Vertical Structure, Melting Layer Heights, and Antecedent Upstream Air Trajectories Associated with Precipitation Events during the 2014-15 Wet Season in the Central Andes of Peru

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ABSTRACT

The aim of this research is to characterize the vertical structure, melting layer heights, cloud top temperatures, and backward air trajectories for precipitation events in Cusco, Peru, during the 2014-2015 wet season. We used data from a vertically pointing Micro Rain Radar installed in Cusco during the period August 2014 to February 2015. The radar measured reflectivity (dBZ) and Doppler velocity (m s^{-1}), allowing for the determination of echo top heights and melting layer heights. GOES infrared temperature data from the Servicio Nacional de Meteorología e Hidrología del Perú (SENAMHI) were used to analyze cloud top temperatures. The National Oceanic and Atmospheric Administration's Hybrid Single Particle Lagrangian Integrated Trajectory Model is used to run 72-hr backward air trajectories for precipitation events in the region. Results indicate that precipitation generally occurs at night with melting layer heights as low as 4000 m asl. Echo top heights vary considerably, with shorter, more intense events having greater vertical development, usually over 7000 m asl. Longer events are characterized by echo top heights of 6000 m asl or lower. Trajectories associated with precipitation events were primarily from the northwest. Lower melting layer heights are often associated with higher dBZ and Doppler velocity values, signifying more intense precipitation, while the most intense events often have poorly defined melting layers. The highest observed dBZ values are associated with cloud top temperatures less than 0°C and frequently less than -10°C.

Keywords: Vertical Structure, Melting Layer Heights, Backward Air Trajectories, Central Andes

INTRODUCTION

The Central Andean region of southern Peru is an important transition zone between the very moist Amazon Basin and more arid *altiplano* and *cordilleras* to the south and west. The area contains tropical glaciers and ice caps that are significant sites for climate, glacier, and paleoclimate research (Thompson *et al.*, 1985, 1986, 2006). It has become evident that precipitation processes are vital in understanding glacier behavior (Francou *et al.* 2003). However, until recently, various aspects of precipitation in the region had not been investigated sufficiently (Perry et al. 2014). A vertically pointing radar has been used in the northern Andes of Ecuador to study daily precipitation patterns (Bendix et al. 2006). We present the first study using ground-based radar to study these patterns in southern Peru. Other than automated systems using temperature to make simple classifications in the Cordillera Real, Bolivia (L'hôte et al. 2005) and on Antisana Volcano (Favier et al. 2004), no other work has been done in the tropical Andes to

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derive melting layer heights using ground-based radar. The aim of this research is to characterize the vertical structure, melting layer heights, cloud top temperatures, and backward air trajectories for precipitation events in Cusco, Peru during the 2014-2015 wet season.

DATA AND METHODS

We used data from a vertically pointing Micro Rain Radar (MRR) installed in Cusco, Peru (3350m), near the Cordillera Vilcanota (Fig. 1) during the period August 2014 to February 2015. The radar measures reflectivity (dBZ) and Doppler velocity (m s^{-1}), allowing for the determination of echo top heights and melting layer heights. GOES IR temperature data processed at SENAMHI were used to analyze cloud top temperatures. The National Oceanic and Atmospheric Administration's Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) Model (Draxler and Hess, 1998; Draxler and Rolph, 2011) was used to run normal 72-hr. backward air trajectories from the same ending point for precipitation events in the region with GDAS half-degree resolution data. Trajectories were then grouped into clusters (e.g., Perry et al. 2014) ending at 4000 and 6000 m asl. A summary of the variables collected, location, temporal resolution, and source can be found in Table 1. MRR data were analyzed for every six-hour period with precipitation. We then ran backward air trajectories from the midpoint of each of these periods and clustered using HYSPLIT.

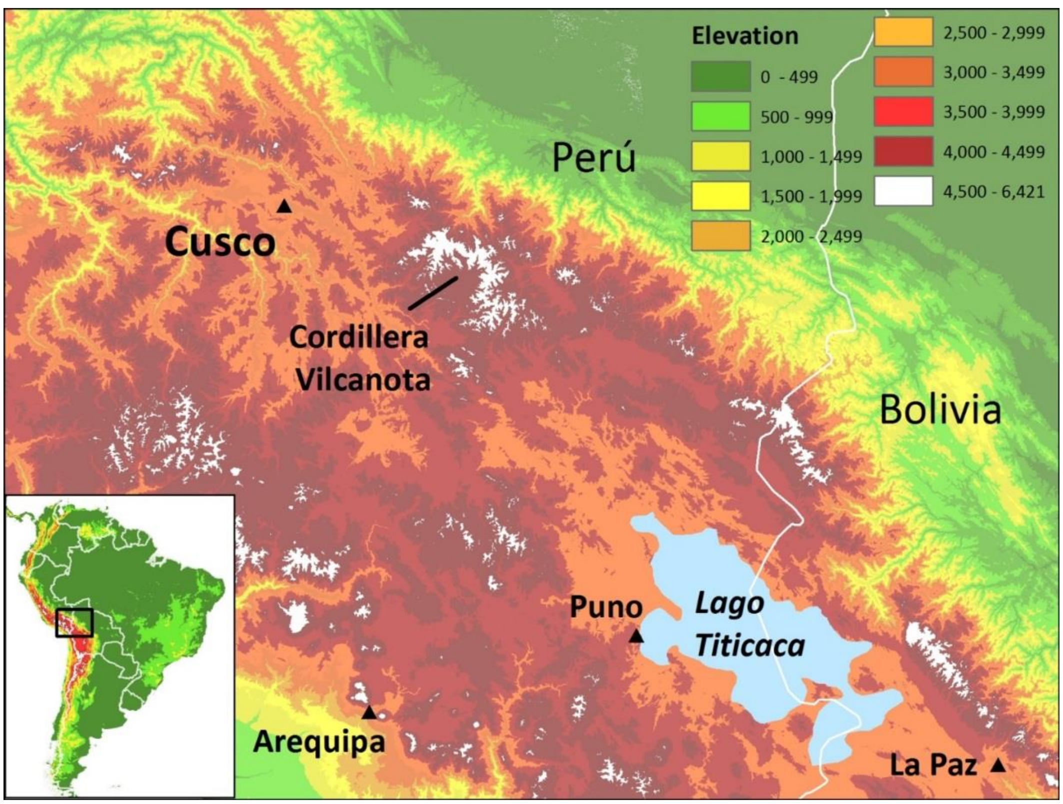


Figure 1. Location and topography of study site and surrounding area.

Table 1. Summary of data sources.

Variable(s)	Elevation or Location	Temporal Resolution	Source
dBZ, Doppler Velocity, and Melting Layer Heights	3350 m	1 min	Micro Rain Radar (MRR)
Cloud Top Temperature	75° W	30 min	GOES 13 IR4
Trajectory and Origin of Air Masses	4000 and 6000 m	1 hr	HYSPLIT

RESULTS AND DISCUSSION

The data collected for this research contain a wealth of information yet to be studied completely. This paper is intended to demonstrate the type of results that will be drawn from this data series in the future. Preliminary analysis of the MRR data from August 2014 to February 2015 yielded multiple results concerning precipitation in the region. There are three peaks in Doppler velocity between 7.5 and 8 m s^{-1}, 9.5 and 10 m s^{-1}, and 10.5 and 11 m s^{-1} (Fig. 2). Maximum dBZ data show a maximum near 27 and a lesser maximum near 35 (Fig. 3). This could represent the proposed predominance of nighttime stratiform precipitation with a lesser maximum of late afternoon convective precipitation (Perry et al. 2014). Higher Doppler velocity and dBZ values signify more intense precipitation and were often associated with lower melting layer heights. Melting layer heights ranged from near 4000 m to just over 5000 m, with modal values of approximately 4750 m asl (Fig. 4). Some events (e.g., 10-11 January 2015: Fig. 5a, and 26-27 January 2015: Fig. 6a) were characterized by late afternoon convection that was followed by nighttime stratiform precipitation and falling melting layer heights. In both cases, melting layer heights (as indicated by the maximum gradient in Doppler velocity) fall to approximately 4400 m asl by the end of the event. Backward air trajectories indicate the presence of a weak low-level northerly flow in both cases and variable mid and upper-level flows (Fig. 5b & 6b). In the long duration nighttime precipitation event from 12 February 2015 (Fig. 7), echo top heights remain high (>5750 m) until the very end of the event, with melting layer heights falling to approximately 4600 m in moderate precipitation between 400 and 500 UTC. Low, mid, and upper-level trajectories all originated from the northwest.

The 72 hr backward air trajectories associated with precipitation events were primarily from the northwest (Fig. 8), in general agreement with the results of Perry et al. (2014). The clusters comprising the largest percentage of events produced by HYSPLIT at 4000 and 6000m both had trajectories from this direction. There were also smaller clusters coming from the east with origins in the Amazon at both ending heights as well as one cluster at both heights from the south out of the Pacific. The clusters, coming from the northwest, had the shortest mean trajectories (i.e., weakest flow) and traveled closer to the ground. For the analysis at 4000m, 65% of the clusters come from the Urubamba Valley (La Convencion Province) constituting the principal point of ingression of the air masses responsible for the precipitation events in Cusco. The region of La Convención is characterized as being one of the orographic convergence sectors forced by the South American Low Level Jet (SALLJ). In this sector, the north to northeast part of the SALLJ impacts the eastern foothills (1000-2000 m asl), generating forced orographic lifting of the air masses from the Amazon and favoring the formation of precipitation (Falvey & Garreaud 2005). In 28% of the trajectories (Clusters 4 and 5) ending at 6000 m, precipitation, most likely convective in nature, is formed from air paths coming from the mountains.

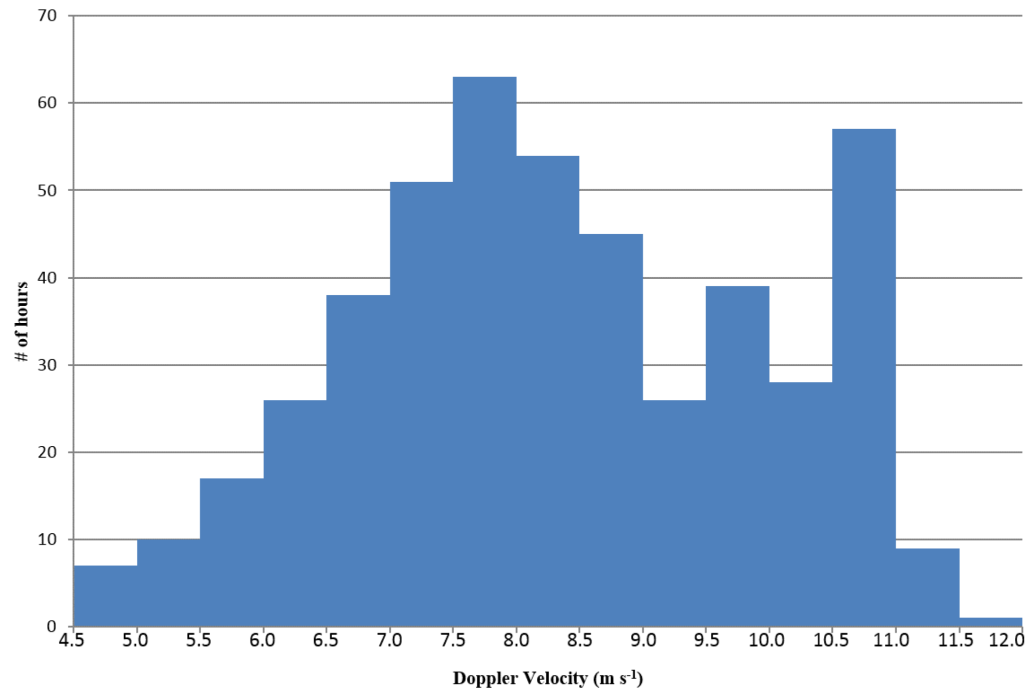


Figure 2. Histogram of maximum downward Doppler velocity values.

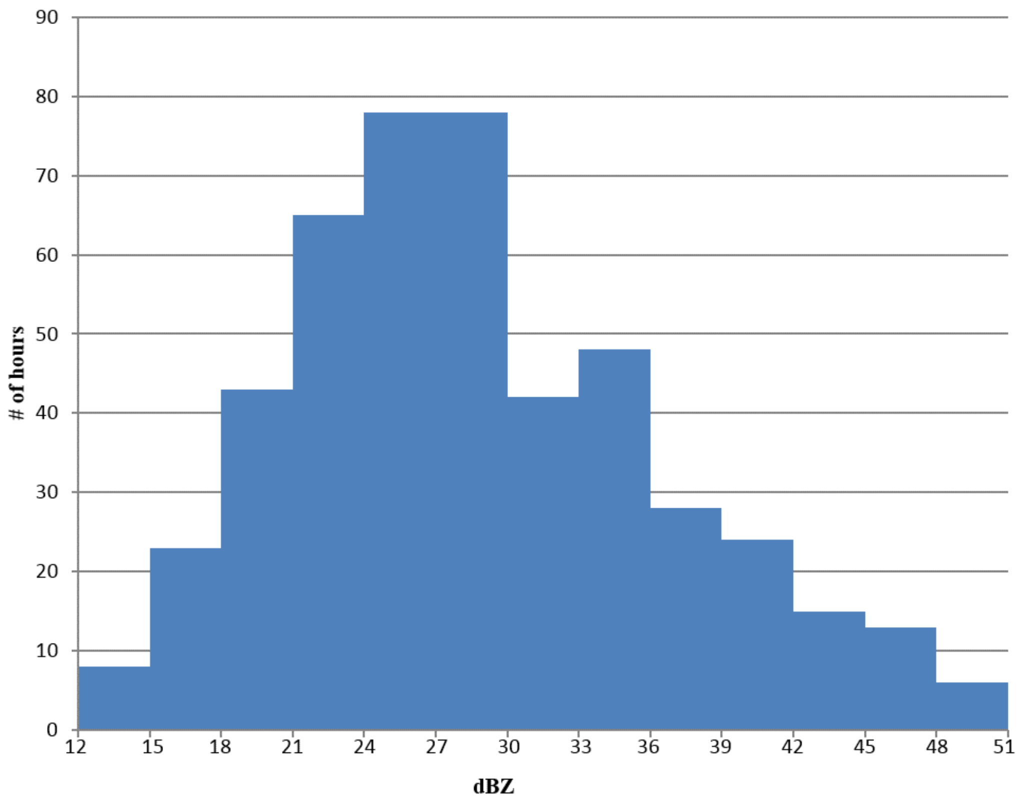


Figure 3. Histogram of maximum dBZ values.

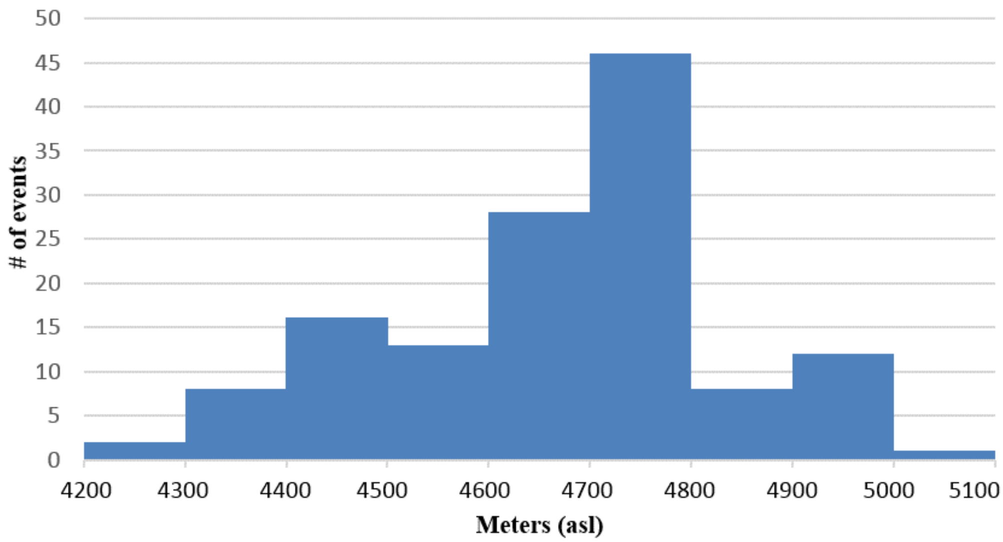
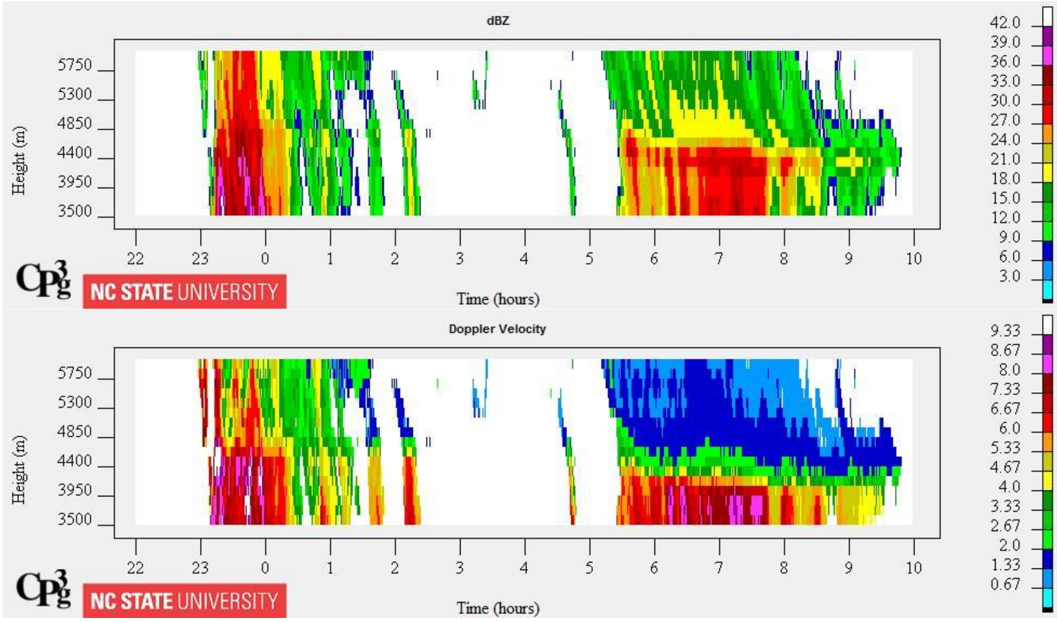


Figure 4. Histogram of melting layer heights.



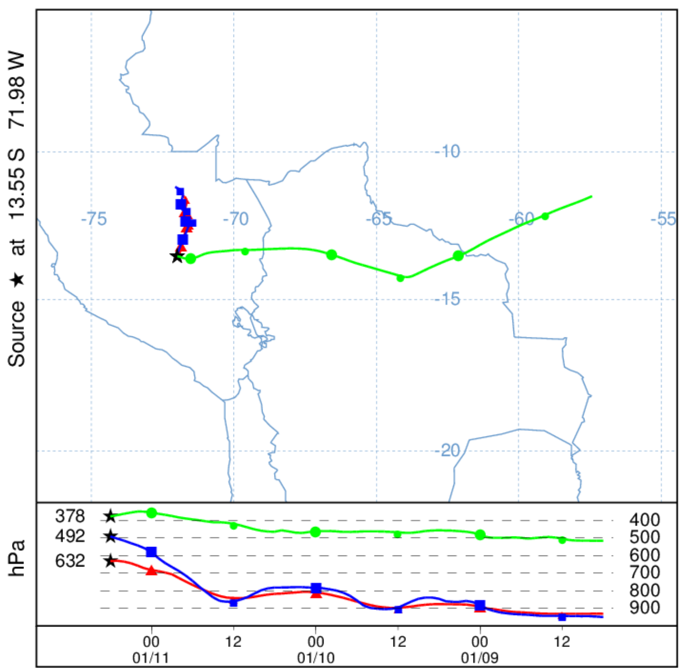
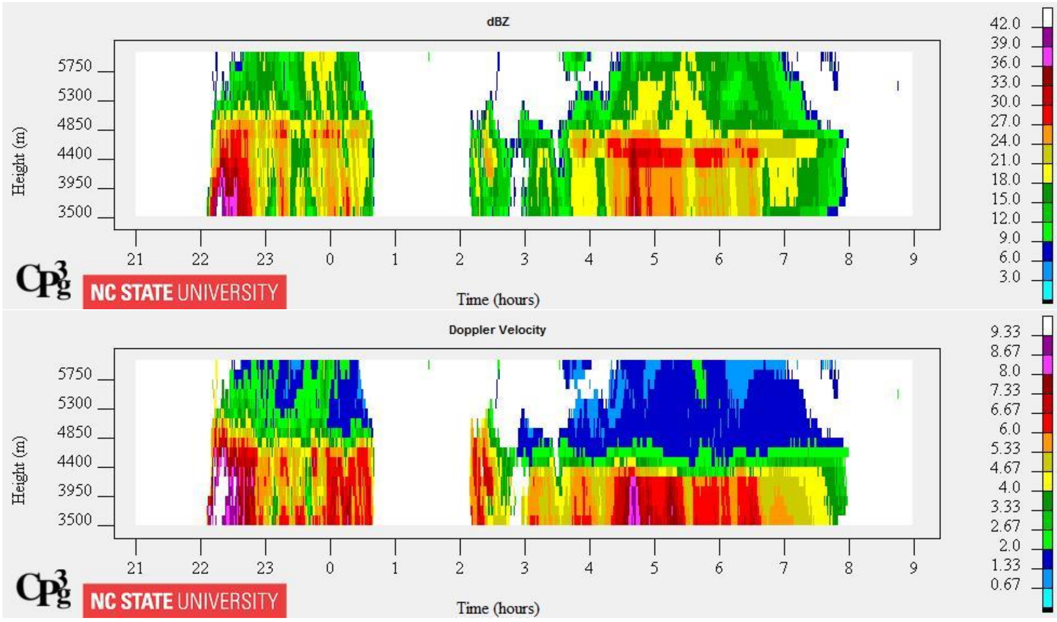


Figure 5a (top). Reflectivity and Doppler velocity from 2200 UTC 10 January 2015 to 1000 UTC 11 January 2015. 5b (bottom). 72-hr backward air trajectory from 0600 UTC 11 January 2015. The event total precipitation was 9.0 mm.



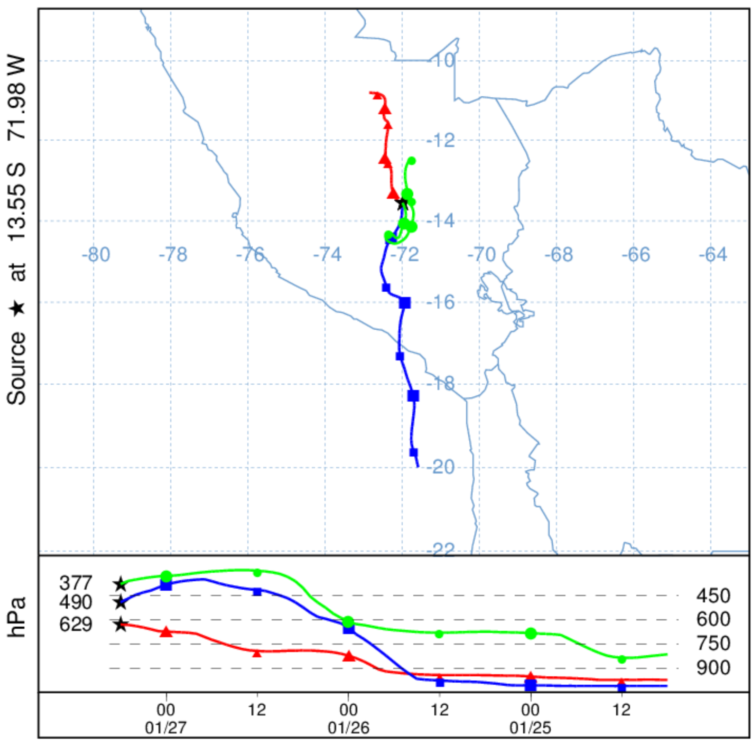
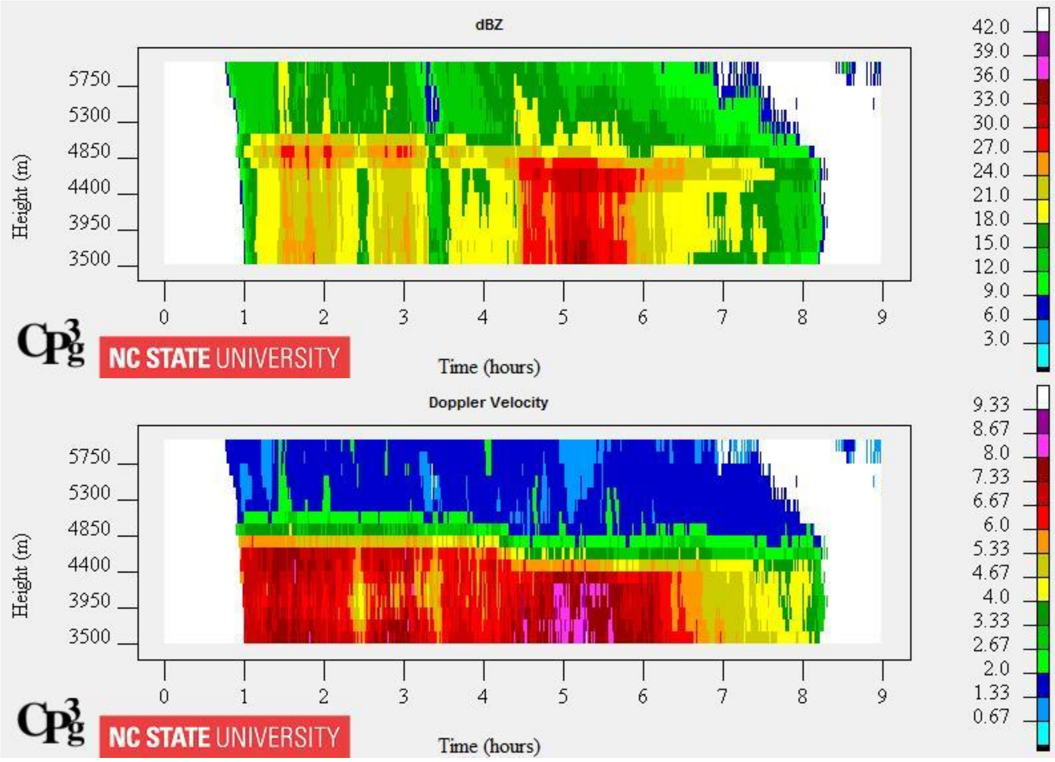


Figure 6a (top). Reflectivity and Doppler velocity from 2100 UTC 26 January 2015 to 900 UTC 27 January 2015. 6b (bottom). 72-hr. backward air trajectory from 600 UTC 27 January 2015. The event total precipitation was 9.8 mm.



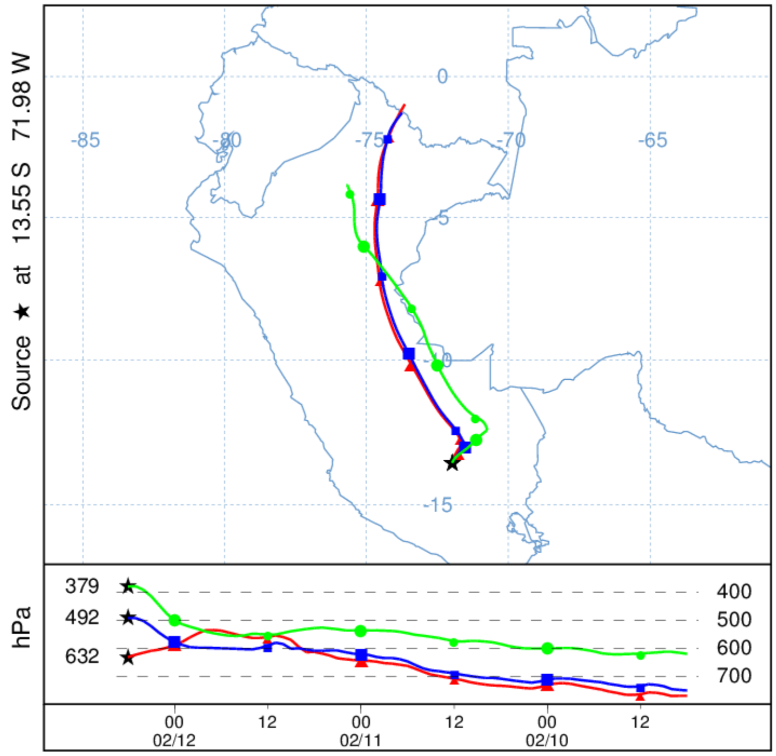


Figure 7a (top). Reflectivity and Doppler velocity from 000 UTC 12 February 2015 to 900 12 February 2015. 7b (bottom). 72-hr backward air trajectory from 600 UTC on 12 February 2015. The event total precipitation was 4.8 mm.

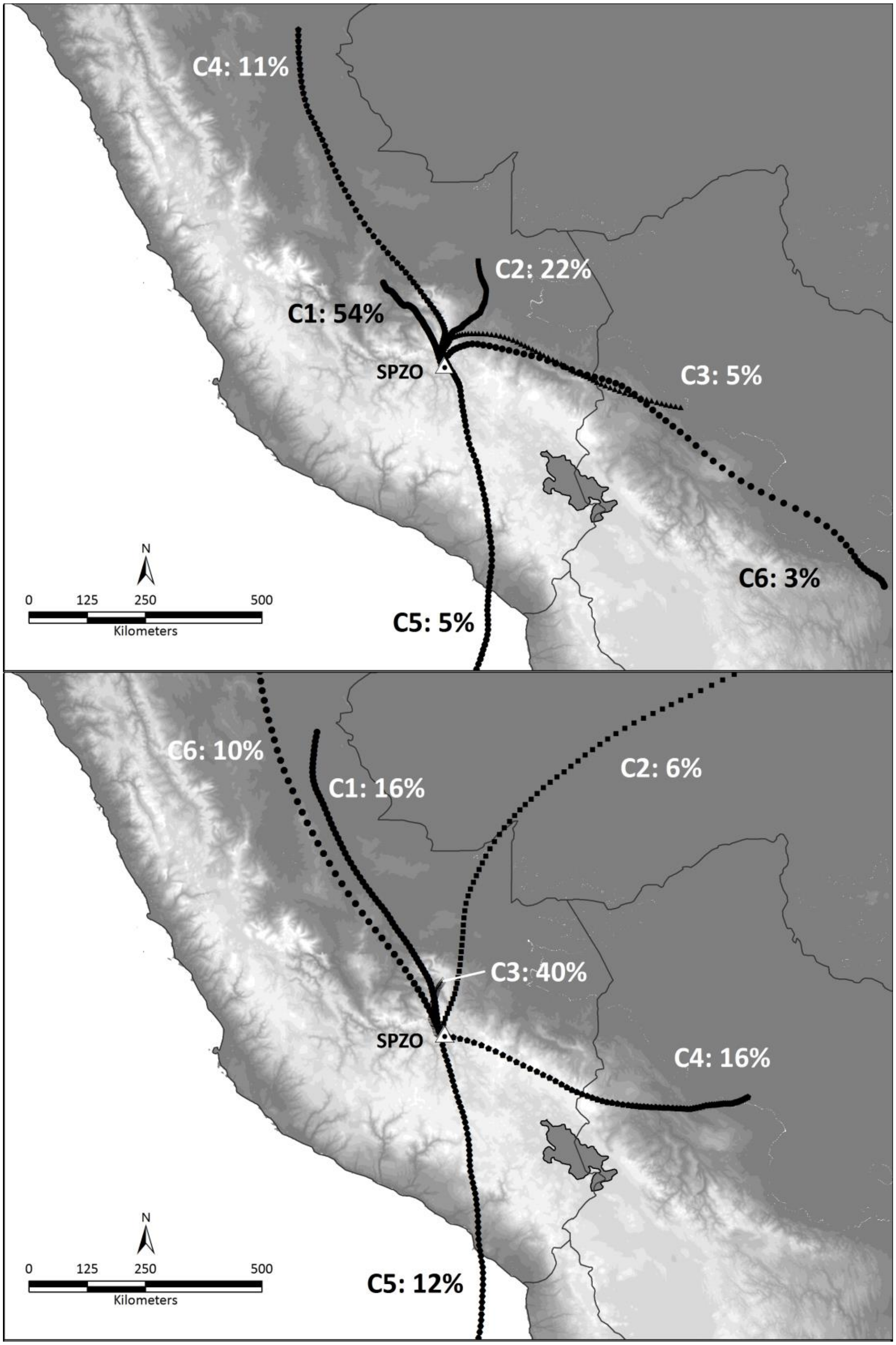


Figure 8. Clustered mean 72 hr backward air trajectories ending at 4000 m asl (top) and 6000m asl (bottom).

SUMMARY AND CONCLUSIONS

During the study period, there was a diurnal cycle in precipitation with the majority of precipitation occurring at night and a lower daytime maximum. Nighttime events were generally inferred to be stratiform in nature. They often had longer durations, well defined melting layers, echo top heights of 6000 m or lower, and were characterized by lower values of radar reflectivity. Daytime events were generally inferred to be convective in nature, had higher echo top heights, and poorly defined melting layers. These events were often shorter and with higher values of radar reflectivity. The majority of all precipitation events had trajectories coming from the northwest, with smaller percentages coming from the Amazon basin and the Pacific. These results provide valuable insight into the meteorological processes responsible for precipitation development and contribute to advancing scientific understanding of precipitation-glacier interactions and paleoclimate reconstruction in the Central Andes.

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