7 PM-7 AM LST).

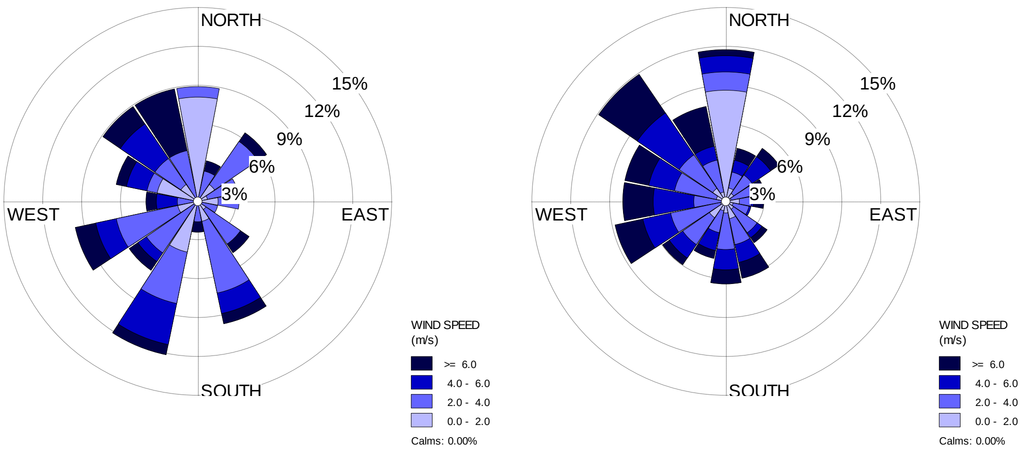


Figure 7. Frequency distribution of wind speed and direction at Osjollo Anante for hours of (a) heavy and (b) light snow.

Table 4. Independent samples t-test for all hours with heavy (73) and light (71) snowfall and for snowfall (71-73) and graupel (87-88). P-values that appear bold denote significance at the 95% confidence interval or greater.

Variable	Heavy v. Light Snow				Snow v. Graupel			
	SN+	**SN-**	**Abs. diff.**	**p-value**	**SN**	**GP**	**Abs. diff.**	**p-value**
	n = 125	n = 641			n = 1342	n = 681		
Radar Reflectivity (dBZ)	32.1	11.3	20.8	**0.000**	18.6	23.9	5.3	***0.000**
Murmurani Temp. (°C)	-0.3	0.6	0.9	**0.000**	0.2	1.2	1.0	**0.000**
Osjollo Temp. (°C)	-2.7	-2.8	0.1	0.538	-2.8	-2.1	0.7	**0.000**
Murmurani RH (%)	94.8	85.4	9.4	**0.000**	88.9	83.7	5.2	**0.000**
Osjollo RH (%)	92.0	89.3	2.7	**0.000**	90.1	86.8	3.3	**0.000**
Lapse Rate (°C km^{-1})	5.0	7.0	2.0	**0.000**	6.3	6.8	0.5	**0.000**

SUMMARY AND CONCLUSIONS

This paper analyzed the meteorological characteristics of precipitation in the Cordillera Vilcanota of Peru, with a particular emphasis on heavy snow and graupel occurrence. Although the majority of precipitation hours (55%) occurred during the daytime and were likely associated with convective activity, longer duration events and heavy snow hours occurred during the nighttime in association with inferred stratiform precipitation. Our results indicate that snow and graupel were the dominant types of precipitation above 5,000 m asl during the period 2012 to 2014. Rain was observed during 5% of all precipitating hours, with potentially important effects on adjacent glacier termini. Heavy snow hours were associated with higher values of relative humidity at both Murmurani Alto and Osjollo Anante, higher temperatures on Osjollo Anante, and northwest flow on Osjollo Anante. These findings help to better characterize precipitation-glacier-climate interactions in a heavily glacierized tropical cordillera and serve as an important baseline for future investigations.

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