Characteristics of Precipitating Storms in Glacierized Tropical Andean Cordilleras of Peru and Bolivia

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Precipitation variability in tropical high mountains is a fundamental yet poorly understood factor influencing local climatic expression and a variety of environmental processes, including glacier behavior and water resources. Precipitation type, diurnality, frequency, and amount influence hydrological runoff, surface albedo, and soil moisture, whereas cloud cover associated with precipitation events reduces solar irradiance at the surface. Considerable uncertainty remains in the multiscale atmospheric processes influencing precipitation patterns and their associated regional variability in the tropical Andes—particularly related to precipitation phase, timing, and vertical structure. Using data from a variety of sources—including new citizen science precipitation stations; new high-elevation comprehensive precipitation monitoring stations at Chacaltaya, Bolivia, and the Quelccaya Ice Cap, Peru; and a vertically pointing Micro Rain Radar—this article synthesizes findings from interdisciplinary research activities in the Cordillera Real of Bolivia and the Cordillera Vilcanota of Peru related to the following two research questions: (1) How do the temporal patterns, moisture source regions, and El Niño-Southern Oscillation relationships with precipitation occurrence vary? (2) What is the vertical structure (e.g., reflectivity, Doppler velocity, melting layer heights) of tropical Andean precipitation and how does it evolve temporally? Results indicate that much of the heavy precipitation occurs at night, is stratiform rather than convective in structure, and is associated with Amazonian moisture influx from the north and northwest. Improving scientific understanding of tropical Andean precipitation is of considerable importance to assessing climate variability and change, glacier behavior, hydrology, agriculture, ecosystems, and paleoclimatic reconstructions. *Key Words: hydrometeorology, melting layer heights, precipitation, tropical Andes.*

热带高山的降水变异, 是影响在地气候表现以及包括冰川行为和水资源的多样环境过程的关键因素, 但却未能受到良好的理解。降雨类型, 日行性, 频率及雨量, 影响着水文径流, 地表反照率及土壤湿度, 而与降雨事件有关的云层覆盖, 则降低了地表的太阳辐射。在影响降雨模式的多重尺度大气过程, 及其在热带安第斯地区中的相关区域变异中, 仍然持续有着大量的不确定性, 特别是有关降雨时期, 时机与垂直结构。本文运用来自多样资源的数据——包括崭新的公民科学雨量站; 在查卡塔雅, 玻利维亚和秘鲁魁尔克亚的冰冠的崭新高海拔综合雨量监控站; 以及垂直观测的微观降雨雷达, 综合从玻利维亚的雷亚尔山脉与秘鲁韦尔卡努塔山脉的跨领域研究活动中有关下列两大问题的发现: (1) 时间模式, 湿度来源区域和圣婴—南方振荡现象, 与降雨发生之间的关系为何有所变异? (2) 什麽是热带安第斯山降雨的垂直结构 (例如反射率, 多普勒速度, 融解层高度), 及其如何随着时间变化? 研究结果指出, 大量降雨多半发生在夜间, 在结构上是层状而非对流的, 并与亚马逊湿气从北方与西北方流入有关。增进对於热带安第斯山降雨的科学性理解, 将对评估气候变异与变迁, 冰川行为, 水文, 农业, 生态系统与古气候的再结构具有重要影响。 *关键词: 水文气象学, 融解层高度, 降水, 热带安第斯山。*

La variabilidad en precipitaciones de las altas montañas tropicales es un factor fundamental, pero todavía pobremente entendido, que influye en la expresión climática local y en una variedad de procesos ambientales, incluyendo el comportamiento de los glaciares y los recursos hídricos. El tipo de precipitación, el carácter diurno, frecuencia y cantidad influyen la escorrentía hidrológica, el albedo de la superficie y la humedad del suelo, mientras que la cubierta de nubes asociada con los eventos de la precipitación reduce la irradiación solar de la superficie. Una considerable incertidumbre subsiste en los procesos atmosféricos de multiescala que influencian los patrones de precipitación y su asociada variabilidad regional en los Andes tropicales—en particular

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lo relacionado con la fase de precipitación, tipo y estructura vertical. Con el uso de datos de una variedad de fuentes—incluyendo estaciones de precipitación de la nueva ciencia ciudadana; las nuevas estaciones de altura que monitorean la precipitación en todos sus aspectos en Chacaltaya, Bolivia, y en el casquete nevado de Quelccaya, Perú; y un Micro Rain Radar orientado verticalmente—este artículo sintetiza los hallazgos de las actividades de investigación interdisciplinaria en la Cordillera Real de Bolivia y en la Cordillera Vilcanota del Perú, en relación con las siguientes dos preguntas de investigación: (1) ¿Cómo varían las relaciones de los patrones temporales, humedad de las regiones fuente y la Oscilación Meridional de El Niño con la ocurrencia de la precipitación? y (2) ¿Cuál es la estructura vertical (e.g., reflectividad, velocidad Doppler, alturas de la capa de fusión) de la precipitación andina tropical y cómo evoluciona ésta temporalmente? Los resultados indican que gran parte de la alta precipitación ocurre durante la noche, es más de estructura estratiforme que convectiva y está asociada con el influjo de humedad amazónica del norte y noroeste. La mejora en el entendimiento de la precipitación andina tropical es de gran importancia para evaluar la variabilidad y cambio climáticos, el comportamiento de los glaciares, la hidrología, la agricultura, los ecosistemas y las reconstrucciones paleoclimáticas.
Palabras clave: hidrometeorología, altura de la capa de fusión, precipitación, Andes tropicales.

Mountains represent approximately 24 percent of the land surface of the Earth and play a vital role in sustaining ecosystems and humanity (Marston 2008). Precipitation is the critical freshwater input to the hydrological system in mountain regions of the world (e.g., Singh, Singh, and Haritashya 2011), is a fundamental influence on mountain glaciers and ecosystems (e.g., Francou et al. 2003; Barry 2008; Kaser et al. 2010; Vuille 2011), and is the primary parameter preserved in ice cores obtained from mountain glaciers and ice caps (e.g., Thompson 2000). Precipitation type (e.g., rain vs. snow), timing, frequency, and amount control surface albedo in mountain environments, whereas cloud cover associated with precipitation events reduces solar irradiance at the surface, together resulting in a major influence on climate.

In the outer tropical Andes Mountains of southern Peru and Bolivia (12–16°S; Figure 1), a region where glacier meltwater is critical for buffering water supplies during the dry season (Chevallier et al. 2011), precipitation is of added significance in influencing glacier mass balance and surface albedo (Francou et al. 2003). Precipitation is the primary influence on oxygen stable isotope ratios (δ^{18}O, hydrogen-deuterium oxide) preserved in tropical ice cores (Vimeux et al. 2009). Precipitation also provides the critical freshwater inputs to hydrological resources (e.g., irrigation,

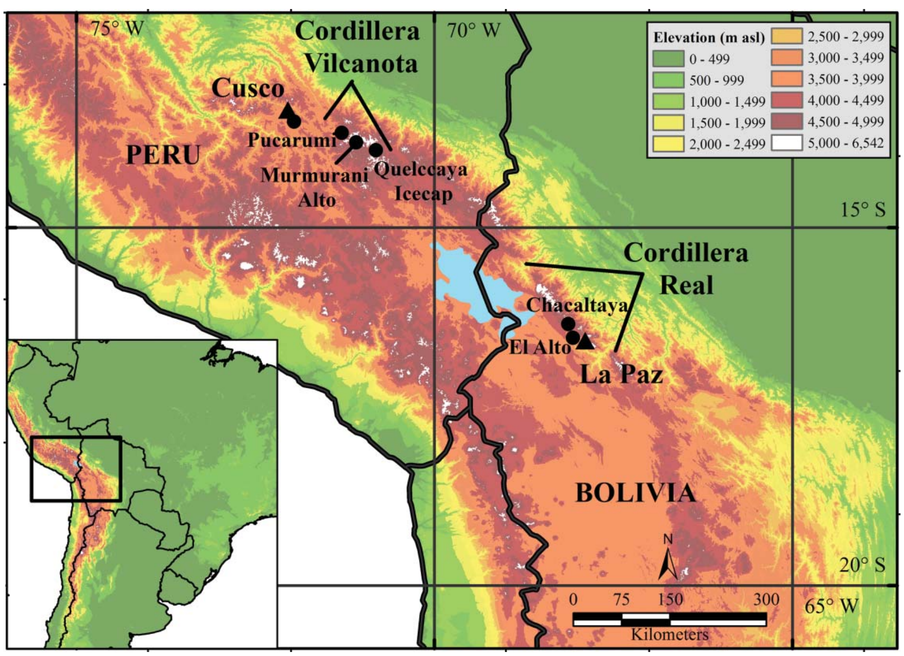

Figure 1. Location of field sites. (Color figure available online.)

hydroelectricity, water reservoirs) and is a major influence on ecosystems and agriculture (Bush, Hanselman, and Gosling 2010; Yager and Meneses 2010).

Previous investigations of tropical Andean precipitation have focused primarily on (1) the large-scale atmospheric circulation on seasonal (wet vs. dry) and interannual timescales (e.g., Garreaud 1999; Vuille 1999; Garreaud, Vuille, and Clement 2003; Vuille and Keimig 2004); (2) precipitation–climate–glacier interactions in the inner and outer tropics (e.g., Hardy et al. 1998; Francou et al. 2003; Favier, Wagnon, and Ribstein 2004; Salzmann et al. 2013); and (3) atmospheric influences on δ^{18}O values recorded in precipitation in the context of paleoclimatic interpretation (e.g., Vimeux et al. 2005). The outer tropical Andes (e.g., 12–16°S) are characterized by distinct seasonality of precipitation, with a wet season from November to March (shorter in the south and west) and a dry season from April through October. Moisture transport, as inferred from backward air trajectories, is almost exclusively from the Amazon basin (Vimeux et al. 2005; Perry, Seimon, and Kelly 2014), although the trajectories vary depending on regional topographic setting. Hurley et al. (2015) even suggested that heavy snowfall events on the Quelccaya Ice Cap in the Cordillera Vilcanota might be tied to extratropical cold surges in southeastern South America.

Tropical Pacific sea-surface temperatures (SSTs) and the associated El Niño-Southern Oscillation (ENSO) provide a strong influence on the interannual variability of precipitation in the outer tropical Andes. According to Vuille (1999), easterly flow and the advection of Amazon moisture is enhanced in the wet season during the cold phase of ENSO (La Niña), resulting in above-normal precipitation, greater cloud cover, and lower temperatures in the outer tropical Andes. In contrast, during the warm phase of ENSO (El Niño), enhanced upper level westerly flow presumably leads to a delay in the onset of the wet season. Additionally, much of the tropical Andes experiences below-normal precipitation and associated reductions in cloud cover (Vuille and Keimig 2004) and higher temperatures (Vuille et al. 2003). Nonetheless, the spatial variability in the ENSO response is complex (e.g., Vuille and Keimig 2004; Ronchail and Gallaire 2006), and precipitation totals are higher in the Cordillera Vilcanota during El Niño years (Perry, Seimon, and Kelly 2014). Several studies (e.g., Wagnon et al. 2001; Francou et al. 2003) have reported rapid glacier ablation and highly negative mass balance in the Cordillera Real of Bolivia during strong El Niño events, such as 1997–1998.

Prior to studies specifically addressing diurnality, tropical Andean precipitation was described simply as the late-day convective response to daytime solar heating in the presence of adequate boundary layer moisture (Johnson 1976; Aceituno 1997; Garreaud, Vuille, and Clement 2003; Vuille and Keimig 2004). New quantitative studies reveal that in reality, nighttime stratiform precipitation contributes a majority of the total annual precipitation in many locations (e.g., Biasutti et al. 2012; Romatschke and Houze 2013; Mohr, Slayback, and Yager 2014; Perry, Seimon, and Kelly 2014). A substantial fraction of satellite-borne reflectivity signatures across portions of the tropical Andes, including the Cordillera Vilcanota and Cordillera Real, are indicative of stratiform precipitation (Romatschke and Houze 2013) and yield a nighttime maximum in the timing of precipitation (Mohr, Slayback, and Yager 2014). This is in agreement with precipitation gauge observations from Cusco and the Cordillera Vilcanota that exhibit a nighttime precipitation maximum, which are inferred to be stratiform in character (Perry, Seimon, and Kelly 2014).

With the exception of simple classifications based solely on an automated system using temperature in the Cordillera Real, Bolivia (L'hôte et al. 2005), and on Antisana Volcano, Ecuador (Favier, Wagnon, and Ribstein 2004), studies discriminating precipitation phase in the tropical Andes using high–temporal resolution present weather sensors (e.g., Yuter et al. 2006) have been limited. Likewise, no studies exist of ground-based radar-derived melting layer heights or their associated tropospheric conditions in the glacierized regions of the outer tropical Andes.

The limited understanding of tropical Andean precipitation patterns and processes introduces considerable uncertainty in interpreting precipitation–glacier–hydroclimate interactions, conducting paleoclimatic reconstructions, and predicting future climate scenarios in the region (Vuille et al. 2008; Perry, Seimon, and Kelly 2014). Taken together, these uncertainties reduce the climatological inference that can be derived from ice cores in the region (e.g., Thompson et al. 1985; Thompson et al. 1986; Ramirez et al. 2003; Thompson et al. 2006; Kellerhals et al. 2010; Thompson et al. 2013). Furthermore, understanding regional variability in climate and precipitation is particularly important to interpreting local implications of precipitation changes projected by climate models

Table 1. Summary of data sources

Location	Elevation (m asl)	Temporal resolution	Period	Source
1. Precipitation				
Cusco	3,350	24 hr	1963–2010	UNSAAC Observatory
La Paz	4,038	24 hr	1980–2010	SENAMHI Bolivia
2. Precipitation, snowfall, and snow depth				
Murmurani Alto	5,050	24 hr	2010–2015	Citizen Science Observers
Pucarumi	4,100	24 hr	2011–2015	Citizen Science Observers
Quelccaya Base	4,950	24 hr	2014–2015	Citizen Science Observers
3. Present weather				
Cusco/SPZO	3,310	1 hr	2011–2015	Aviation METARs
La Paz/SLLP	4,038	1 hr	2011–2015	Aviation METARs
Murmurani Alto	5,050	1 hr	2012–2015	Parsivel Disdrometer
Quelccaya Icecap	5,650	1 hr	2014–2015	Parsivel Disdrometer
Nevado Chacaltaya	5,160	1 hr	2014–2015	Parsivel Disdrometer
4. Liquid equivalent precipitation				
Quelccaya Icecap	5,650	1 hr	2014–2015	Pluvio^2 weighing gauge
Nevado Chacaltaya	5,160	1 hr	2014–2015	Pluvio^2 weighing gauge
5. Backward air trajectories				
South America		1 hr	2014–2015	GDAS 0.5° data
6. Radar reflectivity, Doppler velocity, melting layer height				
Cusco	3,350	1 min	2014–2015	Micro Rain Radar
La Paz	3,440	1 min	2015–2016	Micro Rain Radar

incorporating anthropogenic forcings and multidecadal teleconnections and oscillations (Urrutia and Vuille 2009).

This article is guided by the following research questions:

1. How do the temporal patterns, moisture source regions, and ENSO relationships with precipitation occurrence vary in the outer tropical Andes?
2. What is the vertical structure (e.g., reflectivity, Doppler velocity, melting layer heights) of tropical Andean precipitation and how does it evolve temporally?

The results presented here, although particular to the Cordillera Vilcanota and Cordillera Real, contribute more broadly to the understanding of the meteorological factors that influence precipitation patterns and hydroclimate in the tropical high Andes.

Data and Methods

Precipitation Data Sources and Time Periods

Table 1 summarizes the data sources and time periods used for this study. In situ manual precipitation data were obtained from (1) the Universidad Nacional de San Antonio de Abád de Cusco (UNSAAC, 1963–2010) and (2) the La Paz/El Alto JFK International Airport (SLLP, 1980–2010). We obtained hourly present weather observations from the Cusco International Airport (SPZO) and SLLP Meterological Terminal Aviation Routine (METAR) weather reports for the period 2011 to 2015. Manual observations from three citizen science stations located in the Cordillera Vilcanota also provided a valuable source of data for this study. The citizen science stations are all located above 4,000 m above sea level (asl; all elevations hereafter are asl). Manual liquid equivalent precipitation measurements were taken each morning at the citizen science stations at approximately 0700 LST (1200 UTC) by a trained observer using established protocols developed for measuring snowfall (Doesken and Judson 1996) and for citizen scientist precipitation observers as part of the Collaborative Rain, Hail, and Snow (CoCoRaHS) network in the United States and Canada (Cifelli et al. 2005). Hourly present weather observations were also obtained from three automated high-elevation precipitation monitoring stations: Murmurani Alto and Quelccaya in the Cordillera Vilcanota and Chacaltaya in the Cordillera Real. We used the OTT PARSIVEL present weather sensors (Löffler-Mang and Joss 2000; Löffler-Mang and Blahak 2001) at all three stations to classify the timing, type, and intensity of precipitation.

National Oceanic and Atmospheric Administration's Hybrid Single Particle Lagrangian Integrated Trajectory Trajectory Tool

The National Oceanic and Atmospheric Administration's (NOAA) Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Rolph 2015) was used to simulate seventy-two-hour backward air trajectories ending at the date and time of the maturation hours of precipitation events at Cusco, Quelccaya Ice Cap, and Chacaltaya. We used ending heights of 4,000 m and 6,000 m for Cusco and 5,000 m for both Quelccaya and Chacaltaya. These levels are typically within the lower cloud layer during precipitation events and are therefore used as a proxy for low-level moisture transport. HYSPLIT backward trajectories were derived using four-dimensional (x, y, z, t) meteorological fields from the Global Data Analysis System (GDAS) data set. GDAS data are available from 2007 at three-hourly temporal resolution and 0.5° (latitude/longitude grid) spatial resolution with twenty-three vertical levels. We performed a cluster analysis of the HYSPLIT backward air trajectories for Cusco, Quelccaya, and Chacaltaya. This method groups or clusters similar trajectories and maximizes the differences in the clusters of trajectories (e.g., Taubman et al. 2006; Kelly et al. 2013).

Micro Rain Radar

We deployed a 24-GHz vertically pointing Micro Rain Radar (MRR; e.g., Peters, Fischer, and Andersson 2002) at the SENAMHI Peru office in Cusco from August 2014 to February 2015 and at the UMSA Cota Cota campus in La Paz from October to December 2015. The MRR provided continuous profiles of hydrometeor reflectivity (dBZ) and Doppler velocity from 3,350 m (3,440 m) in Cusco (La Paz) up to 7,850 m (7,940 m) using thirty 150-m gates. MRR data were postprocessed using the technique developed by Maahn and Kollias (2012) to remove noise, improve data quality, and improve data sensitivity in snow. Distinct melting layers are present in vertically pointing radar profiles when vertical air motions are weak, which usually corresponds to periods of stratiform precipitation (Houze 1997). The top of the melting layer observed in radar reflectivity corresponds to the highest altitude 0°C level height during periods of precipitation (Minder and Kingsmill 2013). Particle fall speed increases as snow fully melts into rain at the bottom of the melting layer and is detectable in vertically pointing Doppler velocity (Houze 1993). In our analysis, the bottom of the melting layer is identified as the most negative gradient in Doppler velocity in the profile and the top of the melting layer as the most negative gradient in reflectivity. To determine the top of the melting layer, the average hourly melting layer thickness (top minus bottom) was combined with the 1-minute values of melting layer in that hour. We elected to discard any melting layer height values greater than one standard deviation of the hourly mean. Eight heavy nighttime stratiform events in Cusco and four in La Paz (1) had MRR data available, (2) occurred primarily at nighttime (between 0000 and 1200 UTC), (3) had an hour or more of continuous stratiform precipitation characterized by a well-defined melting layer, (4) had a duration of longer than four hours, and (5) deposited liquid equivalent precipitation of more than ~10 mm at Cusco (SPZO) or Chacaltaya. For these events, HYSPLIT backward air trajectories were also calculated ending at 4,000 m, 6,000 m, and 8,000 m over Cusco and La Paz.

Results and Discussion

2014–2015 Precipitation Totals

Precipitation totals for the 2014–2015 hydrological year for stations analyzed in this article (Table 2) ranged from 633 mm at El Alto to 1,143 mm in Pucarumi, with totals slightly above the long-term mean annual values at most locations. A bimodal diurnal distribution of frequency of precipitation occurrence was evident across all stations, consisting of afternoon and nighttime maxima (Figure 2). The afternoon maximum occurred around 2000 UTC (1500 LST) in Cusco and the Cordillera Vilcanota but nearly two hours earlier, around 1700 UTC (1300 LST), in the Cordillera Real. The timing of the nighttime maximum was very similar across all stations, with a broad peak centered between 0400 and 0500 UTC (midnight LST). An afternoon maximum in frequency of precipitation occurrence existed for the higher elevation stations of Quelccaya, Murmurani Alto, and Chacaltaya, whereas this pattern reversed for the lower elevation stations of Cusco and El Alto, where the nighttime maximum was clearly dominant. The bimodal distribution of precipitation is consistent with the results of Perry, Seimon, and Kelly (2014) and confirms the importance of widespread nighttime precipitation across the region.

Table 2. Precipitation characteristics from 2014–2015 hydrological year

Location	Mean annual precipitation (mm)	2014–2015 hydrologic year precipitation totals (mm)												
		Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Total
Peru														
Cusco	820	3	13	15	79	18	171	167	146	87	73	19	4	794
Pucarumi	1,111	1	10	63	69	78	205	236	178	170	118	11	6	1,143
Murmurani Alto	732	−99	8	39	66	67	132	125	121	89	109	34	18	809
Quelccaya Base	−99	−99	12	22	30	61	89	155	89	59	110	85	18	730
Bolivia														
El Alto	618	4	17	46	29	26	115	135	86	96	76	4	0	633
Chacaltaya	−99	−99	−99	−99	−99	51	144	196	110	161	102	11	0	779

Note: −99 denotes missing data. See Table 1 for years used for the calculation of the mean annual precipitation.

Precipitation Type

Observations of precipitation type at the three stations located above 5,000 m indicated that the frequency of precipitation was greatest in the austral summer (December–February) and that solid precipitation dominated, representing more than 95 percent of all precipitation hours (Figure 3). Snow was the primary precipitation type, but graupel (*phati* in the native Quechua language) also constituted a significant fraction of precipitation hours, particularly on the Quelccaya Ice Cap and at Murmurani Alto during the austral winter. Detailed field observations of snow particle type and degree of riming during research expeditions over a five-year period confirm that the particles are indeed graupel, consisting of a heavily rimed snow crystal whose original structure is unrecognizable (e.g., Mosimann, Weingartner, and Waldvogel 1994). Although liquid precipitation (rain and freezing rain) was infrequent (5 percent of precipitation hours; range of 0–18 percent of precipitation hours per month), its presence at elevations above 5,000 m is noteworthy, as many glacier termini in the Cordillera Vilcanota (e.g., Salzmann et al. 2013) and Cordillera Real are found below this elevation. As freezing levels continue to rise globally in the tropics (Diaz et al. 2003) and in the tropical Andes (Bradley et al. 2009), it is not surprising that liquid precipitation occurs in 5 percent of our observations at Murmurani Alto at 5,050 m. This suggests that rain occurs on occasion in the ablation zone of nearby glaciers, promoting enhanced melting of the glacier surface and reducing surface albedo and likely influencing glacier mass balance (e.g., Francou et al. 2003). High-altitude liquid precipitation occurrence might therefore be a strong indicator of climate change in the region.

Backward Air Trajectories

The seventy-two-hour backward air trajectories for precipitation events in Cusco were primarily from the northwest (Figures 4A, 4B), in general agreement with the results of Perry, Seimon, and

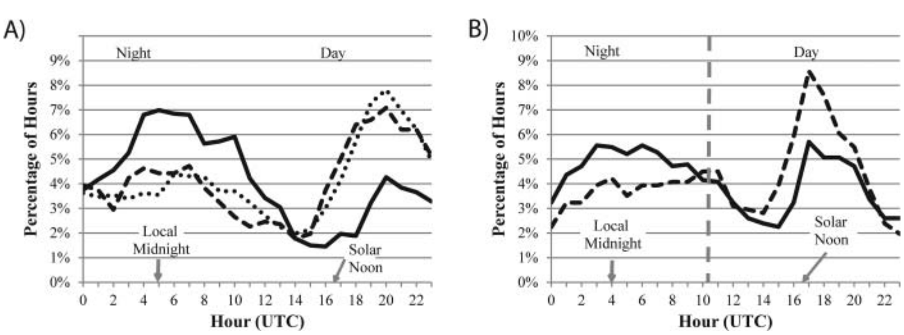

Figure 2. Precipitation timing at (A) Cusco (solid), Murmurani Alto (dotted), and Quelccaya Ice Cap (dashed); and (B) El Alto (solid) and Chacaltaya (dashed). Data time period for Cusco is 11 August 2011 to 30 June 2015; Murmurani Alto is 4 April 2012 to 13 January 2015; Quelccaya Ice Cap is 4 November 2014 to 30 June 2015; El Alto is August 2011 to 30 June 2015; and Chacaltaya is 1 November 2014 to 30 June 2015.

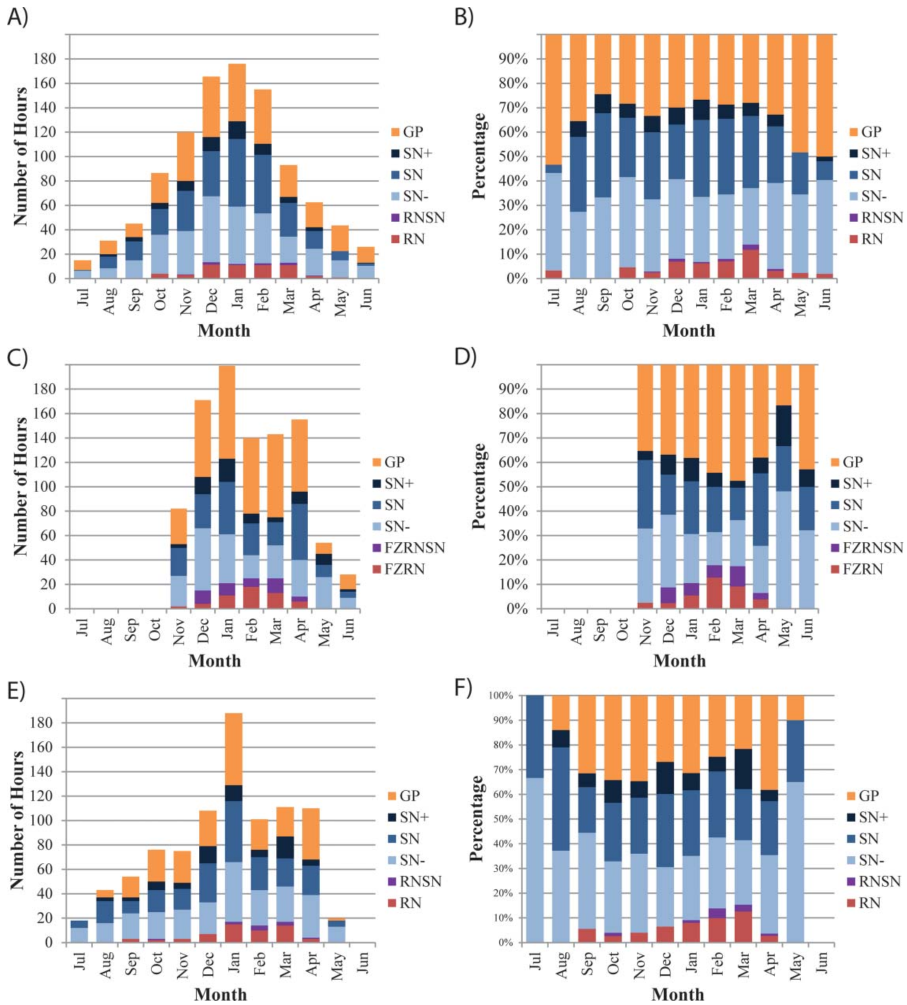

Figure 3. All precipitation hours by month at (A, B) Murmurani Alto, (C, D), Quelccaya, and (E, F) Chacaltaya. GP = graupel; SN+ = heavy snow; SN = moderate snow; SN− = light snow; RN/SN = rain and snow mix; RN = rain. Data time period for Murmurani Alto is 1 July 2012 to 30 July 2014 and monthly averages are plotted; Quelccaya is 4 November 2014 to 30 June 2015; and Chacaltaya is 1 December 2014 to 30 November 2015. (Color figure available online.)

Kelly (2014). The clusters comprising the largest percentage of events produced by HYSPLIT at 4,000 and 6,000 m both had trajectories from this direction. There were also smaller easterly clusters that originated in the Amazon at both ending heights as well as one southerly cluster at both heights from the Pacific. The northwest clusters had the shortest mean trajectories (i.e., weakest flow) and traveled closer to the ground. In general, the trajectory analyses for both Quelccaya and Chacaltaya are similar (Figures 4C, 4D) and suggest that Amazon air parcels originating to the northwest and north of the Cordillera Vilcanota and Cordillera Real were associated with the majority of the precipitation events during the 2014–2015 wet season. These trajectories are consistent with the climatologically favored backward trajectories for the Zongo Valley of the Cordillera Real calculated by Vimeux et al. (2005), which were predominantly out of the north and north-northwest during the austral wet season. Nonetheless, these trajectories represent precipitation events for only one hydrological year and a longer time series will increase confidence of the climatological relationships.

Multidecadal ENSO–Precipitation Relationships

Long-term (greater than twenty-five years) hydrological year annual precipitation totals at Cusco (UNSAAC) and La Paz (SLLP) plotted according to ENSO phase (Figures 5A, 5B) highlight the complexity of ENSO–precipitation relationships in the outer tropical Andes. In Cusco, strong El Niño years are

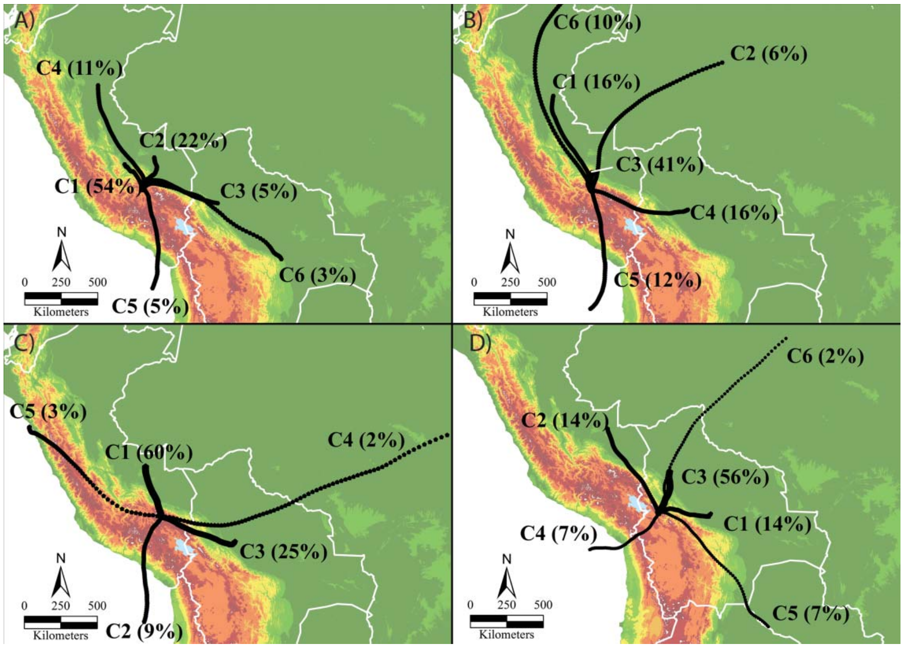

Figure 4. Clustered mean seventy-two-hour backward air trajectories for 2014–2015 precipitation events at (A) Cusco (ending at 4,000 m asl), (B) Cusco (ending at 6,000 m asl), (C) Quelccaya (ending at 6,000 m asl), and (D) Chacaltaya (ending at 6,000 m asl). (Color figure available online.)

characterized by positive precipitation anomalies, in contrast to strong La Niña years, which are associated with negative anomalies. In La Paz, both strong El Niño and strong La Niña years exhibit negative precipitation anomalies, with all other years much wetter. The positive (negative) anomalies associated with El Niño (La Niña) in Cusco are generally consistent throughout the hydrological year, whereas in La Paz precipitation with both El Niño and La Niña is close to normal until the austral fall (March–May), when negative anomalies predominate.

Vertical Structure of Precipitation

Observations of the vertical structure of precipitation from the MRR in the Cordillera Vilcanota and Cordillera Real indicate that the afternoon precipitation maxima was primarily convective, whereas the nighttime precipitation was largely stratiform in character. A fifteen-hour period in Cusco on 11 and 12 February 2015 (Figure 6) illustrates the discontinuous and cellular nature, widely varied reflectivity signatures, and lack of a well-defined melting layer typical

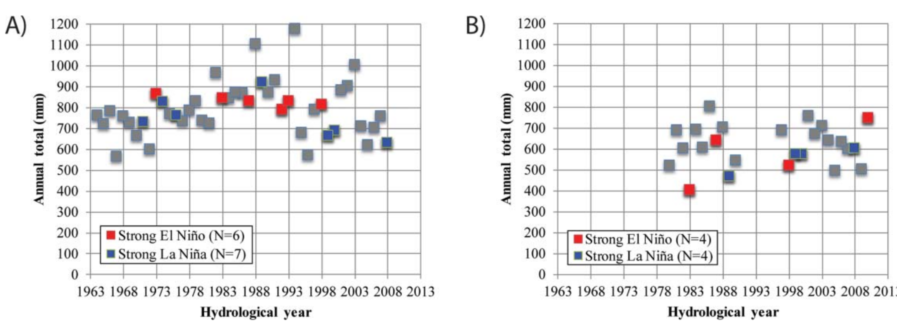

Figure 5. Hydrological year scatterplots of annual precipitation by El Niño-Southern Oscillation phase for (A) Cusco–UNSAAC (3,365 m) 1963–2009 and (B) La Paz–El Alto (4,038 m) 1979–2009 according to December to March Multivariate El Niño-Southern Oscillation Index means. The characterization of strong events is determined by the mean December to March MEI, with values > +1.00 used to identify strong El Niño events and values < −1.00 used for strong La Niñas; given that MEI is assessed based on bimonthly statistics this means average December to January, January to February, and February to March MEI values. All other "regular" years fall between these two thresholds; that is, MEI values < +1.00 and > −1.00. Source data for MEI are from National Oceanic and Atmospheric Administration–Earth System Research Laboratory, Physical Sciences Division (2017). MEI = Multivariate El Niño-Southern Oscillation. (Color figure available online.)

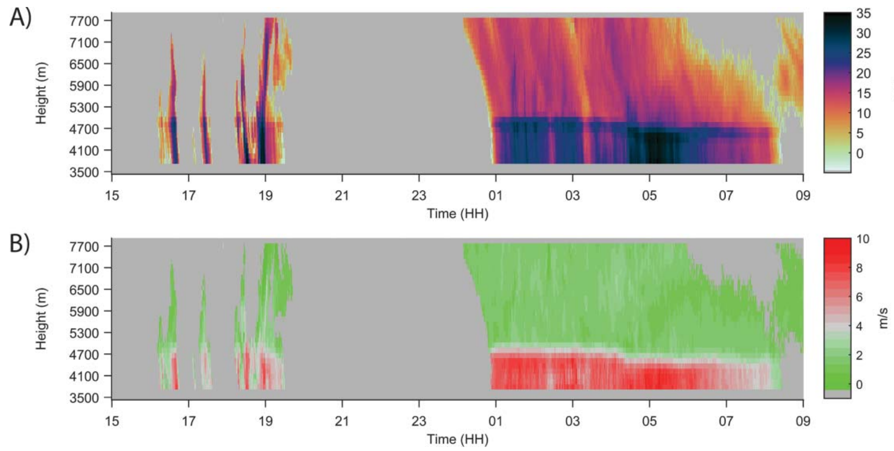

Figure 6. Summary of Micro Rain Radar (A) radar reflectivity (dBZ) and (B) Doppler velocity (m s^{-1}) for 1500 UTC 11 February 2015 to 0900 UTC 12 February 2015 in Cusco. (Color figure available online.)

of convective precipitation between 1500 and 2100 UTC (1000–1600 LST). In contrast, the more continuous nature, longer duration, and presence of a well-defined melting layer between 0100 and 0800 UTC (2100–0300 LST) indicate largely uniform layers of stratiform precipitation. These cases, along with many others at both Cusco and La Paz (not shown), confirm previous inferences by Perry, Seimon, and Kelly (2014) that afternoon precipitation is largely convective and nighttime precipitation is primarily stratiform. Considerable uncertainty remains as to the origin of the nighttime stratiform events and will require detailed investigations of individual events.

Frequency distributions of melting layer heights for precipitation observed by the MRR in Cusco and La Paz (Figure 7) share common characteristics. Median values (standard deviations) for melting layer heights at Cusco were 4,810 m (264 m) and 4,786 m (255 m) for La Paz, with most melting layer heights between 4,400 and 5,100 m. Although these median values are still below the ablation zones of most glaciers in the Cordillera Vilcanota and Cordillera Real, an increase in median melting layer heights of 200 m would result in rain falling during 49 percent (54 percent) of all precipitating hours at 5,000 m in Cusco (La Paz), compared to 14 percent (16 percent) during the periods of study.

Case Studies

An analysis of eight heavy (liquid equivalent precipitation > ~10 mm) nighttime stratiform precipitation events in Cusco (Table 3) and four in La Paz (Table 4) highlights numerous consistencies in their timing (peak around 0400 to 0500 UTC [~midnight LST]), total precipitation (~10–20 mm), maximum column reflectivity (40–45 dBZ), mean column reflectivity (18–22 dBZ), and mean melting layer heights (4,500–4,700 m). The seventy-two-hour backward trajectories ending at 4,000 m for the Cusco precipitation events all originated in the Amazon basin to the northwest, whereas the trajectories ending at 6,000 m and 8,000 m were more varied, with several originating over the Pacific Ocean. The seventy-two-hour backward trajectories for the four events in La Paz were all characterized by north or north-northwest flow that originated in the Amazon basin at all levels.

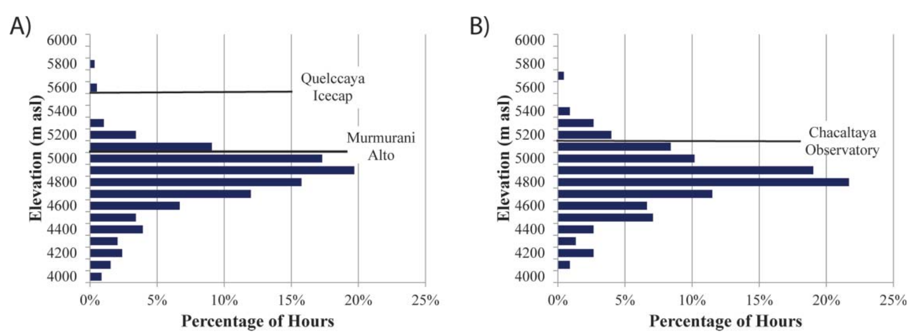

Figure 7. Frequency distribution of melting layer heights for (A) Cusco and (B) La Paz. Cusco data are for August 2014 to February 2015 and La Paz data are for October to December 2015. (Color figure available online.)

Table 3. Characteristics of heavy nighttime stratiform precipitation events in Cusco

Date(s)	Time range (UTC)		Total precipitation (mm)	Maximum reflectivity (dBZ)	Mean column reflectivity (dBZ)	Mean melting layer height (m asl)	Trajectory origin		
	Start	End					4,000 m	6,000 m	8,000 m
8 Oct 2014	0100	0700	16.6	42.2	21.4	4,545	N/Amazon	NW/Amazon	E/Amazon
9 Dec 2014	0300	0700	15.2	41.2	22.5	4,719	NW/Amazon	S/Pacific	SW/Pacific
17 Dec 2014	0000	0900	23.0	38.6	19.2	4,571	NW/Amazon	S/Pacific	E/Amazon
19–20 Dec 2014	2300	0600	15.6	40.7	18.2	4,688	NW/Amazon	S/Pacific	S/Pacific
19 Jan 2015	0100	0700	14.6	44.0	20.0	4,550	NW/Amazon	S/Andes	W/Andes
26–27 Jan 2015	2200	0800	9.8	43.6	17.3	4,639	NW/Amazon	E/Amazon	SE/Amazon
10 Feb 2015	0800	1300	13.0	39.2	19.8	4,550	NW/Amazon	NW/Amazon	NW/Amazon
11 Feb 2015	0100	1000	14.4	39.7	18.9	4,704	NW/Amazon	NW/Amazon	NW/Amazon

Table 4. Characteristics of heavy nighttime stratiform precipitation events in La Paz

Date(s)	Time range (UTC)		Total precipitation (mm)	Maximum reflectivity (dBZ)	Mean column reflectivity (dBZ)	Mean melting layer height (m asl)	Trajectory origin		
	Start	End					4,000 m	6,000 m	8,000 m
3 Oct 2015	0700	1100	11.4	32.0	15.0	−99	N/Amazon	N/Amazon	N/Amazon
29 Oct 2015	0100	0600	21.3	39.0	18.0	4,578	N/Amazon	N/Amazon	N/Amazon
12 Nov 2015	0100	0700	10.8	36.0	18.0	4,715	NNW/Amazon	NNW/Amazon	NNW/Amazon
19 Dec 2015	0500	1200	9.7	39.9	15.0	4,640	N/Amazon	N/Amazon	N/Amazon

These results suggest that all of the analyzed heavy nighttime stratiform events were associated with low-level moisture in association with north or northwest flow originating in the Amazon basin and mid- and upper level moisture primarily originating in the Amazon basin but with greater variability in the backward trajectories for Cusco.

Summary and Conclusions

In this article, we have investigated the spatiotemporal patterns, moisture source regions, ENSO relationships, and vertical structure of precipitation in the Cordillera Vilcanota of southern Peru and the Cordillera Real of Bolivia. Results indicate that much of the heavy precipitation occurs at night, is stratiform rather than convective in structure, and is associated with Amazonian moisture influx from the north and northwest. Our findings of positive (negative) precipitation anomalies during El Niño (La Niña) in Cusco and negative anomalies during both El Niño and La Niña in La Paz also highlight the complex ENSO–precipitation relationships in the region. Melting layer heights for most precipitation hours are currently beneath the levels of glacier termini in the Cordillera Vilcanota and Cordillera Real, but in situ observations of precipitation type in the vicinity of ablation zones of glaciers in the region indicate that liquid precipitation accounts for 5 percent of all precipitation hours. Melting layer height increases of only 200 m, however, could result in approximately half of the total precipitation falling as rain on tropical Andean glaciers. Such height increases, which equate to approximately a 1.2°C midtropospheric temperature increase (which is close to the midcentury projected value according to the Intergovernmental Panel on Climate Change 5th Assessment Report; Cubasch et al. 2013), would act to augment the rapid ablation of regional glaciers already exhibiting strongly negative mass balance under the current warming regime. As such, the capacity of tropical Andean glaciers to serve as reliable buffers for water supply to human and natural systems, already in decline, looks to dwindle even more rapidly as rainfall encroaches steadily higher into the Andean nival zone.

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