SYNOPTIC PATTERNS ASSOCIATED WITH WET SEASON ONSET IN THE TROPICAL HIGH ANDES OF SOUTHERN PERU AND BOLIVIA

A Thesis
by
TANIA KATHERINE ITA VARGAS

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Abstract

SYNOPTIC PATTERNS ASSOCIATED WITH WET SEASON ONSET IN THE TROPICAL HIGH ANDES OF SOUTHERN PERU AND BOLIVIA

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In the southern Andes of Peru and Bolivia there is a clear distinction between the wet and dry season. Precipitation is one of the most relevant factors in determining glacier mass balance since the wet season onset interrupts the ablation period caused by low albedo and intense solar radiation at the end of the dry season. This study examines daily precipitation observations from 1979 to 2017 in Peru and Bolivia and identifies the wet season timing, interannual variability, and tendencies. The ERA-Interim Reanalysis (0.75° Lat/Lon - 6 hours) provide insights into the seasonal variation of wind, moisture and geopotential height related to the wet season timing over the study area. We identify spatiotemporal variations in the wet season timing mostly associated with the distance to the equator and to the Amazon basin, in which onset dates exhibits a pronounced variability. Significant trends showing the delay of the wet season onset in 0.4 to 0.8 days/year were found in the southwestern subregions, which are closely related with the occurrence of early/late wet season onset cases. A low-level northwesterly flow east of the Andes is the main feature in the lower troposphere related to the wet season onset, as well as an anticyclonic circulation in mid-troposphere and northwesterly winds in the upper troposphere. Changes in the position and strength of these circulations are observed during early vs late wet season onset cases. This result has implications for improving seasonal precipitation predictions from tropical high Andes and in the interpretation of tropical Andean ice cores.

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Completing my Master's degree is so far the most important academic accomplishment for me, which have not been possible without the absolute support of my parents, Mirtha Vargas and Jaime Ita. Especially when years ago, they supported my decision to drop up my career in Management to start a new one in Meteorology at Agrarian La Molina National University, Lima- Peru. The National Weather Service of Peru (SENAMHI-Peru) plays also an instrumental role in my personal and academic formation. I completed my internship and worked at SENAMHI for five years as a weather forecaster, during that time I had the opportunity to analyze and forecast, of course, different weather events in the country, as well travel around Peru, experiencing different climates and interacting with weather observers, their families, and local Andean communities. SENAMHI also has given me the chance to travel for the first time to the USA and participate to the International Desk Meteorology at NOAA where I got valuable training forecasting for South America. I also would like to thank my boyfriend Paul Alva, my colleague and best friend for all his emotional support, for all our daily talks, and for his guidance in personal and meteorological subjects.

I would like to thank Dr. Baker Perry, who made it possible for me to be here in the first place. Since I began with the admission process back in the fall of 2017, his guidance and support have been invaluable for me. Dr. Perry has also opened up his family's home to me for dinners and holiday celebrations. Along with the development of my thesis, Dr. Perry always promote papers discussions, which were the base to land on my current research topic. He always motivates me and thoughtfully guides my research through every graphic, presentation, and draft of my thesis. I would also thank my committee members, Dr. Margaret Sugg, who provided insightful guidance in the statistical analysis of the thesis, and Dr. Isabel Moreno, which guidance on the formulation of the data analysis was important, as well as her knowledge in the Bolivian climate. Also thanks to my peer, Christian Barreto Schuler, who worked with me on the methodology applied in this work and helped me with processing the numerical model data. Special thanks to Joe Jonaitis, who processed all the precipitation data, simplifying this step for me, and for his sincere friendship during the time we share together in the Department of Geography and Planing.

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Foreword

The main body of this thesis is formatted to the guidelines for manuscript submission to the *Journal of Applied Meteorology and Climatology*, an official journal of the American Meteorological Society.

Introduction

The tropical high Andes of southern Peru and Bolivia are part of the outer tropical region of South America, an area characterized by a well distinguished wet and dry season during the year (Kaser 2001). The annual precipitation regimen in this region is commonly associated with a wet summer and dry winter (Garreaud, et al. 2003). During the wet season, precipitation plays a relevant role in increasing water supplies that are used for domestic consumption, agriculture, hydropower, mining, and other industrial and social activities. While during the dry season, melting of glaciers located at high elevations in this area, provide fresh water used in many of the same activities. In addition, from a glaciological perspective, precipitation is one of the most relevant factors determining glaciers mass balance because it interrupts the high ablation period at the end of the dry season caused by low albedo and intense solar radiation (Francou et al 2003; Rabatel et al. 2013; Sicart et al. 2011; Wagnon et al. 1999a, b).

The study area of this work comprises Cordillera Vilcanota in Peru and Cordillera Real in Bolivia, two important glaciered areas that together account for more than 60% of all tropical glaciers in the Andes between 12 - 16°S (Rabatel et al. 2013). Since 1970s these glaciers have been experiencing an extraordinary retreat with the highest rate since the 1980s (Rabatel et al. 2013; Salzmann et al. 2013, Vuille et al. 2018), including the disappearance of small glaciers, particularly those located below 5200 m asl (Hanshaw and Bookhagen 2014). Future projections suggest that this trend will continue, changing the availability of the water resource and affecting different sectors such as hydropower, agriculture, tourism, etc., as well as ecosystems in the Andes (Vergara et al. 2007; Drenkhan et al. 2015; Kronenberg et al. 2016), increasing social and political conflicts in Andean communities (Vuille at al. 2018).

Moreover, although previous studies highlight the role of the timing and duration of the wet season as a crucial factor for glacier mass balance (Francou et al. 1995; Francou et al. 2003; Sicart et al. 2011), currently it is not fully understood when the wet season actually begins and ends or the associated synoptic patterns.

This study examine daily precipitation observation from 1979 to 2017 from 43 weather stations in southern Peru and Bolivia to identify the wet season timing following the procedure stablished by Liebmann and Marengo (2001), Liebmann et al. (2007), and Dunning et al. (2016). Secondary objectives in this work are the examination of the interannual variability, tendencies, and the analysis of two ENSO events, the very strong El Niño (1982-83) and the strong La Niña (1988-89). Atmospheric fields from the ERA-Interim Reanalysis (0.75° Lat/Lon - 6 hours) are analyzed in the same period (from 1979 to 2017) to provide insights into the seasonal variation of zonal and meridional wind, moisture content of the air and geopotential height related to the wet season timing over the study area.

Results from the precipitation data analysis reveal spatiotemporal differences in the wet season timing across the study area, with an early wet season onset in sites adjacent to the Amazon basin and late wet season onset in areas located close to the Pacific basin. Additionally, within the wet season timing, the onset dates show a high interannual variability, reflected in the 37-day period in which the wet season is established throughout the study area, contrary to the end dates that occurs almost at the same time across the study area. Over the period analyzed, the wet season onset was strongly correlated with the wet season duration. In this sense, most of the cases of early wet season onset are associated with a long wet season. Statistically significant positive trends in the onset dates were found in sites southwest to the Titicaca Lake, indicating a delay in the wet season onset in the range of

0.4 and 0.8 days per year. Moreover, detected cases of early and late wet season onset are commonly associated with positive and negative annual and wet season precipitation anomalies. The comparison of El Niño and La Niña cases show positive and negative precipitation anomalies, respectively, in the month in which the wet season onset is stablished. The analysis of the reanalysis data reveal that a low-level northwesterly flow in lower troposphere is the main feature related to the establishment of the wet season onset in the study area, while in middle troposphere a eastward movement of an anticyclonic circulation favors the moisture transport from the Amazon basin into the high Andes of the southern Peru and Bolivia. In the upper troposphere, northwesterly flow, with velocities below to the annual mean moves to the south with the Bolivian high, a anticyclonic circulation, while divergence to support precipitation is generated by the interaction of the northwesterly flow and the Bolivian High. Changes in the position and strength of these circulations are observed during early vs late wet season onset cases.

Findings from this study will help to complete our understanding on the seasonality of precipitation in this region. In addition, results can be used to improve short and mid-range forecast of the wet season timing in order to develop and implement contingency plans when forecast conditions are far from normal. Special attention deserve the areas in which a delay trend were found, since this trend would considerably affect the availability of water in the future. We also believe that these results have implications for improving the interpretation of tropical Andean ice cores.

In the development of this project, Tania Ita took a leading role in its formulation. She assisted with the collection of precipitation and reanalysis data and completed all of the data analysis, figure generation, writing, and formatting of this manuscript. Dr. Baker Perry

provided invaluable guidance and knowledge, contributing to ideas discussed in this study, and providing financial and emotional support. Dr. Magaret Sugg, contributed with her expertise in statistical analysis applied in this work and provided different perspectives on the data analysis. Dr. Isabel Moreno, provided guidance on the formulation of the data analysis and her knowledge in the Bolivian climate was relevant for this work. Christian Barreto provided valuable help in the analysis of precipitation and reanalysis datasets.

Synoptic Patterns Associated with Wet Season Onset in the Tropical High Andes of Southern Peru and Bolivia

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ABSTRACT

In the southern Andes of Peru and Bolivia there is a clear distinction between the wet and dry season. Precipitation is one of the most relevant factors in determining glacier mass balance since the wet season onset interrupts the ablation period caused by low albedo and intense solar radiation at the end of the dry season. This study examines daily precipitation observations from 1979 to 2017 in Peru and Bolivia and identifies the wet season timing, interannual variability, and tendencies. The ERA-Interim Reanalysis (0.75° Lat/Lon - 6 hours) provide insights into the seasonal variation of wind, moisture and geopotential height related to the wet season timing over the study area. We identify spatiotemporal variations in the wet season timing mostly associated with the distance to the equator and to the Amazon basin, in which onset dates exhibits a pronounced variability. Significant trends showing the delay of the wet season onset in 0.4 to 0.8 days/year were found in the southwestern subregions, which are closely related with the occurrence of early/late wet season onset cases. A low-level northwesterly flow east of the Andes is the main feature in the lower troposphere related to the wet season onset, as well as an anticyclonic circulation in mid-troposphere and northwesterly winds in the upper troposphere. Changes in the position and strength of these circulations are observed during early vs late wet season onset cases. This result has implications for improving seasonal precipitation predictions from tropical high Andes and in the interpretation of tropical Andean ice cores.

1. Introduction

The Cordillera Vilcanota and Cordillera Real are two very important glacierized areas located in the tropical high Andes of southern Peru and Bolivia. Together, they account for more than 60% of all tropical glaciers in the Andes between 12 - 16° S (Rabatel et al. 2013). As part of the outer tropical Andes, this region is characterized by an annual precipitation regimen, which is associated with a well distinguished wet summer and dry winter (Garreaud et al. 2003). During the wet season, precipitation is the primary input for domestic consumption, agriculture, hydropower, and other industrial activities. During the dry season, however, glacier runoff provides fresh water used in different socioeconomic activities. Moreover, from a glaciological perspective, precipitation is one of the most relevant factors determining the mass balance of glaciers because it interrupts the high ablation period at the end of the dry season caused by low albedo and intense solar radiation (Wagnon et al. 1999a,b; Francou et al. 2003; Sicart et al. 2011; Rabatel et al. 2013).

Since the 1970s, glaciers in the outer tropical Andes have been experiencing an exceptional retreat, the highest rate since the 1980s (Rabatel et al. 2013; Salzmann et al. 2013; Vuille et al. 2018). Small glaciers have disappeared in this period, particularly those located below 5200 m asl (Hanshaw and Bookhagen 2014). Future climate projections suggest that this tendency will change the availability of the water resource affecting different sectors such as hydropower, agriculture, tourism, etc., as well as ecosystems in the Andes (Vergara et al. 2007; Drenkhan et al. 2015; Kronenberg et al. 2016; Schauwecker et al. 2017). Social and political conflicts are likely to increase, not only due to water availability, but also due to conflicting cultural beliefs of Andean communities about glaciers (Vuille et al. 2018). Although previous studies highlight the role of the timing and duration of the wet season as a crucial factor for glacier mass balance (Francou et al. 1995, 2003; Sicart et al. 2011), there is no objective method for determining beginning/end of the wet season or the associated synoptic patterns.

By using daily precipitation data from weather stations located at high elevations in the southern Andes of Peru and Bolivia ERA-Interim Reanalysis datasets, this study investigates synoptic-scale atmospheric circulation associated with wet season onset in the outer tropical Andes. Secondary objectives include 1.) the determination of the interannual variability of the wet season timing; 2.) the identification of trends in the onset dates; 3.) the evaluation of early versus late wet season onsets; and 4.) the examination of the wet season timing during one El Niño and La Niña event. The analysis of the ERA-Interim Reanalysis will provide insight into the atmospheric circulations over the outer tropical Andes associated with the wet season onset and cases of early/late wet season onset.

The remainder of the manuscript is structured as follows: in section 2, a synthesis about the current understanding of the atmospheric mechanisms that control precipitation in different time scales is presented; section 3 describes the data and the methods used to assess the wet season timing and its implementation, as well as the statistical tests used to assess the interannual variability, trends and comparison among the data– this section also describes the computational process performed with ERA-Interim Reanalysis; in section 4 and 5, the results and their implications are presented and discussed, respectively; finally, section 6 summarizes the findings and presents the future direction of this work.

2. Background and Literature Synthesis

a. The seasonal and sub-seasonal cycle of precipitation in the outer tropical Andes

The seasonal cycle of wet summer and dry winter in the outer Andes of South America have been widely described in many studies (Vuille 1999; Lenters and Cook 1999; Garreaud et al. 2003). Perry et al. (2013) found that between 2004 and 2010 in Cordillera Vilcanota (southern Peru) the annual mean of precipitation is 697 mm, with more than 50% of the annual mean occurring during the austral summer (December, January, and February) and only 1-2% of the annual mean falling during the austral winter (June, July, and August). Moreover, Andrade (2018) found that over southern Peru and western Bolivia 80% of the annual precipitation falls between November and April in a period called the extended wet season, while the remaining 20% occurs between May and October, called the extended dry season. This study also revealed that in the western region almost 100% of precipitation occurs during the extended wet season. In addition, from a glaciological perspective, some authors also define a transition season between the dry and the wet season, in which precipitation increases gradually until the height of the wet season, when the amount and frequency of precipitation is highest (Kaser 2001; Francou et al. 2003; Sicart et al. 2011; Rabatel et al. 2013). Regarding that, Andrade (2018) described that the transition from the dry to wet season occurs in two months (October and November), while the transition to the dry season occurs just in one month (April). Indeed, this pronounced seasonal cycle of rainfall can also be observed at the continental scale and it seems to be closely related with the South America Monsoon System (Garreaud et al. 2009).

During the austral winter (JJA), westerly winds prevail in the middle and upper troposphere over the Altiplano, consequently with the north most position of the subtropical jet stream. Near-surface moisture is low, with values below 2 gkg^{-1} mixing ratio that cannot support convective rainfall

(Garreaud et al. 2003). Nevertheless, precipitation can occur in this season, which is associated with upper-level mid-latitude disturbances moving abnormally north of their mean paths, such as cut-offs lows and deep troughs. In addition, cold fronts that penetrate the Altiplano are also responsible for precipitation in this season (Vuille 1999; Garreaud et al. 2003). During austral spring (SON), these patterns gradually change due to the southward shift of the peak insolation. By late spring, clear variations are observed in all levels of the troposphere, such as the southward shifting of the subtropical jet stream and the enhance in convective precipitation in the central part of the continent and southern Amazon basin (Garreaud et al. 2003).

During the austral summer (DJF), the release of latent heat due to convection in the Amazon basin leads to the development of the Bolivian high, an upper-level anticyclone circulation center approximately at 15° S and 65° W during the summer, also accompanied by a cyclonic circulation downstream over the northeast of Brazil (Lenters and Cook 1995, 1999). The establishment of this system, along with the southward displacement of the subtropical jet stream, allow the southward expansion of the equatorial belt of easterly winds that persist in middle and upper levels to the troposphere in this season transport moist air from the Amazon basin into the Altiplano and thus enabling the development of precipitation (Garreaud et al. 2003). In addition, trajectory analyses highlight the importance of the low-level moisture transport into the Cordillera Vilcanota of Peru, and Cordillera Real of Bolivia by a northwesterly flow east of the Andes during precipitation events in this region (Perry et al. 2013, 2017). Indeed, during the austral summer, a deep continental low lays over the Chaco region forcing winds, east to the Andes, turn southward while exhibiting a low-level jet structure (Garreaud et al. 2009). Moreover, Chavez and Takahashi (2017) suggest a close relation between the nocturnal precipitation in this region and the peak of the SALLJ, which also occurs during the night and more frequently with a maximum extension along the eastern flank of the Andes during the summer (Nogués-Paegle and Mo 1997; Marengo et al. 2004).

In the wet season, precipitation in the outer tropical Andes is overall episodic; rainy days are grouped in a series of about one to two weeks and separated by dry periods of similar durations (Garreaud et al. 2003; Andrade 2018; Guy et al. 2019). Two main synoptic circulations over the Altiplano related with the wet episodes are stronger than average easterly winds in the middle and upper troposphere, and a southward displacement of the Bolivian high (Vuille 1999; Garreaud et al. 2003). Additionally, Lenters and Cook (1999) describe three synoptic circulations related to intraseasonal wet periods in the Altiplano. The first synoptic circulation is a low pressure located southeast of the Altiplano in the form of El Chaco low or a propagating extratropical cyclone further south. The second synoptic circulation is northerly winds along the northern central Andes and along the eastern flank of a cold core low located in southeastern South America. Finally, the third synoptic circulation is the westward enhancement of the South American Convergence Zone SACZ (Lenters and Cook 1999).

The daily cycle of precipitation is commonly bimodal, with two peaks, one during the afternoon around 16:00 LST and the other one around midnight, local time (Perry et al. 2013, 2017; Chavez and Takahashi 2017; Junquas et al. 2017; Endries et al. 2018). The character of afternoon precipitation is the primary convective product of the thermal heating of the Andes. Nighttime precipitation is generally stratiform (Perry et al. 2017; Chavez and Takahashi 2017; Endries et al. 2018) and the meteorological forcing seems to be related with a mesoscale convective system located in a downslope region in the Peruvian jungle around 700 m asl, with its stratiform component extending upslope in the Peruvian mountains. Moreover, these convective systems are stronger under SALLJ conditions, whose maximum peak also occurs during the night (Chavez and Takahashi 2017; Junquas et al. 2017).

b. Impact of ENSO on the wet season in the outer tropical Andes

In South America, ENSO is the principal mode of interannual variability of summer precipitation (Zhou and Lau 2001), generating different effects throughout the continent. Lenters and Cook (1999) found in the Altiplano region dry conditions during the 1987 El Niño summer, associated with a weakened and northward displacement of the Bolivian high, and the presence of cold and dry southerly flow in lower levels of the troposphere east of the Andes. Vuille (1999) also found a deficit of precipitation in the Nevado Sajama region during El Niño and precipitation above the normal conditions during La Niña and in summers following El Niño years, despite the fact that these changes in precipitation were statistically insignificant at 95% level. Meanwhile, Garreaud and Aceituno (2001) indicated that rainfall anomalies in the Altiplano during ENSO events strongly depend on the locations of zonal wind anomalies that are associated with a warming or cooling troposphere during the warm and cold phase of ENSO, respectively. Recent studies, also found differences in the spatial distribution of precipitation in southern mountains of Peru and Bolivia, showing precipitation amounts above the average during El Niño and amounts below the average during La Niña years in Cusco, Peru, and negative precipitation anomalies during El Niño and La Niña in El Alto, Bolivia (Perry et al. 2013, 2017).

From a glaciological point of view, on interannual timescales, ENSO plays an important role in the evolution of tropical glaciers. Francou et al. (2003) found that changes in the Chacaltaya glacier were controlled by SST anomalies in the eastern equatorial Pacific Ocean (Niño 1+2 area). Additionally, Rabatel et al. (2013) concluded that the variability of the tropical Pacific SST is the main factor controlling the interannual variability of glacier mass loss. Moreover, in a close analysis of the 1991-92 El Niño event in the Zongo glacier, Bolivia, Francou et al. (1995) found accelerating melting conditions in the ablation area due high temperatures and low precipitation during the warm season. Then, during the 1997-98 strong El Niño event, the Zongo glacier again experienced a deficit in precipitation, increase in temperature, and a strongly negative mass balance (Wagnon et al. 2001). After a detailed evaluation of radiative fluxes, Wagnon et al. (2001) concluded that the main factor in the highly negative glacier mass balance was the substantial increase in net all-wave radiation, which was three times higher than the previous years.

3. Data set and Methods

a. Data sets

The study area of this research was in southern Peru and western Bolivia, part of the outer Tropical Andes of South America (Fig. 1). The National Weather Services of Peru (SENAMHI-Peru) and Bolivia (SENAMHI-Bolivia), and the project Data on Climate and Extreme Weather for the Central Andes (DECADE) (Andrade 2018; Hunziker et al. 2018) provided daily precipitation data from 43 weather stations located at high elevations from 1979 to 2017 (Fig. 1). For the analysis, only weather stations with more than 90% of complete information were used; also, only operating weather stations were used to ensure future evaluation of the evolution of the wet season timing in the region. In addition, the mean product of the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010), with a spatial resolution of 0.0020833333 decimal degrees (Danielson and Gesch 2011) was used for the South American region to obtain variables, such as slope and aspect in the location of each weather stations. Finally, the Era-Interim Reanalysis, a global atmospheric reanalysis dataset with 0.75° latitude/longitude horizontal resolution and 6 hours of temporal resolution (Dee et al. 2011) were used to assess the synoptic conditions associated with wet season timing.

b. Method

To determine the timing of the wet season, we adapted the method used by Liebmann and Marengo (2001); Liebmann et al. (2007) in South America and more recently applied in Africa by Dunning et al. (2016). For the identification of the onset and end dates of the wet season in an annual precipitation regimen, the cumulative daily mean rainfall anomaly was calculated $C(d)$. The calculation starts with the climatological mean rainfall, Q_i, where i goes from 1 January to 31 December. Then, the climatological daily mean rainfall, $\overline{Q}$, is computed. Thus, the cumulative daily mean rainfall anomaly on day d, $C(d)$, is found:

$$C(d) = \sum_{i=1Jan}^{d} Q_i - \overline{Q} \tag{1}$$

In the equation, $C(d)$ is calculated for each day of the calendar year from 1 January to 31 December, however, Liebmann et al. (2007) states that the calculation can be started at any time of the year, but in practice it is started 10 days prior to the beginning of the driest month and is continued for a year. Thus, the onset and end dates are determined by finding the minimum and maximum values of the cumulative daily mean rainfall anomaly curve, respectively, which increases when the daily precipitation is above the climatological daily mean rainfall, and decreases when it is below the climatological daily mean rainfall (Dunning et al. 2016). Additionally, as a previous step to this calculation, it was necessary to adjust the data. This process included the construction of the hydrologic years that span from July 1 to June 30 of the next year, and the elimination of February 29 according to Liebmann and Marengo (2001). Thus, the calculation of the cumulative daily rainfall mean anomaly starts on July 1, instead of on January 1. Moreover, henceforth we will use the term precipitation instead of rainfall since both solid and liquid precipitation types can occur in the study area.

Given that wet season timing in the region was variable across the study area, groups were identified following a weighing process and a quantile classification. A first step involved the examination of the distribution of the climatological onset, end, and duration of the wet season, together with the latitude, longitude, elevation, slope, and aspect by using the Shapiro-Wilk test. The second step was assessing the the strength of the relationship among these variables. The purpose of correlating the wet season timing with the geographic variables and topographic characteristic of each precipitation site was to identify relationships to help in the identification of similar spatiotemporal patterns. Latitude, longitude, and elevation information were provided by SENAMHI-Peru, SENAMHI-Bolivia and DECADE Project, while slope and aspect values were calculated from the terrain elevation model for the location of each weather station. Correlation matrix were constructed to all variables using the Pearson or Kendall correlation coefficient, which was determined based on the normality of the data. In both cases, the duration of the wet season showed the highest correlation values with the geographic and topographic variables than the onset and end dates (Table A1), and since the duration of the wet season is a summary measure of the onset and end dates, its correlation values were used in the weighting process. The geographic and topographic variables were standardized using the z-scores before performing the weighting process using the correlation values of both the Pearson and Kendall methods, separately, in which the sign of the correlation was omitted given that in this step only the magnitude of the correlation is important, not the direction. Finally, the number of groups was found following quantile classification and mapped to evaluate the spatial distribution.

To determine the number of groups, as well as the best option in the weighting process (Pearson or Kendall methods) the spatial distribution and a sensitivity analysis, which included the evaluation of wet season timing and wet season precipitation, as well as the trend analysis using the Mann-Kendall, Sen's slope and Pettitt's test, was done to examine these variables among the groups. The sensitivity analysis revealed that by reducing the number of groups from four to three, the wet season timing and precipitation were more homogeneous among the groups; likewise, trends found in the four-group classification were not observed when applying a three-group classification. Therefore, we decided to use the Pearson correlation and the four-group classification, which achieve a better detail of the characteristics of the study region. Once the groups were determined, the mean annual precipitation (mm), wet season precipitation (mm), the percentage of precipitation during the wet season (%), and coefficient of variation CV (%), were computed for each group.

In a second stage, the climatic wet season timing was found for each group. Then, the onset and end dates were identified for each individual hydrologic year, using the mean precipitation of each group. The high year-to-year variation in precipitation amount complicates the identification of the minimum and maximum point in the entire cumulative curve at once. Thus, the onset date was found between the first day of the hydrologic year (July 1) and the last day, in which the cumulative daily mean precipitation anomaly of a particular group still presents negative values. The end dates were found between the first day, in which the cumulative daily mean precipitation anomaly of a particular region presented a positive value, and the last day of the hydrologic year (June 30). With his yearly information, early and late cases of wet season onset were identified and taken into account thresholds, which were determined by the bottom and top quartile of the onset dates for each group, respectively.

The trend analysis was carried out for each group from 1979-80 to 2016-17 hydrologic years, with the data obtained in the second stage of the determination of the wet season timing. The Mann-Kendall test is widely used to asses hydro-meteorological time series since it is more suitable for non-normal distributed data and it is less sensitive to outliers (Hamed and Raos 1998; Yue et al. 2002). Nevertheless, it was necessary to first examine the assumptions of the Mann-

Kendall test; in this sense, the serial correlation among the onset dates was evaluated using the Autocorrelation Function (ACF) and Partial Autocorrelation Function (Partial ACF). Since no serial correlation was found, the Mann Kendall test was applied; also, the Sens slope and Pettitts test were used to add more information to the traditional trend analysis, being able to detect the slope of the trend line (the magnitude) and a possible break point in the time series, respectively. All tests previously mention before are available in the trend package in R (Pohlert 2018).

To investigate the synoptic conditions associated with the wet season timing, particularly, the wet season onset, we constructed a daily climatology of the ERA-Interim Reanalysis using the 4-time daily products of this reanalysis. Variables analyzed included zonal and meridional wind (ms^{-1}), specific humidity (gkg^{-1}), and geopotential (m^2s^{-2}). The daily climatology also follows the hydrologic year and has the same period as the precipitation data from 1979-80 to 2016-17. Then, the seasonality of these variables was examined using the same equation we used with precipitation data. This computation was done by averaging grid cells of the reanalysis dataset between 18 and 12° S and 72.75 to 66.75° W, we include all the mandatory levels in this analysis, however, the low level was not considered. To assess the synoptic conditions during the evolution of the wet season onset and during cases of early and late wet season onset, daily and monthly composites were done, particularly for the early versus late cases. Differences between those cases (early minus late) were computed for lower (850 hPa), middle (500 hPa), and upper (200 hPa) levels of the troposphere. Finally, we compare the behavior of the wet season timing during two ENSO events, the very strong El Niño of 1982-83 and the strong La Niño of 1988-89. Results obtained in the second stage of our analysis were used for this purpose; in addition, for a close analysis, monthly precipitation and monthly precipitation anomalies, based on the 1979-2017 time period, were calculated during the 1982-83 and 1988-98 hydrologic year.

4. Results

a. Climatological wet season timing

Along the study area, four groups were identified Fig. 2. The spatial distribution of these reveals an NW-SE orientation, where groups 1 and 2 are located to the southwest of the Titicaca Lake, over the Peruvian and Bolivian Altiplano and close to the Pacific basin. Groups 3 and 4 are situated northeast to the Titicaca Lake, nearby to Cordilleras Vilcanota and Real and to the Amazon basin. The daily evolution of precipitation in each group (Fig. 2) shows a gradual increase in precipitation amounts during the transition from the dry to the wet season. However, the transition from wet to the dry season occurs in a short time period for all groups. There also exist differences in daily precipitation amount along the year, with group 1 showing the lowest precipitation values among the others.

Additionally, differences are shown in Table 1, in which we observe a gradual progression of the onset dates that initiate first in the group 4 on 24 October, then progress to groups 3 and 2 on 12 and 13 November, respectively, and lastly it occurs on group 1 on 11 November. The end of the wet season takes place between 5 and 11 April, in which the end of the wet season occurs first in the group 1 and gradually occurs in the group 4 in a seven-day period. Hence, due to this opposite behavior in the occurrence of the onset and end dates, the longest duration of the wet season occurs in group 1 with 170 days, and the shortest in group 4 with 127 days. The amount of annual precipitation reveals an increase from groups 1 to 3 and then a decrease in group 4; however, the total amount of precipitation during the wet season increases from group 1 to group 4. The percentage of precipitation during the wet season reveals slight differences between groups 2 and 3, still showing an upward tendency from groups 1 to 4. The variability among the wet season timing was assessed through the coefficient of variation (CV), revealing that there exist more variability in the duration of the wet season in the onset dates than in the end dates. Regarding the onset, this is reflected in the long period in which the wet season onset occurs, 37 days between the onset in group 1 and 4. Moreover, since the duration of the wet season is more strongly correlated to the onset (Table A1), the CV is even higher for the duration given that this also depends on the end dates variability. The end dates have a lower variability, related in the seven day period between the occurrences of this from groups 1 to 4. CV values tend to decrease from groups 1 to 4 for the end dates and wet season duration, while the opposite behavior is observed for the onset dates, except for groups 4 that shows the second lower value.

b. The relationship between wet season timing and atmospheric circulations

During the onset date of groups 1, on October 24, a northwesterly flow in 850 hPa (Fig. 3a) extent east to the Andes from the central jungle of Peru to southern Bolivia, then, the flux turned to the east over Paraguay and central Argentina. This low-level flux reaches its highest velocities over central Bolivia, Paraguay, and Argentina. By the time of the onset date of group 3, on 13 November (Fig. 3d) (the onset in group 2 occurs just one day before), the low-level flux became more elongated, particularly in its northward site, showing high velocities along the jungle of Colombia and Peru and a decrease in wind speed over Bolivia and Paraguay. Lastly, at the moment of the onset date of group 4 (Fig. 3g) the northwesterly flux shows a notable increase of the wind speed in the north of the continent, over Colombia and Peru, and again over Bolivia, while a decrease is observed over Argentina. The Atlantic high-pressure winds show a weakening with the temporal progression of wet season onset, which is related to the confinement of the moisture content in the center of the continent during the onset date of group 1. The evolution of this low-level flow is closely associated with the southwest displacement of the northern trade winds that allow the increase of wind speed, particularly over the Colombia jungle and favoring the southward displacement of moisture toward southern latitudes (Nogués-Paegle and Mo 1997). The decrease in velocities over Argentina can be linked to the displacement of the convection to the north, since the exit region of the low-level jet is related with convective activity (Nogués-Paegle and Mo 1997; Marengo et al. 2004).

In 500 hPa, an anticyclonic circulation shifts to the west, toward the Pacific ocean, as the winds at latitudes south of the 20° S slow down since the occurrence of the onset date in group 1 (Fig. 3b) until the onset date in group 4 (Fig. 3h). This anticyclonic circulation is indicated to be part of the Bolivian high by Vuille (1999), and from the dry to the wet season it moves to the southwest to finally reach a location between south Bolivia and northern Argentina around January (Gilford et al. 1991). The movement of the 500 hPa circulation favors southeasterly winds over the study area, that are intensified toward the onset date in group 4, generating at the same time a major moisture influx. In upper levels of the troposphere (200 hPa), a gradual increase in geopotential height values, as well as an NW-SE expansion occurs (Fig. 3c, f, and i), associated with the development of the Bolivian high. However, the southward shift of this system is slight compared to its position over central Bolivia during wet periods within the wet season (Vuille 1999). Moreover, the northwesterly winds over the Pacific Ocean prevail from 24 October to 30 November despite the presence of the Bolivian high.

c. The seasonal cycle of wind, moisture content, and geopotential height over the central Andes

The analysis of the seasonal cycle of atmospheric variables from the ERA-Interim reanalysis reveals differences in the temporal evolution of zonal and meridional wind, specific humidity and geopotential height in middle and upper levels of the troposphere over the study. The zonal wind has a positive annual mean (from the west) in all levels analyzed. The detection of the maximum and minimum points in the cumulative curve (minimum and maximum point for the other variables) marks the period associated with the onset and end of the wet season, respectively. Among 400 and 100 hPa (Fig. 4a), these points occur almost at the same time, between 14 and 15 October for the maximum point, and between 15 and 17 April for the minimum point. By the time the maximum point occurs, the zonal wind maintains its direction from the west and its speed around 4, 10, 7, and 3 ms^{-1} in 100, 200, 300 and 400 hPa, respectively, which are close to their annual mean. When the minimum point occurs, the zonal wind again reveals a direction from the west, while velocities are similar to the ones before. Moreover, during the establishment of the wet season in all groups, westerly winds prevail, with magnitude lower than the annual mean of each particular level. Therefore, at the beginning of the wet season, the presence of easterly winds is not necessary, but there is a decrease in wind speed. After that, the wind speed decreases and eventually it comes from the east but not during the entire wet season. In middle levels of the troposphere (Fig. 4b), the behavior of the zonal wind is quite similar to the one in upper levels; nevertheless, the seasonality is barely noticeable in 700 hPa, since at this level wind direction does not considerably change along the year keeping its westerly direction. Principally, in 500 hPa, before the establishment of the wet season, a change in wind direction occurs, and easterly winds prevail until the end of the wet season.

Contrary to what we found analyzing the zonal wind, the seasonality of the meridional wind in upper levels (Fig. 5a) reveals a different pattern of two cycles of decreasing and increasing magnitude of southerly winds that prevails during the year between 300 and 100 hPa. While in the 400 hPa level, a slight change in wind direction is observed, following the pattern of middle level winds. Nevertheless, by the time the wet season is established an increase in the magnitude is observed. In 400 hPa, the minimum point occurs on 16 October and the maximum on 30 March. Contrary to what was stated in the zonal wind, the cumulative curve here shows first a decrease and then an increase; this difference is due to the direction of the wind. In 600 and 500 hPa (Fig.

5b), the seasonality is clearer due to the change in wind direction by the time of the wet season. Despite this, change does not last the entire wet season. The minimum point in the cumulative curve occurs on 30 September and 3 October, in the 500 and 600 hPa level, respectively, before the wet season onset in all subregions. The maximum point in this curve occurs on March 26 and April 14, for the same levels. In 700 hPa, like the 100, 200 and 300 hPa, the change in wind speed along the year is slight.

Specific humidity (Fig. 6) shows a clear evolution in all levels analyzed. However, it is hard to distinguish in 100 and 200 hPa because of the low moisture content in these levels. The annual mean of specific humidity ranges from 0.003 gkg^{-1} in 100 hPa to 6.7 gkg^{-1} in 700 hPa. Similar to the zonal wind, the minimum and maximum point in the cumulative curve occurs when the mean daily specific humidity reaches values near annual mean in each specific level. Dates of the minimum point in the cumulative curve occur almost at the same time in all levels, with the exception of the 100 hPa. This is between 17 and 22 October, while the maximum point occurs in a 15 days range, between 12 and 27 April.

The seasonal cycle of geopotential height (Fig. 7) reveals a different behavior in the cumulative curve, showing a decrease toward the wet season onset and an increase toward the end of the wet season in upper levels (Fig. 7a); the behavior of the cumulative curve shows the opposite behavior in middle levels (Fig. 7b). Like the specific humidity and zonal wind, the minimum and maximum points in the curve are associated with the annual mean values in each level. Dates related to the wet season onset occur in a wide range in middle and upper levels. In the upper level, dates associated with the wet season onset are 20 and 22 October, in 200 and 300 hPa, respectively. It occurs later on 10 and 21 November, in 100 and 400 hPa. In middle levels, dates are 30 September and 10 October, in 700 and 600 hPa. Dates related with the end of the wet season are late in May and early June in upper levels and between February and March in middle levels.

d. The character of early and late wet season onset

After identifying years in which an early and late wet season occurs in each group, we found that since 1979, an average of eight cases of early wet season onset have occurred, while the average of late-onset cases increased to nine. Years characterized by an early wet season onset (Table B1-B4) reveal different behaviors in the occurrence of an early or a late wet season end; however, since the onset is strongly correlated with the wet season duration, in most of the cases, early onsets are associated with a long wet season. In addition, both the total amount of annual and wet season precipitation mostly present positive anomalies during early onset cases. On the other hand, years that present a late wet season onset (Table B1-B4) do not present a clear association with early or late end of the wet season; however, the duration of the wet season is shorter compared to its climatic values. The total annual and wet season precipitation decreases for most of the cases. This decrease is observable in the percentage of precipitation during the wet season. After this comparison, it was clear that an early or late wet season onset does not mean an early or late wet season end. The role of topography is also pointed out in this analysis since that in any given year, groups can present a case of an early or late wet season onset at the same time. In this sense, it is possible to present an event of early onset in a group and a late case in another. Even though this behavior is not common during the period analyzed. The inspection of the daily mean precipitation during early and late wet season onsets reveals differences in the temporal distributions of precipitation in each group (Fig. 8, 9, 10, 11).

e. Synoptic conditions associated with early and late wet season onset

Atmospheric circulation in 850 hPa (Fig. 12) reveals that the main difference between cases of early and late wet season onset is related to a stronger low-level northwesterly flow over Bolivia, Paraguay and Argentina that in turn is associated with southward moisture transport. Other atmospheric features include the presence of low pressure over northern Argentina and Paraguay, and a high-pressure east of this system, on the Atlantic ocean. From October to November, these systems appear more intense, particularly, the high-pressure system. Although these systems are common for the four groups, a better configuration, as well as larger differences in the moisture content and wind speed are observed for the group 1. The more intense low-level flow is supported by the development of a low pressure over the continent. In addition, the high-pressure system also helps to transport moisture content to southern latitudes, and as a result, a contrast is observed in the continent, with dry conditions on the northern part and moist conditions in the southern part of South America.

In mid-troposphere (Fig. 13) a pattern of weakening westerly winds between 15 and 25° S is observed, while more intense westerly winds are present in mid latitudes, reveling a anticyclonic circulation, with the axis determining the line of change in wind speed. This pattern is well defined during November, and the weakening westerlies are accompanied by positive values in specific humidity in the same region of weakening westerly winds, even in northern latitudes near to 10° S. The pattern in upper levels (Fig. 14) show a similar configuration with weakening westerly winds during cases of early wet season onset during October, while in November, wind configurations reveal a wide region of weakening northwesterly winds, which can be related with an early southward migration and expansion of the Bolivian high.

f. Trends in the wet season onset dates

Results from the Mann-Kendall test reveal that groups 1 and 2 have experienced a delay in the wet season onset since 1979 (Table 2). The first evaluation of this test, using the two-sided and one sided Mann-Kendall test, expose a significance difference for these groups (alpha $<$0.05). With a p-value of 0.0719 and 0.0285, groups 1 and 2 are significant at a 90 and 95% level, respectively.

Groups 3 and 4 do not reveal a significant trend in the onset dates in either the two-sided or the one-sided Mann-Kendall test, despite p-values decrease. The Sens slope test (alpha <0.05) reveals the magnitude of the trend in groups 1 and 2, which is 0.389 and 0.815 days per year, respectively. Since 1979 group 1 has experienced a delay in onset dates of 0.4 days per year, while a higher delay of 0.8 days per year has occurred in group 2. The Pettitt's test (alpha <0.05) reveal differences in breaking points in the time series among the four groups. Particularly for groups 1 and 2, the breaking point marks the year after which late cases of wet season onset become more frequent, despite this test is only significant at a 90% level for group 1.

g. Study cases: The very strong El Niño (1982-83) and the strong La Niña (1988-89)

During El Niño year (Table 3), the wet season onset in each group occurs earlier than their respective climatological onset date, with the beginning of the wet season taking place between 20 September and 11 November. Similarly, the wet season end occurs early, between 19 February and 08 April. The wet season duration varies among the four groups. Group 4 present the longest wet season whereas group 1 present the shortest wet season length. The analysis of the annual and wet season precipitation reveals negative precipitation anomalies in both fields. Nevertheless, a close analysis of the monthly precipitation (Table C1), reveals that between September and November positive precipitation anomalies prevailed in the all groups, except, only for group 4 that present negative precipitation anomaly of 2.7 mm in October. During La Niña year, the wet season onset in each group occur later than their climatological dates, between 30 November and 18 December (Table 4). The end of the wet season also occurs late in groups 1, 2, and 3 whereas it occurs early in group 4. The wet season duration range from 124 days in the group 4 to 135 days in group 2. The annual and wet season precipitation in all groups were characterized by negative precipitation anomalies. However, during October and November, negative precipitation anomalies were common in the majority of the groups (Table C2).

5. Discussion

The main objective of this study was to determine the synoptic patterns related to wet season timing in the tropical high Andes of southern Peru and Bolivia. Secondary objectives included the examination of the interannual variability, including the comparison of cases of early vs late wet season onset, the examination of trends on the wet season onset, and the analysis to ENSO events (El Niño and La Niña). Results from this work reveals spatiotemporal differences in the establishment of the wet season across the study area and a strong association between the wet season onset and the duration of the wet season. In addition, we found that the gradual establishment of the wet season onset was associated with the gradual transition to the summer atmospheric features in South America. Across the study area groups 1 and 2, located southwest of the Titicaca Lake, presented significant trends in the Mann-Kendall test, reveling that since 1979 they have experienced a delay in the onset of the wet season in 0.4 and 0.8 days/year, respectively. More study is necessary to assess the causes of these trends; however, a possible strength of westerly winds in the middle and upper levels of the troposphere, associated with cases of late wet season onset, can be related to these trends. In addition, cases of early and late wet season onset were associated with changes in the position and strength of synoptic circulations in lower, middle, and upper troposphere, that in turn are associated with the South American See-Saw. Finally, the ENSO events analyzed showed an opposite behavior at the beginning of the wet season; however, further analysis is needed to examine the main synoptic patterns at the very beginning of the wet season during ENSO events.

a. Seasonal cycle of precipitation

This work uses a simple methodology based on the cumulative daily mean precipitation anomaly to determine the exactly wet season timing across the tropical Andes of southern Peru and Bolivia. The minimum and maximum point in the cumulative curve are tipping points associated with the beginning and cessation of the wet season. These tipping points are reached when the daily mean precipitation reaches the annual mean precipitation; this is, when the daily anomaly is zero or close to zero. Our results reveal that along the study area, differences exists on the wet season timing, particularly during the onset, where we found 37 days of difference between the onset in group 4 that occurs first and the onset in group 1 that occurs later. On the other hand, the end of the wet season happens almost at the same time in all groups, which is reflected in a lower coefficient of variation in each group. These variations range from 4.8 to 7.1% compared to the ones obtained for the wet season onset that vary from 14.8 to 19.9%. These results are in agreement with Andrade (2018) whom work revealed a two month period (October and November) for the establishment of the wet season. Additionally, Ramallo (2013) found similar difference in days in the establishment of the wet season between stations located in the proximity to Zongo valley (Bolivia) and stations located over the Bolivian Altiplano. Moreover, the evolution of the mean daily precipitation in all groups reveal a gradual increase in precipitation amount from the dry to the wet season, in a period is called transition season in glaciological studies (Francou et al. 2003; Rabatel et al. 2013; Sicart et al. 2011; Wagnon et al. 1999a,b). However, the transition from the wet to the dry season occurs in a short period.

The high variability among the wet season onset can be associated with the apparent movement of the sun and the latitudinal shift in the peak of insolation, in which solar rays strike perpendicularly over the Earth surface (Garreaud et al. 2003). Atmospheric systems, such as the semipermanent high pressures, over the Pacific and Atlantic oceans, and wind belts in middle and upper troposphere, follow this apparent movement, exhibiting a southward displacement from the June (winter solstice) until December (summer solstice), and then shifting northward until March (fall equinox). Therefore, there is more time to establish the wet season onset than there is to establish the end of the wet season. The end dates do not reveal high variability because from March onward solar rays will radiate most over the northern hemisphere, losing their influence over the tropics in the southern hemisphere. Weather stations located in the north of the study area will experience an early wet season onset. Indeed, the correlation analysis shows a strong relationship between onset and latitude ($r = -0.61$), while longitude demonstrates a weaker relationship with the wet season onset ($r = 0.27$). These correlations can be associated with a close proximity to the Amazon basin, the main moisture source for precipitation events in the outer Andes (Perry et al. 2013, 2017). Results from the correlation matrix also reveal a strong relationship between the onset and duration ($r = -0.97$). Moreover, since the end of the wet season does not reveal high variability (lower CVs), we can conclude that the wet season length mostly depends on the wet season onset. Similar results were achieved by Ramallo (2013) whom study found a strong significant relationship between the wet season onset and the duration of the wet season after analyzed four different methods to identify the rainy season in the Zongo valley.

b. Synoptic patterns associated with wet season onset

During the 37 days period, in which the wet season onset in established, the low-level northwesterly flow east of the Andes showed a distinguished evolution. The progressively increase in wind speed, over the Colombian, Peruvian, and northern Bolivian Jungle, is associated with the southward displacement of the North Atlantic high-pressure that impulse the northeasterly Trade winds toward South America (Nogués-Paegle and Mo 1997; Marengo et al. 2004). The development of this low-level flux is related, as well to the presence of the South American Low-Level Jet (SALLJ) during precipitation events in the outer Andes given its role transporting moisture from the Amazon basin into the mountains (Lenters and Cook 1999; Vuille 1999; Perry et al. 2013, 2017; Guy et al. 2019; Chavez and Takahashi 2017). Different mechanisms have suggested the relationship between the SALLJ and precipitation events in the Andes (Perry et al. 2013, 2017; Junquas et al. 2017; Chavez and Takahashi 2017). Particularly, for the wet season onset, the main feature is the increase in wind speed of this low-level flow, between the Colombian and northern Bolivian jungle and the decrease in wind speed over Paraguay and northern Argentina. Romatschke and Houze (2010) found a similar pattern, with a SALLJ restricted to the subtropics, during deep convection events in the foothills of the central Andes. Nevertheless, we found that the increase in wind speed of the SALLJ was gradual. Therefore, at the beginning of the wet season convective cores in the foothills of the central Andes and its associated stratiform precipitation over the Andes (Chavez and Takahashi 2017; Romatschke and Houze 2010; Endries et al. 2018) may not be the main mechanism that generates precipitation. Moisture influx through the valleys and upslope winds, as a reaction to heating of the mountains and the Altiplano, would result in the development of convective precipitation in the afternoon. However, more study is needed to assess the spatiotemporal evolution of stratiform and convective precipitation in the outer tropical Andes. This low-level configuration, in conjunction with the mid-troposphere anticyclonic circulation and a southward displacement of westerlies in the subtropics favors the moisture transport into areas located far from the Amazon basin. The anticyclonic circulation is also present during wet episodes in the Andes, reveling, however, weak easterly winds and less moisture transport during dry episodes (Vuille 1999). In addition, the low and middle level configuration can be related to the development of the South Atlantic Convergence Zone (SACZ) associated with precipitation events in the study area (Lenters and Cook 1999; Vuille 1999; Guy et al. 2019) given that a less intense low-level jet in the subtropics favors a northern shift of precipitation over an extense area of tropical South America influence by SACZ (Nogués-Paegle and Mo 1997; Liebmann et al. 2004; Carvalho et al. 2004). In upper levels of the troposphere, geopotential height values reveal a vertical and horizontal expansion related with the establishment of Bolivian high. Nevertheless, northwesterly winds prevail over easterly winds, associated with the Bolivian high, above the Pacific Ocean and part of the western Andes Mountain. Since these northwesterly winds demonstrate a trough configuration, divergence in this level seems to be not completely associated with the Bolivian high but to the interaction of these two systems. Overall, the intensification of the SALLJ in the northern and central part of the continent, the southward displacement of the westerlies in the subtropics and the establishment of the Bolivian high have been describe as part of the development phase of the South American Monsoon System (Zhou and Lau 2001).

c. Seasonal cycle of atmospheric variables

The analysis of the regimens of wind, specific humidity, and geopotential height reveals that among these variables, tipping points associated with the onset and end of the wet season vary in function of the latitude, longitude, and altitude in the troposphere. Of the two components of the wind, its zonal component reveals a clear seasonality between 100 and 600 hPa. Despite tipping points in high levels of the troposphere (400 to 100 hPa) are not directly associated with a changes in wind direction, the detection of these tipping points, in average 10 days prior to the wet season onset, reveals the importance of this wind component for the establishment of the wet season. On the other hand, the evaluation of the meridional wind did not reveal a clear seasonality as the zonal component in all levels analyzed. Tipping points associated with the wet season onset and end were not identify in high levels of the troposphere over the study area; however, were identify tipping points in lower and middle levels of the troposphere, between 925 to 400 hPa. In middle levels, it was observed a decrease in southerly winds and the presence of northerly winds during the period related to the wet season. In low levels, northerly winds prevails during the wet season; however, this behavior was only found east to the Andes over the Peruvian jungle, and can be closely related to the development of the low-level jet. We believe, that this seasonality has gone unnoticed due to low values of wind speed in the areas compare to the high values over southeast South America and due to established threshold used to identify the SALLJ. The specific humidity seasonality is similar to the zonal wind patterns. In middle levels of the troposphere, tipping points in this variable commonly occurs, in average, seven days after the occurrence of tipping point in the zonal wind. This results, demonstrate the importance of zonal wind to transport moisture from the Amazon basin into the high Andes. Nevertheless, mid-level moisture transport is not the only mechanism in charge of increase moisture in the Andes. The low-level northwesterly flow is another important mechanism, present during wet season episodes during the wet season, and, as we mention before, for the begging of the wet season. The geopotential height seasonality in high troposphere, reveal an indistinct pattern regarding its vertical evolution. However, the horizontal evolution demonstrate a radial pattern. Overall, the change in seasonality of the geopotential height in high levels occurs in a similar period to the establishment of the wet season onset. Thus, the establishment of the Bolivian High occurs in conjunction with the development of the wet season. This analysis reveals that zonal wind in middle and upper troposphere over the study area is a good indicator to predict the wet season onset in the outer tropical Andes, as well as the meridional wind, in mid-troposphere over the study region and in low-troposphere over the eastern slope of the Andes, and specific humidity in mid troposphere over the study area.

d. Early versus late wet season onset

Cases of early and late wet season onset tend to occurs indistinctly among groups in the study area. Nevertheless, these cases present analogous characteristics. The majority of years that present an early wet season onset have a longest wet season compared to their climatological mean and to the cases of late wet season onset. Additionally, cases of early wet season onset were more likely to present positive anomalies in the annual and wet season precipitation, while the opposite behavior was observed in cases of late wet season onset. (Ramallo 2013) found similar results in Zongo valley, where humid years where associated with a long wet season and dry years with a short wet season. However, other variables such as the frequency and intensity of precipitation among these cases need to be addressed in future studies; a particular case that deserve special attention is the occurrence of late wet season onset and early wet season end due to its implications in water availability. These two scenarios (early and late wet season onset) do affect water resources, as well as tropical glaciers. Despite cases of early wet season onset usually present positive precipitation anomalies during the hydrologic year, principally, during the establishment of the wet season, from October to November, anomalous dry periods were also present within the wet season. These dry periods in the core of the wet season enhance melt rates due to low albedo, mainly in the low surfaces of glaciers (Francou et al. 1995, 2003). On the other hand, late cases of wet season onset revealed a more critical scenario because of the negative precipitation anomalies and the extended dry periods in the wet season and in the transition season that characterized these years. Hence, glacier melt rates occur in a longer period compared to cases of early wet season onset. Furthermore, since positive precipitation anomalies are found in the majority of cases of early wet season onset, as well as extended dry periods, it may be possible that heavy precipitation events occur within the wet season during years characterized by an early wet season onset.

The analysis of the synoptic patterns revealed a slight intense (around 3-5 ms^{-1}) low-level northwesterly over southern Bolivia and Paraguay during cases of early wet season onset compared to the late cases of wet season onset. This wind intensification is associated with an increase in moisture content between southern Peru and central Argentina in about 2 gkg^{-1}. A deeper low-pressure over central-northern Argentina together with an intense high-pressure in the Atlantic Ocean are responsible for the wind intensification, given that winds in the northern part of the continent did not reveal high differences between the two scenarios evaluated. This low-level pattern is opposite to what was found by Romatschke and Houze (2010) during deep convection episodes in the foothills of the central Andes. Thus during cases of early wet season onset, deep convection may be reduced in the foothills, and so the stratiform precipitation in the outer Andes. Convection due to the heat of the Altiplano and surrounding mountains may be the main mechanism responsible for generating precipitation during cases of early wet season onset. In addition, a contrast in moisture content is observed at a continental scale, with low values over the northern and central part and high values in southeast South America. This dipole pattern, with a stronger SALLJ in the subtropics than in the tropics is related to the one of the phases of the South American See-Saw (Guy et al. 2019), associated with precipitation events in Cordillera Vilcanota and Cordillera Real. the other phase, is determinate by an intense SACZ and a week SALLJ over the subtropics. (Carvalho et al. 2004) in a close analysis of the SACZ determined that intense precipitation on north-northeastern Brazil is characterized by a phase of the MJO, in which the suppressed rainfall is found over Indonesian and enhanced precipitation over the central Pacific: while the opposite features were found during a decrease in rainfall in the same area. Thus, this continental-scale See-Saw pattern may be closely related to the MJO, as (Nogués-Paegle and Mo 1997) suggested.

Meanwhile, in the middle troposphere, a pattern of weakening westerly winds between 15 and 25S was observed, which is clearer during November. This weakening is accompanied by positive values in specific humidity in the same region of weakening westerly winds. The presence of weaker westerly winds during early wet season onsets would also reduce vertical wind shear, favoring the development of convective clouds over the outer tropical Andes. Moreover, a trough pattern off the coast of Chile in middle levels observed in groups 1, 3, and 4, during October can induce the development the low-pressure over northern Argentina through the advection of vorticity while crossing the Andes. Nevertheless, a close analysis even by even is needed, since the monthly means can smooth atmospheric conditions. The pattern in upper levels shows a similar configuration with weakening westerly winds during cases of early wet season onset during October, while in November, wind configuration reveals a wide region of weakening northwesterly winds, which can be related with an early southward migration and expansion of the Bolivian High.

e. Trends in the wet season onset

Significant trends were just found in two of the four groups analyzed, groups 1 and 2, at a 95% significant level. These trends reveal a delay in about 0.4 and 0.8 days/year in these groups, respectively. These results are in agreement with the occurrence of cases of early wet season onset, which were more frequent in the 80s and 90s, while cases of late wet season onset were more common from late 90s in ahead. Nevertheless, since this work did not examine the relationship among the wet season onset and wet season precipitation or frequency and intensity of precipitation, we cannot conclude that this delay can be associated with a reduction of rainfall during the wet season or other characteristics. These results reveal, however, that socioeconomic sectors such as agriculture, hydropower, mining, etc. can be affected in the following years if these trends continue, endangering, as well water used for domestic consumption. Factors that may be responsible for this trends need to be examined in future works, particularly changes in the mid and upper-level zonal wind since our findings, as well as other researches, suggest a strong relationship between this component of the wind and precipitation in the central Andes in all time scales (Garreaud et al. 2003; Andrade 2018). Moreover, the importance of the SALLJ for precipitation in the central Andes point out the necessity to evaluate changes in the moisture transport into the central Andes, in a context in which this system is becoming more intense in recent decades affecting, as well, the hydrologic cycle over the Plata basin (Montini and Jones 2018). Furthermore, since many glaciological studies report an exacerbating glacier retreat since the 1970s in the outer tropical Andes (Rabatel et al. 2013; Salzmann et al. 2013), relating glacier shrinking with changes in the precipitation regimens, other variables need to be analyzed, given that no significant trends were found in the onset dates in groups 3 and 4, the closest areas to the glaciers. Lastly, the increasing trend in moisture in upper troposphere close to glaciers may play an important role in the exacerbated glacier loss since slight and no significant trend in the total amount of precipitation was found (Salzmann et al. 2013).

f. Comparison between the very strong El Niño and the strong La Niña years

The comparison between the two ENSO events reveal that the onset of the wet season has an early occurrence during the very strong El Niño year and a late occurrence during the strong La Niña. This in agreement with the positive and negative precipitation anomalies, respectively, found during the months in which the wet season is established. The presence of negative precipitation anomalies during the rest of the wet season were common in both cases. Nevertheless, largest anomalies were found during the very strong El Niño. Just in April during the strong La Niña positives anomalies prevailed, associated with the late occurrence of the wet season end. The duration of the wet season is greater during El Niño than during La Niña year, except for group 1. Therefore, despite present an early wet season onset and long wet season, the very strong El

Niño years did not present positive precipitation anomalies as the majority of the cases analyzed in section 4d, which present an early wet season onset, a long wet season, and positive precipitation anomalies. Negative precipitation anomalies in the core of the wet season were presented in both events affecting glaciers mass balance, as well as impacting on the socioeconomic activities over the Altiplano (Andrade 2018; Vuille et al. 2018). Negative precipitation anomalies over the Altiplano during the 1982-83 El Niño year have been associated with upper-level westerly wind anomalies, which inhibited the moisture transport from the Amazon basin into the Andes, and probably with the volcanic eruption of Chichón that caused a reduction of incoming shortwave radiation over the Altiplano (Andrade 2018). However, at the beginning of the wet season, particularly in September and October, positive precipitation anomalies could be associated with winter patterns, such as cut-off lows, frequent in the transition months from the dry to the wet season (Vuille 1999; Garreaud et al. 2003).

6. Conclusions

This study improve the understanding on the establishment of the wet season in the outer tropical Andes of South America. In this regions spatiotemporal differences in the wet season timing were found, revealing an NW-SE orientation mostly associated with the distance to the equator and to the Amazon basin. Among the wet season timing, the onset presents high variability, revealing 37 days of differences between its occurrences along groups located in the eastern and western side of the study region. Moreover, the duration of the wet season is strongly influenced by the wet season onset, given that the wet season end did not reveal high variability over the period analyzed. A key factor in the establishment of the wet season is the southward displacement of the synoptic system toward the austral summer and the proximity to the Amazon basin. In lower levels of the troposphere, the evolution of the SALLJ plays an important role in transporting moisture from the

Amazon basin into the outer tropical Andes, particularly for regions located close to the Amazon basin. While regions located near to the Pacific basin, moisture transport in mid-troposphere from the southeast Amazon basin is relevant for the occurrence of the wet season onset. In the upper troposphere, divergence during the establishment of the wet season is generated by the interaction between a trough located over the Pacific ocean and the Bolivian high. In addition, a close analysis of atmospheric variables reveals that the change in the seasonality of zonal wind in the mid and upper troposphere, occurs in average 10 days prior to the establishment of wet season onset in the group 1; likewise, the change in seasonally in specific humidity occurs in about 3 days after the change in the zonal wind. The comparison between early and late wet season onset demonstrate that groups can present indistinctly cases of early or late wet season onset. In most of the cases analysed, early (late) wet season onsets are related to positive (negative) annual and wet season precipitation anomalies. At synoptic scale, an intense low-level northwesterly flow between Bolivia and Argentina prevails during early wet season onset during October and November, as well as weaker westerly and northwesterly winds in the mid and upper troposphere, respectively. Statistically significant trends using the Mann-Kendall test were found in groups 1 and 2, reveling that since 1979 these groups have experienced a delay in the wet season onset in 0.4 and 0.8 days per year, respectively. Both ENSO events examined show an opposite behavior in the occurrence of the wet season onset. Further analysis is needed to assess the causes of ongoing delay of the wet season onset in the southwestern side of the study area, as well as, the synoptic circulations related with wet and dry episodes at the beginning of the wet season during ENSO events. Finally, results from this paper can be used to improve water management by local governments paying special attention to the groups in which a delay of the wet season was found.

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APPENDIX A

Correlation Analysis

APPENDIX B

Cases of early and late wet season onset

a. Cases of early and late wet season onset in group 1 betweem 1979-80 and 2016-17 hydrologic years

b. Cases of early and late wet season onset in group 2 between 1979-80 and 2016-17 hydrologic years

c. Cases of early and late wet season onset in group 3 between 1979-80 and 2016-17 hydrologic years

d. Cases of early and late wet season onset in group 4 between 1979-80 and 2016-17 hydrologic years

APPENDIX C

Study cases El Niño 1982-83 and La Niña 1988-89

a. The very strong El Niño year (1982-83)

b. The strong La Niña year (1988-89)

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Table A1. Correlation matrix perform following Pearson method among climatological wet season timing (onset, end, and duration) and geographic and topographic characteristic of each particular weather stations.

	Elevation	Latitude	Longitude	Aspect	Slope	Onset	End	Duration
Elevation	1							
Latitude	-0.26	1						
Longitude	0.23	-0.86	1					
Aspect	0.16	-0.03	0.06	1				
Slope	-0.30	0.21	-0.10	0.20	1			
Onset	0.09	-0.61	0.27	-0.10	-0.17	1		
End	0.17	0.45	-0.46	-0.10	-0.13	-0.29	1	
Duration	-0.04	0.66	-0.36	0.07	0.12	-0.97	0.51	1

Table B1. Years with an early and late wet season onset in group 1 (upper and bottom in the table, respectively), showing the wet season timing, annual and wet season precipitation (mm), percentage of wet season precipitation (%), and annual and wet season precipitation anomalies (mm).

Year	Onset	End	Duration	Annual precipitation (mm)	We season precipitation (mm)	Percentage wet season precipitation (%)	Annual precipitation anomaly (mm)	Wet season precipitation anomaly (mm)
1984-85	07/10	25/04	201	637.9	602.5	94.5	145.1	225.9
1985-86	12/11	16/04	156	725.0	642.6	88.6	232.2	266.0
1987-88	12/10	08/04	179	552.7	475.2	86.0	59.9	98.5
1990-91	19/10	23/03	156	497.6	418.1	84.0	4.9	41.4
1992-93	13/11	27/03	135	459.5	378.1	82.3	-33.3	1.4
1996-97	07/11	29/03	143	600.7	533.9	88.9	107.9	157.3
1997-98	01/11	03/04	154	427.2	317.4	74.3	-65.6	-59.3
2009-10	12/11	05/03	114	514.6	403.9	78.5	21.9	27.2
1981-82	16/12	10/04	116	554.6	433.1	78.1	61.8	56.5
1988-89	18/12	21/04	125	429.1	358.4	83.5	-63.7	-18.2
1989-90	29/12	18/03	80	341.7	192.5	56.3	-151.1	-184.2
1991-92	25/12	07/03	73	302.2	210.5	69.7	-190.6	-166.1
1999-00	23/12	12/03	80	466.3	341.1	73.1	-26.5	-35.6
2003-04	18/12	04/04	108	408.7	361.8	88.5	-84.1	-14.8
2006-07	15/12	02/04	109	426.3	314.3	73.7	-66.5	-62.4
2015-16	17/12	13/03	87	412.5	239.2	58.0	-80.3	-137.5
2016-17	26/12	04/04	100	462.1	337.4	73.0	-30.7	-39.2

Table B2. Years with an early and late wet season onset in group 2 (upper and bottom in the table, respectively), showing the wet season timing, annual and wet season precipitation (mm), percentage of wet season precipitation (%), and annual and wet season precipitation anomalies (mm).

Year	Onset	End	Duration	Annual precipitation (mm)	We season precipitation (mm)	Percentage wet season precipitation (%)	Annual precipitation anomaly (mm)	Wet season precipitation anomaly (mm)
1979-80	02/10	01/04	182	684.8	644.2	94.1	-2.9	106.7
1982-83	20/09	18/03	180	549.1	421.0	76.7	-138.6	-116.5
1984-85	03/10	27/04	207	1111.7	1023.0	92.0	423.9	485.5
1985-86	25/10	27/04	185	1171.2	1067.5	91.1	483.5	530.0
1987-88	12/10	12/04	183	754.7	656.9	87.0	67.0	119.4
1990-91	18/10	26/03	160	711.5	585.9	82.3	23.8	48.4
1996-97	06/10	17/04	163	740.5	669.7	90.4	52.8	132.2
1988-89	14/12	28/04	136	582.6	458.5	78.7	-105.1	-79.0
1989-90	12/12	18/02	69	570.4	287.1	50.3	-117.3	-250.4
1991-92	24/12	06/03	73	413.8	268.9	65.0	-273.9	-268.6
1997-98	19/12	02/04	105	581.4	358.3	61.6	-106.3	-179.2
1999-00	23/12	14/03	82	624.6	413.9	66.3	-63.1	-123.6
2004-05	13/12	05/04	114	567.3	426.7	75.2	-120.4	-110.8
2014-15	12/12	24/04	134	678.3	511.0	75.3	-9.4	-26.5
2015-16	18/12	13/03	86	582.7	338.1	58.0	-105.0	-199.4

Table B3. Years with an early and late wet season onset in group 2 (upper and bottom in the table, respectively), showing the wet season timing, annual and wet season precipitation (mm), percentage of wet season precipitation (%), and annual and wet season precipitation anomalies (mm).

Year	Onset	End	Duration	Annual precipitation (mm)	We season precipitation (mm)	Percentage wet season precipitation (%)	Annual precipitation anomaly (mm)	Wet season precipitation anomaly (mm)
1979-80	02/10	01/04	182	653.1	606.0	92.8	-40.5	65.5
1982-83	13/10	16/03	155	553.4	412.9	74.6	-140.2	-127.6
1984-85	11/10	25/04	197	934.8	863.6	92.4	241.2	323.1
1990-91	09/10	27/03	170	709.9	587.4	82.7	16.3	46.9
1993-94	02/10	27/04	208	784.6	717.3	91.4	91.1	176.8
1997-98	25/09	02/04	190	665.4	615.1	92.4	-28.2	74.6
2000-01	08/10	27/03	171	823.4	727.8	88.4	129.9	187.3
2002-03	01/10	05/04	187	868.0	766.2	88.3	174.4	225.7
2005-06	02/10	06/04	187	687.1	639.5	93.1	-6.4	99.0
1980-81	06/12	14/04	130	785.9	582.1	74.1	92.4	41.6
1986-87	05/12	23/03	109	671.7	457.0	68.0	-21.8	-83.6
1988-89	15/12	21/04	128	535.2	421.2	78.7	-158.3	-119.3
1989-90	23/12	18/03	86	559.3	324.3	58.0	-134.3	-216.3
1999-00	20/12	18/03	89	633.6	414.3	65.4	-60.0	-126.2
2001-02	06/12	23/04	139	728.7	555.9	76.3	35.2	15.4
2003-04	12/12	01/04	111	710.0	546.9	77.0	16.5	6.4
2004-05	09/12	07/04	120	600.1	441.7	73.6	-93.5	-98.8
2008-09	01/12	26/03	116	576.4	441.0	76.5	-117.2	-99.5
2010-11	04/12	02/04	120	585.7	488.4	83.4	-107.8	-52.1

Table B4. Years with an early and late wet season onset in group 2 (upper and bottom in the table, respectively), showing the wet season timing, annual and wet season precipitation (mm), percentage of wet season precipitation (%), and annual and wet season precipitation anomalies (mm).

Year	Onset	End	Duration	Annual precipitation (mm)	We season precipitation (mm)	Percentage wet season precipitation (%)	Annual precipitation anomaly (mm)	Wet season precipitation anomaly (mm)
1981-82	16/10	10/04	177	797.4	690.1	86.5	129.9	130.7
1982-83	14/10	08/04	177	556.5	468.6	84.2	-111.1	-90.8
1984-85	11/10	25/04	197	871.5	790.2	90.7	203.9	230.8
1987-88	16/10	14/04	181	773.4	693.2	89.6	105.9	133.8
1994-95	12/10	30/03	170	635.3	574.6	90.5	-32.3	15.2
1998-99	18/10	05/04	170	596.0	519.6	87.2	-71.6	-39.8
2000-01	11/10	28/03	169	756.8	655.9	86.7	89.2	96.5
2002-03	04/10	12/04	191	830.4	745.0	89.7	162.8	185.6
2013-14	12/10	28/03	168	674.0	586.2	87.0	76.4	26.8
1980-81	07/12	12/04	127	757.9	576.0	76.0	90.4	16.6
1988-89	30/11	02/04	124	602.0	481.8	80.0	-65.6	-77.6
1989-90	14/12	18/03	95	544.4	311.1	57.1	-123.2	-248.3
1999-00	06/12	14/03	99	575.6	389.9	67.7	-92.0	-169.5
2003-04	09/12	29/03	111	677.7	480.8	70.9	10.1	-78.6
2004-05	09/12	03/04	116	587.2	418.0	71.2	-80.3	-141.4
2010-11	04/12	08/04	126	607.6	503.9	82.9	-60.0	-55.5
2011-12	09/12	02/04	115	644.7	439.8	68.2	-22.8	-119.6
2014-15	08/12	16/04	130	660.1	481.3	72.9	-7.4	-78.1

Table C1. Monthly precipitation (mm) (above) and monthly precipitation anomaly (mm) (below) during the very strong El Niño year (1982-83).

Group	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
1	1.2	1.6	28.9	36.2	54.1	23.7	42.8	52.1	22.9	24.6	3.6	1.5
2	2.7	3.5	63.8	78.0	88.9	44.9	58.3	65.1	60.6	53.4	21.7	8.2
3	0.8	12.0	46.3	70.8	105.6	57.7	77.8	67.1	50.9	45.8	14.1	4.5
4	0.8	7.9	35.7	47.3	116.5	62.1	80.4	82.3	58.1	51.6	9.5	4.3
1	-3.1	-7.1	14.5	11.9	20.0	-49.6	-79.6	-44.7	-52.3	-3.1	-2.5	-3.9
2	-3.4	-8.4	39.4	35.6	36.7	-54.0	-97.9	-59.4	-45.9	8.4	10.0	0.5
3	-3.5	0.4	22.8	20.1	42.7	-51.8	-70.1	-51.1	-51.1	-0.9	4.2	-1.8
4	-3.6	-1.9	13.6	-2.7	51.0	-40.3	-60.2	-28.3	-42.1	5.2	-0.6	-1.3

Table C2. Monthly precipitation (mm) (above) and monthly precipitation anomaly (mm) (below) during the strong La Niña year (1988-89).

Group	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
1	1.7	0.7	14.8	19.1	7.3	55.3	95.7	86.7	91.5	47.0	5.1	4.1
2	4.6	1.6	29.0	29.2	20.8	89.4	137.5	87.8	90.5	74.1	12.3	5.7
3	0.6	0.0	13.0	41.3	13.2	100.9	128.4	78.3	76.8	67.9	9.8	5.2
4	0.0	0.5	7.4	40.6	21.3	104.9	135.6	105.3	121.2	49.3	8.2	7.8
1	-2.6	-7.9	0.4	-5.3	-26.8	-18.0	-26.8	-10.1	16.4	19.3	-1.0	-1.3
2	-1.5	-10.3	4.5	-13.2	-31.4	-9.5	-18.6	-36.7	-16.0	29.1	0.6	-2.0
3	-3.8	-11.6	-10.5	-9.4	-49.8	-8.7	-19.5	-39.9	-25.2	21.2	-0.1	-1.1
4	-4.4	-9.3	-14.8	-9.4	-44.1	2.6	-4.9	-5.3	21.0	2.8	-1.9	2.1

TABLE 1. Climatological wet season timing (onset, end, and duration), annual precipitation (mm), total wet season precipitation (mm), the percentage of wet season precipitation (%), and coefficient of variation (%) of the onset, end and duration according to each group in the study area.

Group	Onset	End	Duration	Annual Precipitation (mm)	Wet season precipitation (mm)	Percentage wet season precipitation (%)	Coefficient of variation (%)		
							Onset	End	duration
1	30/11	05/04	127	492.8	376.7	76.4	14.8	7.1	26.3
2	13/11	07/04	146	687.7	537.5	78.2	17.1	6.6	24.8
3	12/11	08/04	148	693.5	540.5	77.9	19.9	5.3	20.6
4	24/11	11/04	170	667.5	559.4	83.8	16.3	4.8	18.7

TABLE 2. Trend Analysis, showing results from the Mann Kendall, two-sided (*) and one-sided- upward (**), Sens Slope and Pettitts test according to each group.

Group	Mann Kendall					Sen's slope			Pettitt's		
	tau	S	Var	p-value *	p-value **	slope	95% confidence interval	p-value	Change point	Kt	p-value
1	0.206	144	6314.667	0.0719	0.0360	0.389	-0.037-1.333	0.0719	1998-99	168	0.0989
2	0.251	175	6313.000	0.0285	0.0143	0.815	0.067-1.688	0.0285	1987-88	155	0.1547
3	0.043	30	6321.333	0.7153	0.3576	0.212	-0.714-1.000	0.7153	2002-03	68	1.2220
4	0.138	96	6312.667	0.1378	0.1159	0.357	-0.278-1.133	0.2318	2002-03	147	0.2001

TABLE 3. Wet season timing (onset, end, and duration) during the very strong El Niño year (1982-83), annual and wet season precipitation amounts and anomalies (mm) according to each group

Group	Onset	End	Duration	Annual precipitation (mm)	Annual precipitation anomaly (mm)	Wet season precipitation (mm)	Wet season precipitation anomaly (mm)
1	16/11	19/02	96	293.3	-199.5	155.4	-221.3
2	20/09	18/03	153	549.1	-138.6	421.0	-116.5
3	13/10	16/03	155	553.4	-140.2	410.5	-130.1
4	14/10	08/04	177	556.5	-111.1	468.6	-90.8

TABLE 4. Wet season timing (onset, end, and duration) during the strong La Niña year (1988-89), annual and wet season precipitation amounts and anomalies (mm) according to each group

Group	Onset	End	Duration	Annual precipitation (mm)	Annual precipitation anomaly (mm)	Wet season precipitation (mm)	Wet season precipitation anomaly (mm)
1	18/12	21/04	125	429.1	-63.7	358.4	-18.2
2	14/12	28/04	135	582.6	-105.1	458.5	-79.0
3	15/12	21/04	128	535.2	-158.3	411.0	-129.5
4	30/11	02/04	124	602.0	-65.6	481.8	-77.6

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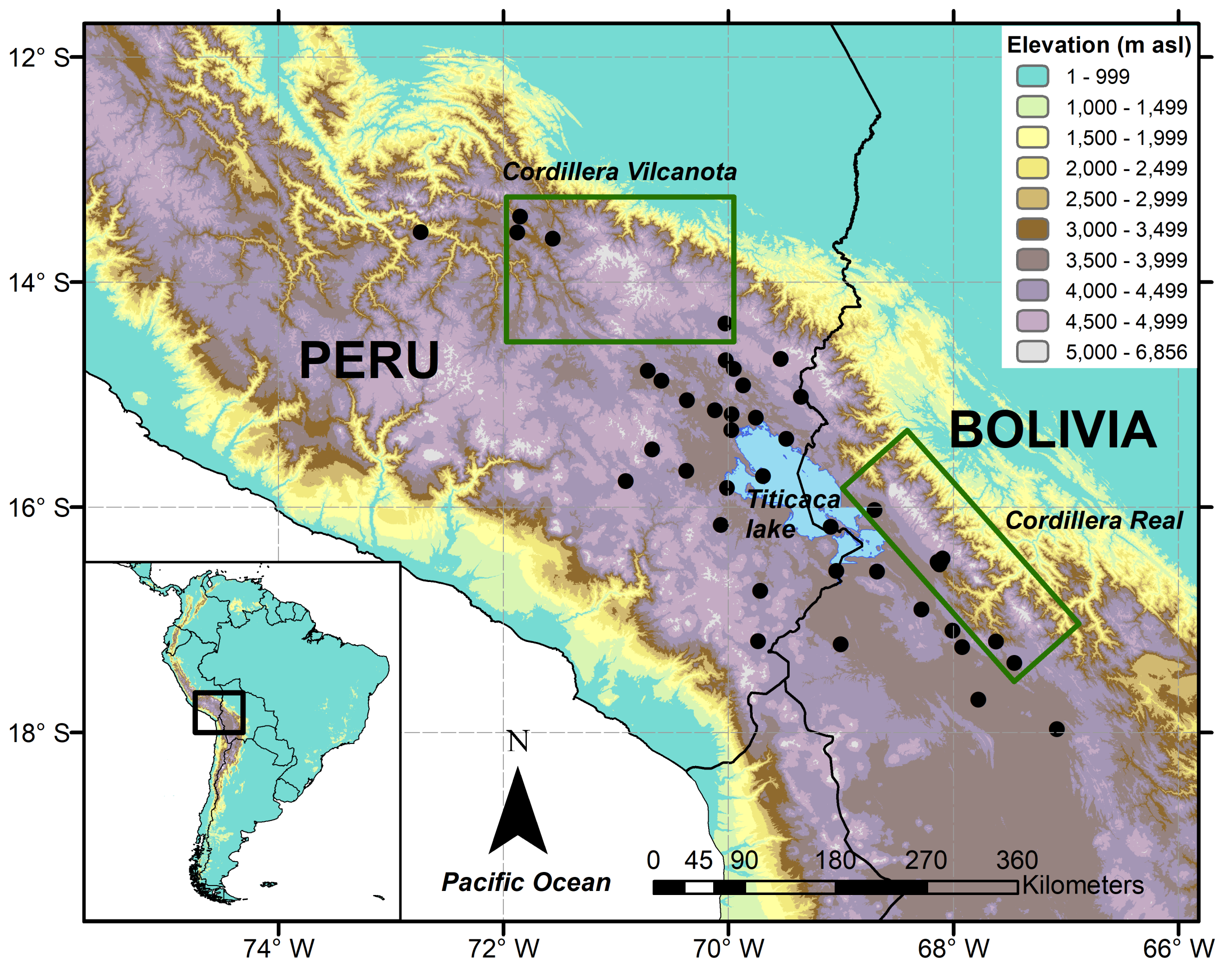


FIG. 1. Study area showing the location of the 43 weather stations (black dots) located above 2500 m asl, with more than 90% completeness of precipitation observations and currently operating, and the surrounding cordilleras.

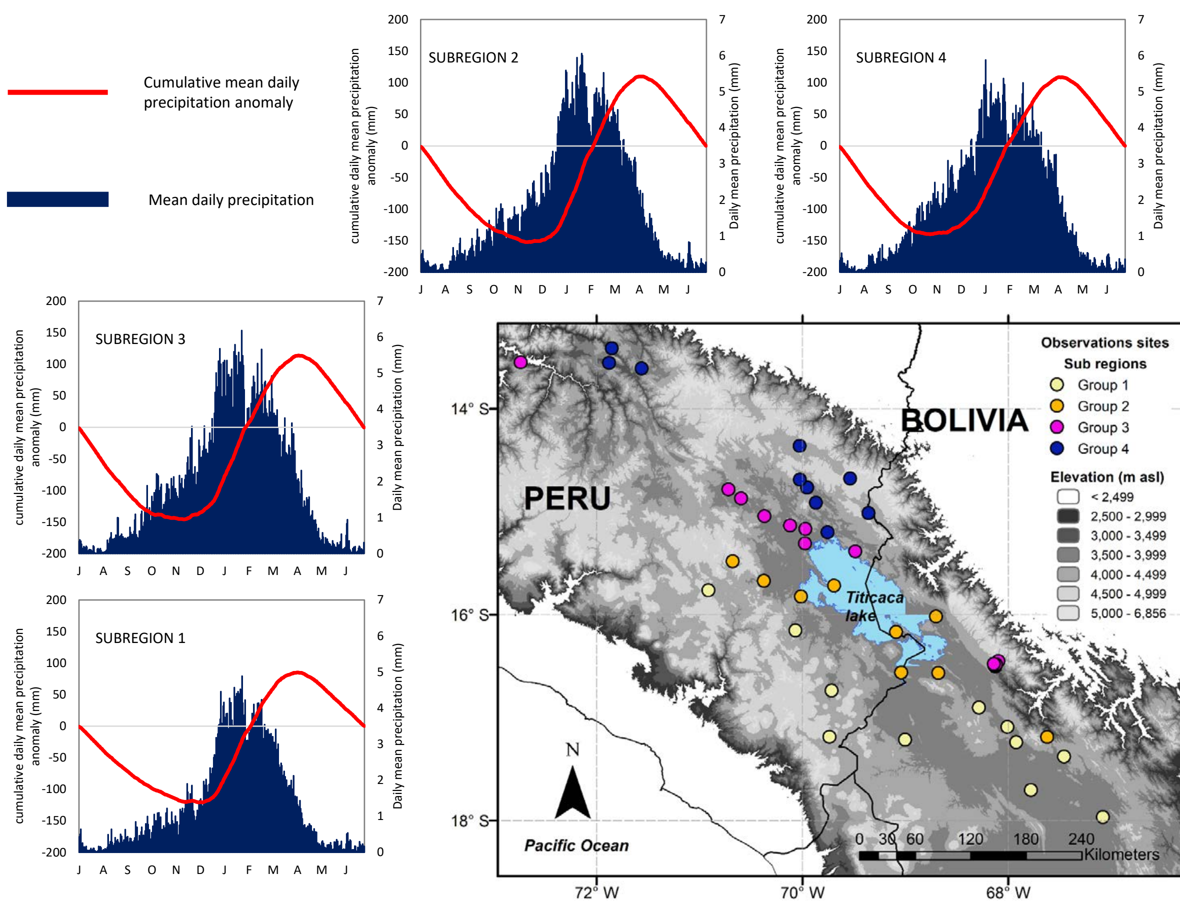
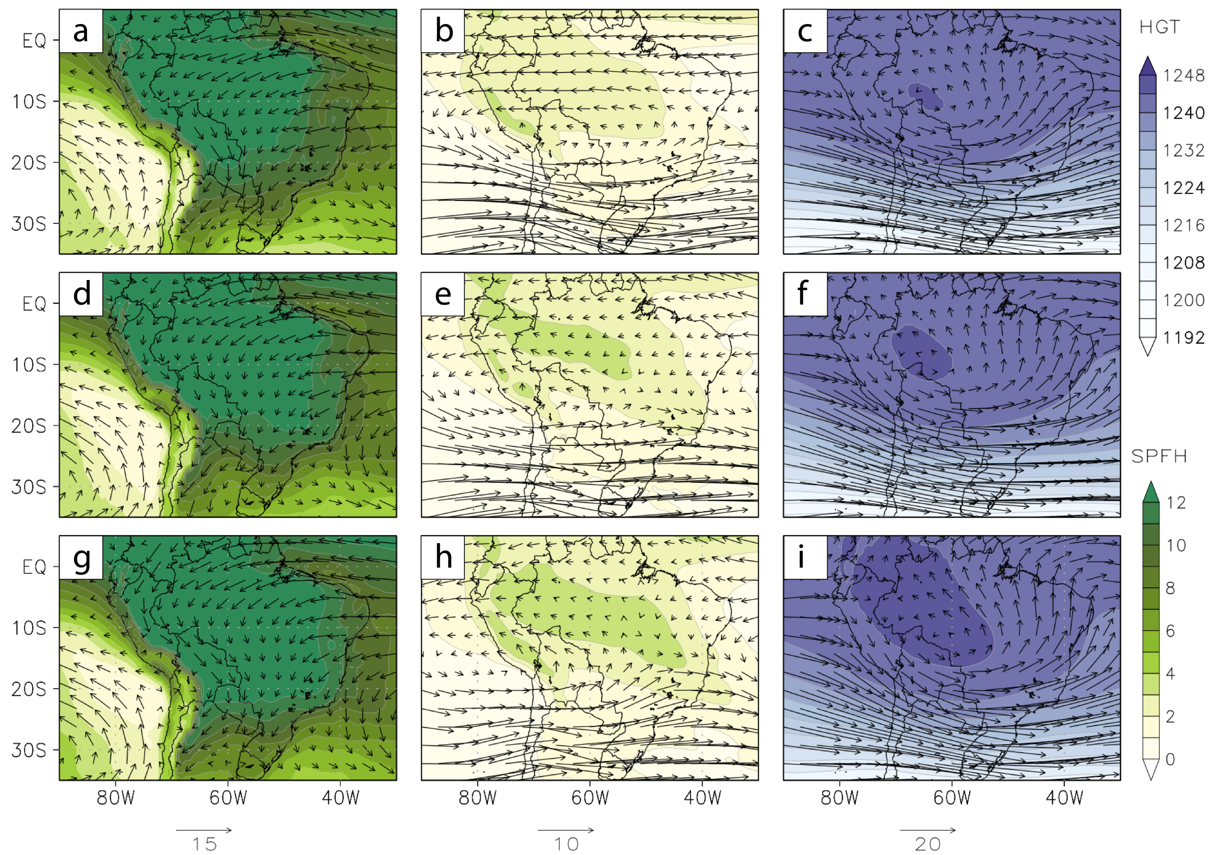


FIG. 2. Spatial distribution of the four subregions, cumulative daily mean precipitation anomaly (red line) and daily mean precipitation (blue bars) in each group. The minimum and maximum points in the red line mark the onset and end dates of the wet season.



1007 FIG. 3. Temporal progression of the atmospheric conditions in lower (850 hPa), middle (500 hPa) and upper
1008 (200 hPa) levels of the troposphere for the onset dates in group 4 (a, b, c), group 2 (d, e, f), and group 1 (g, h, i).

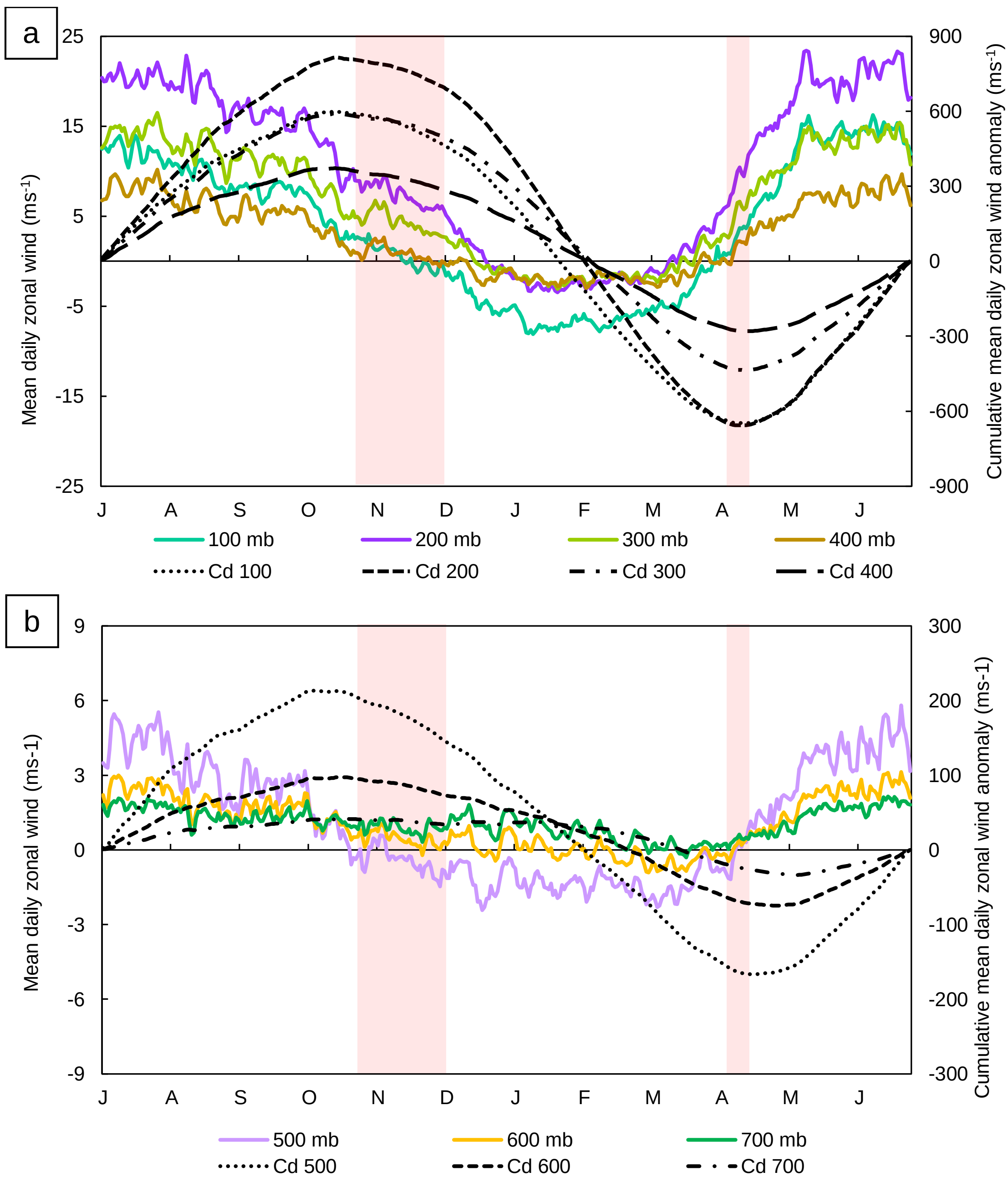
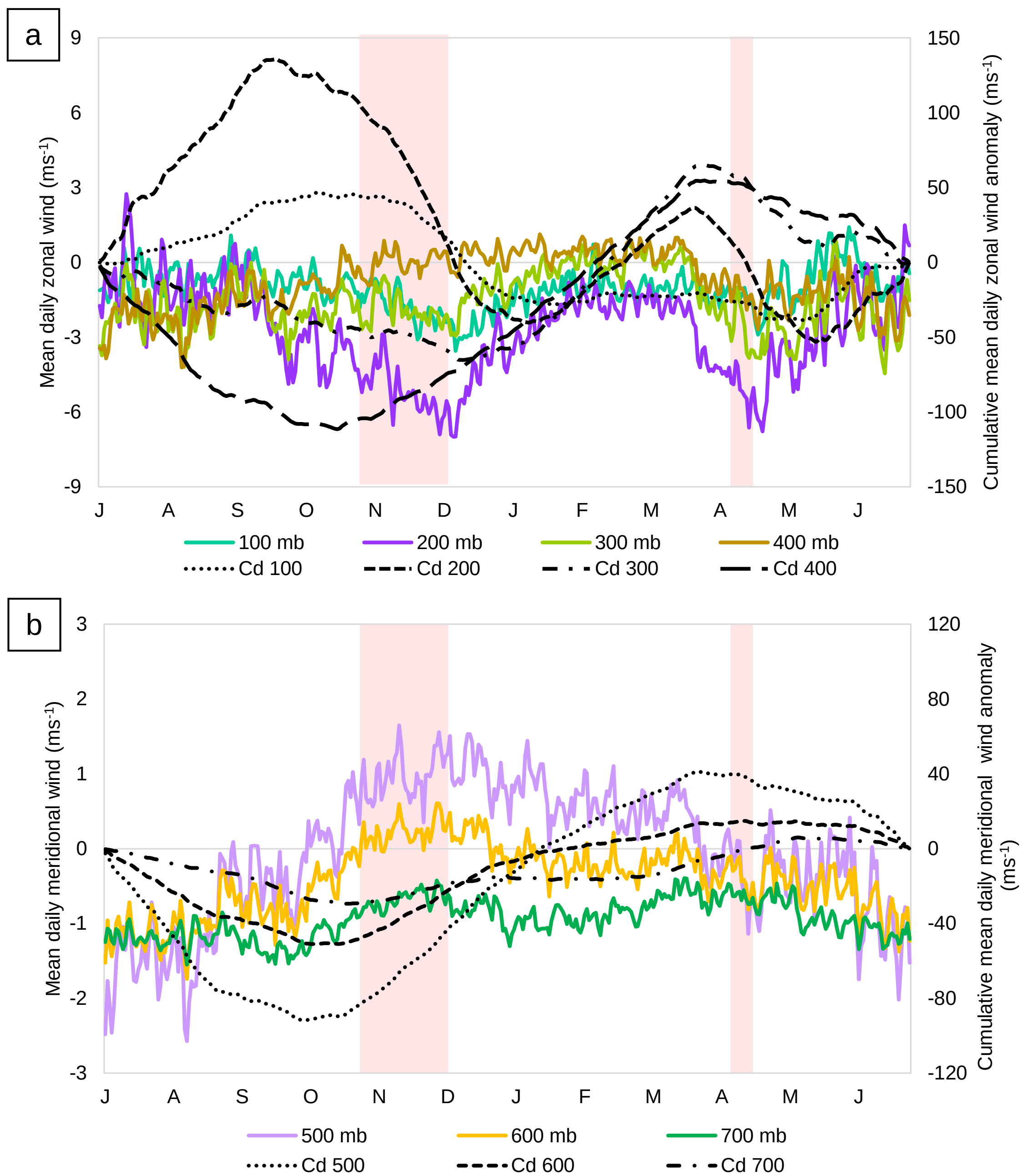


FIG. 4. The seasonal cycle of the zonal wind (ms^{-1}) in upper (a) and middle (b) levels of the troposphere averaged for the area between 18 and 12° S and 72.75 and 66.75° W. Black lines show the cumulative mean daily anomaly of this variable from 100 to 700 hPa. Colored lines represent the climatological mean daily values of the zonal wind. The pink rectangle marks the period in which wet season onset and end is established in all groups.



1014 FIG. 5. The seasonal cycle of the meridional wind (ms^{-1}) in upper (a) and middle (b) levels of the troposphere
1015 averaged for the area between 18 and 12° S and 72.75 and 66.75° W. Black lines show the cumulative mean daily
1016 anomaly of this variable from 100 to 700 hPa. Colored lines represent the climatological mean daily values of
1017 the meridional wind. The pink rectangle marks the period in which wet season onset and end is established in
1018 all groups.

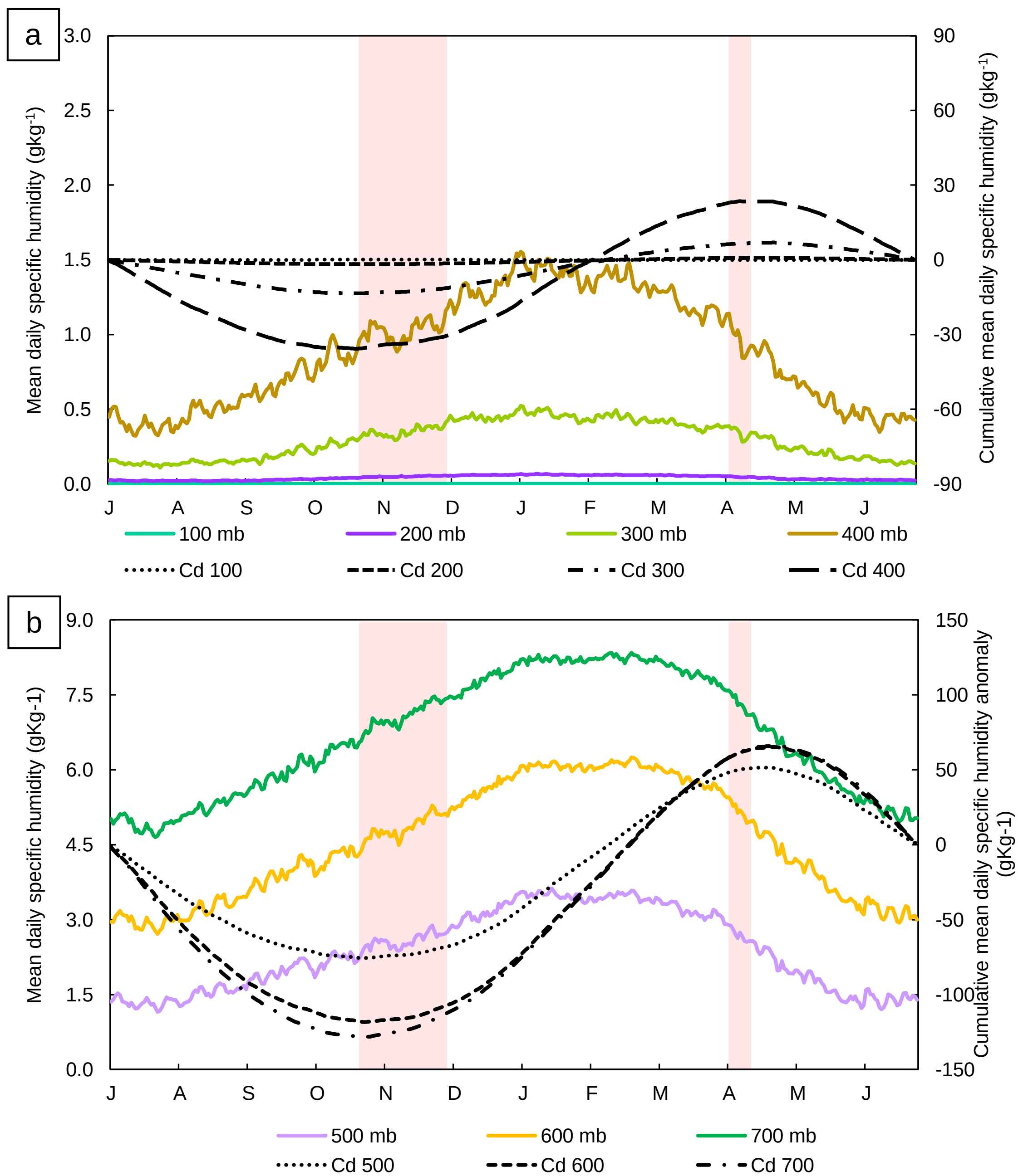


FIG. 6. The seasonal cycle of the specific humidity (gkg^{-1}) in upper (a) and middle (b) levels of the troposphere averaged for the area between 18 and 12° S and 72.75 and 66.75° W. Black lines show the cumulative mean daily anomaly of this variable from 100 to 700 hPa. Colored lines represent the climatological mean daily values of the specific humidity. The pink rectangle marks the period in which wet season onset and end is establishmed in all groups.

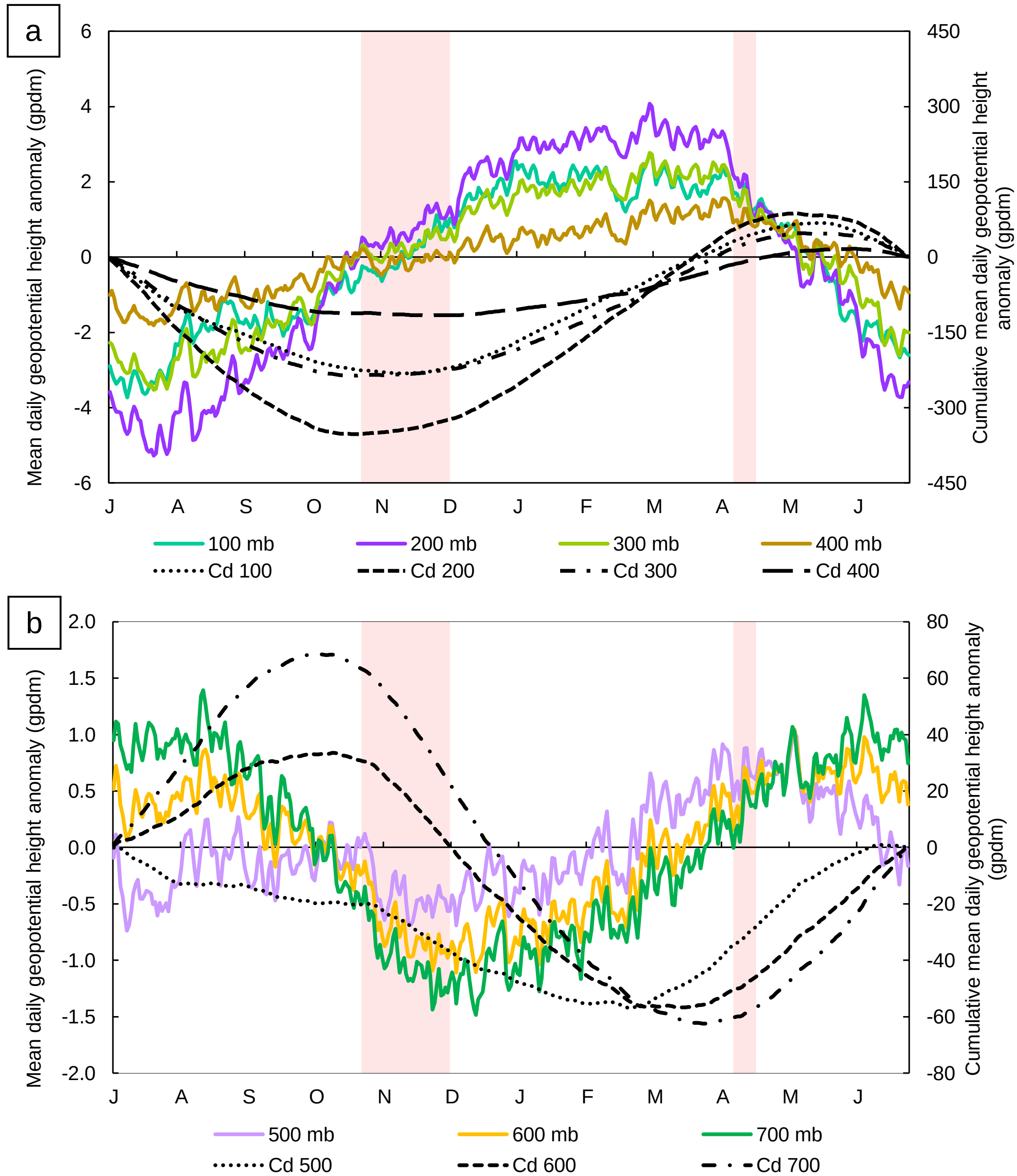
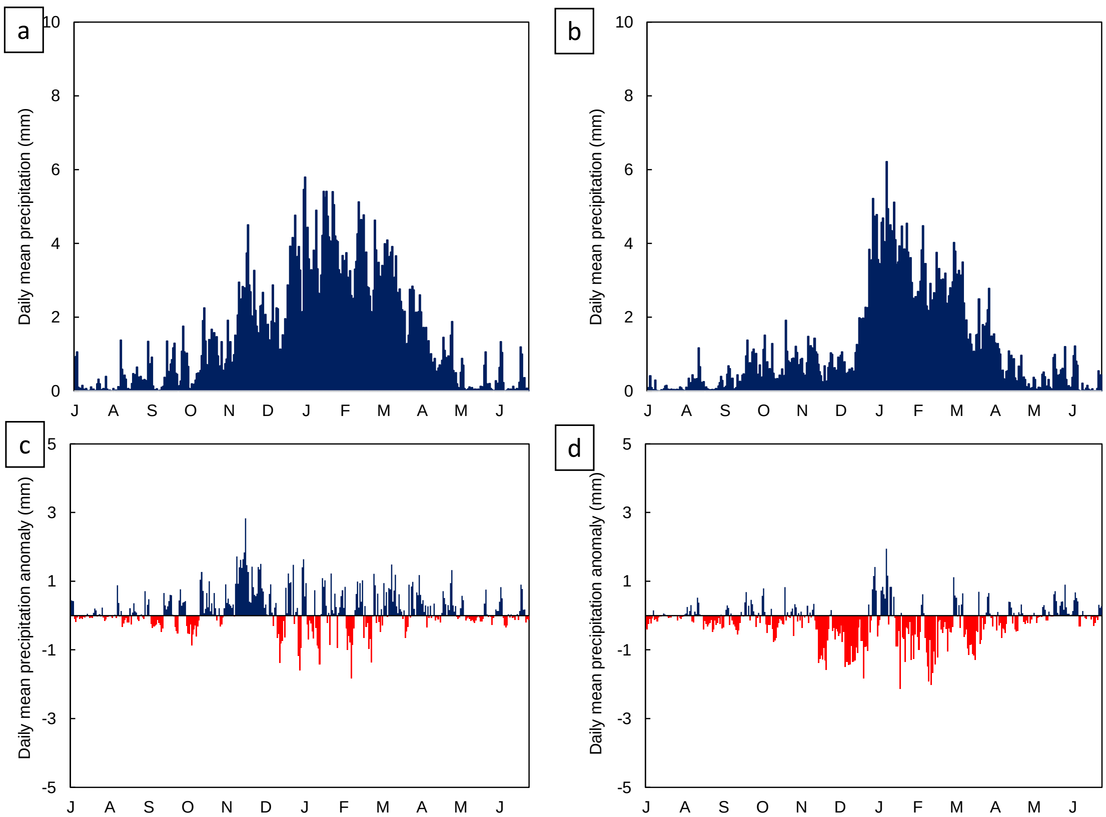


FIG. 7. The seasonal cycle of the geopotential height (*gpdm*) in upper (a) and middle (b) levels of the troposphere averaged for the area between 18 and 12° S and 72.75 and 66.75° W. Black lines show the cumulative mean daily anomaly of this variable from 100 to 700 hPa. Colored lines represent the climatological anomaly daily values of the geopotential height. The pink rectangle marks the period in which wet season onset and end is establishment in all groups.



1029 FIG. 8. Mean daily precipitation (mm) and mean daily precipitation anomaly (mm) during early (a and c) and late (b and d) wet season onset cases in group 1.

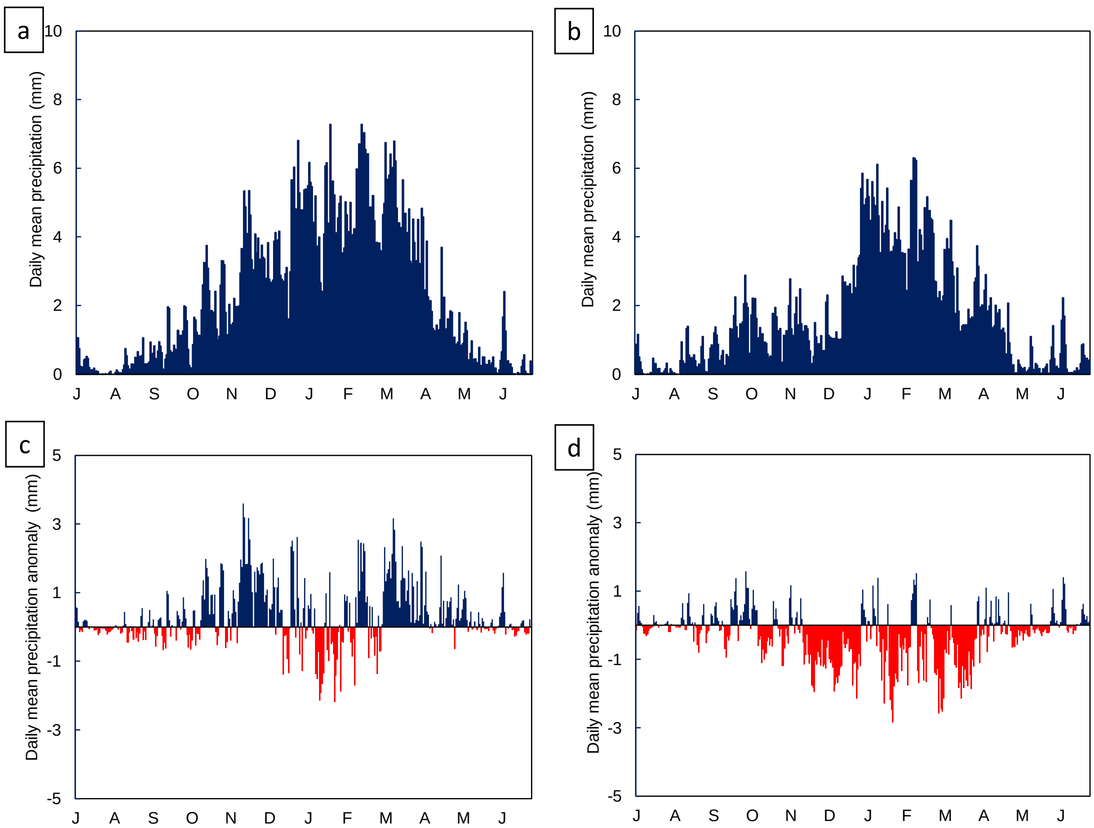


FIG. 9. Mean daily precipitation (mm) and mean daily precipitation anomaly (mm) during early (a and c) and late (b and d) wet season onset cases in group 2.

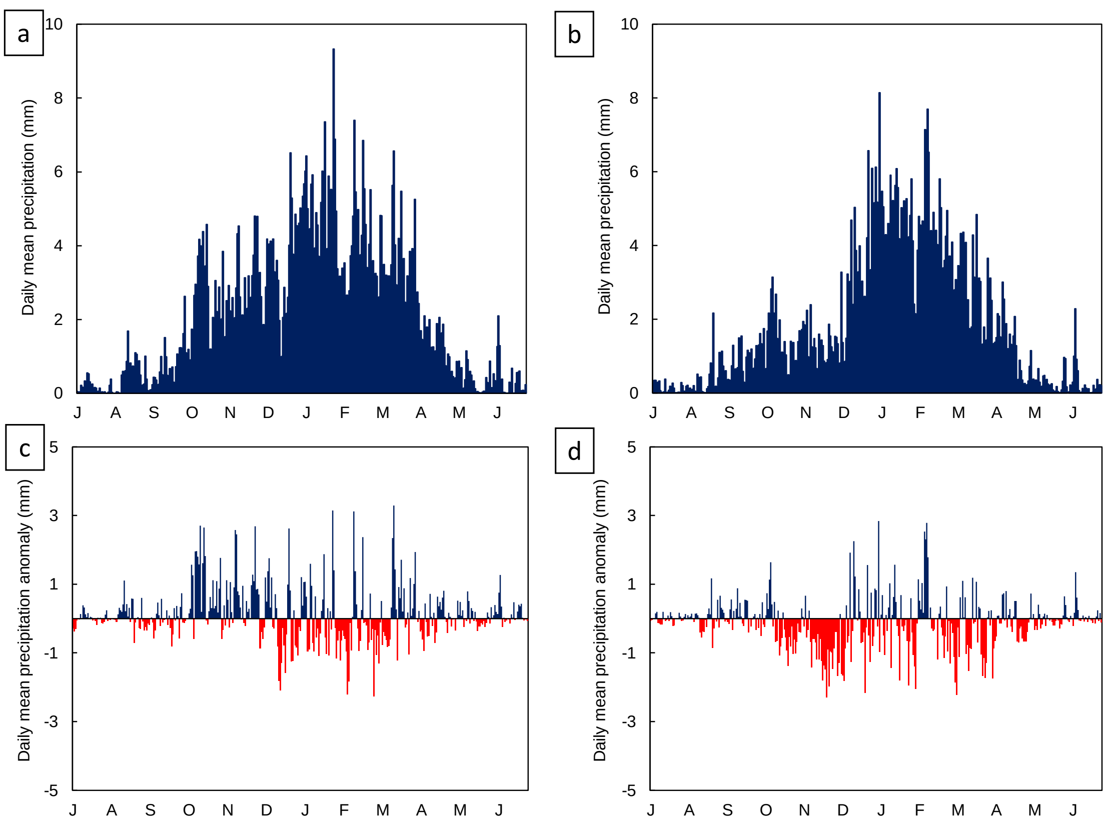


FIG. 10. Mean daily precipitation (mm) and mean daily precipitation anomaly (mm) during early (a and c) and late (b and d) wet season onset cases in group 3.

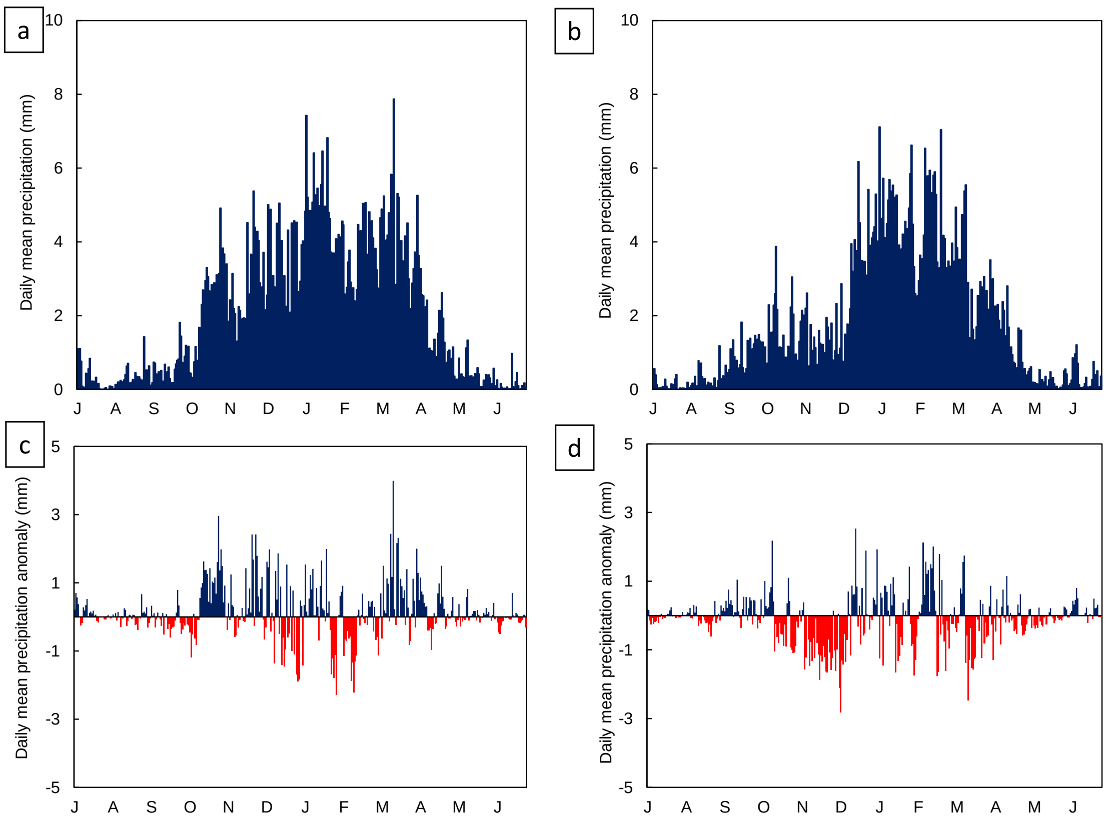


FIG. 11. Mean daily precipitation (mm) and mean daily precipitation anomaly (mm) during early (a and c) and late (b and d) wet season onset cases in group 4.

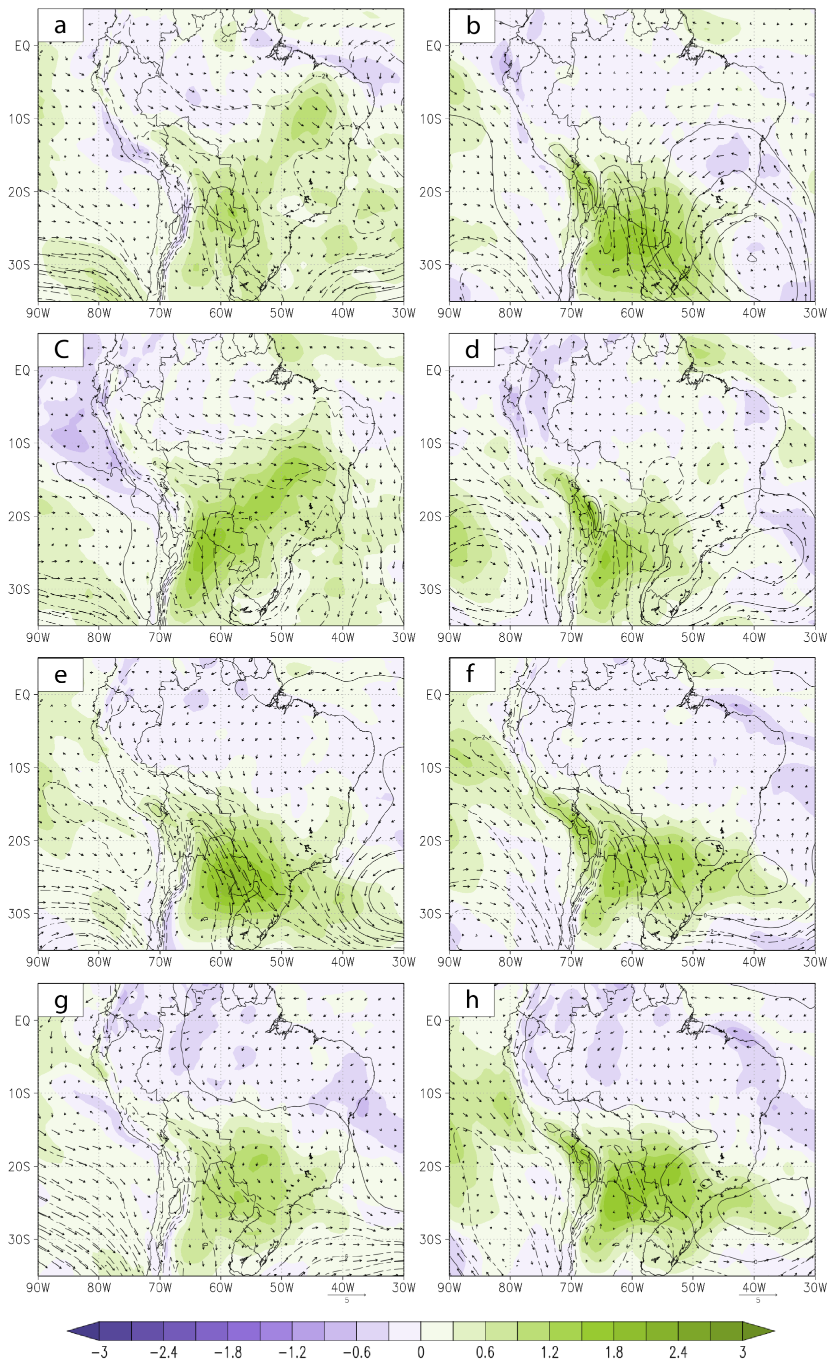


FIG. 12. Monthly differences in 850 hPa between early and late wet season onset among the four groups 1 (a and b), 2 (c and d), 3 (e and f), and 4 (g and h) in October (left panels) and November (right panels). Wind in vectors (ms^{-1}), specific humidity in shaded (gkg^{-1}), and geopotential height in contour ($gpdm$) with solid line showing positive differences and dotted lines, negative differences.

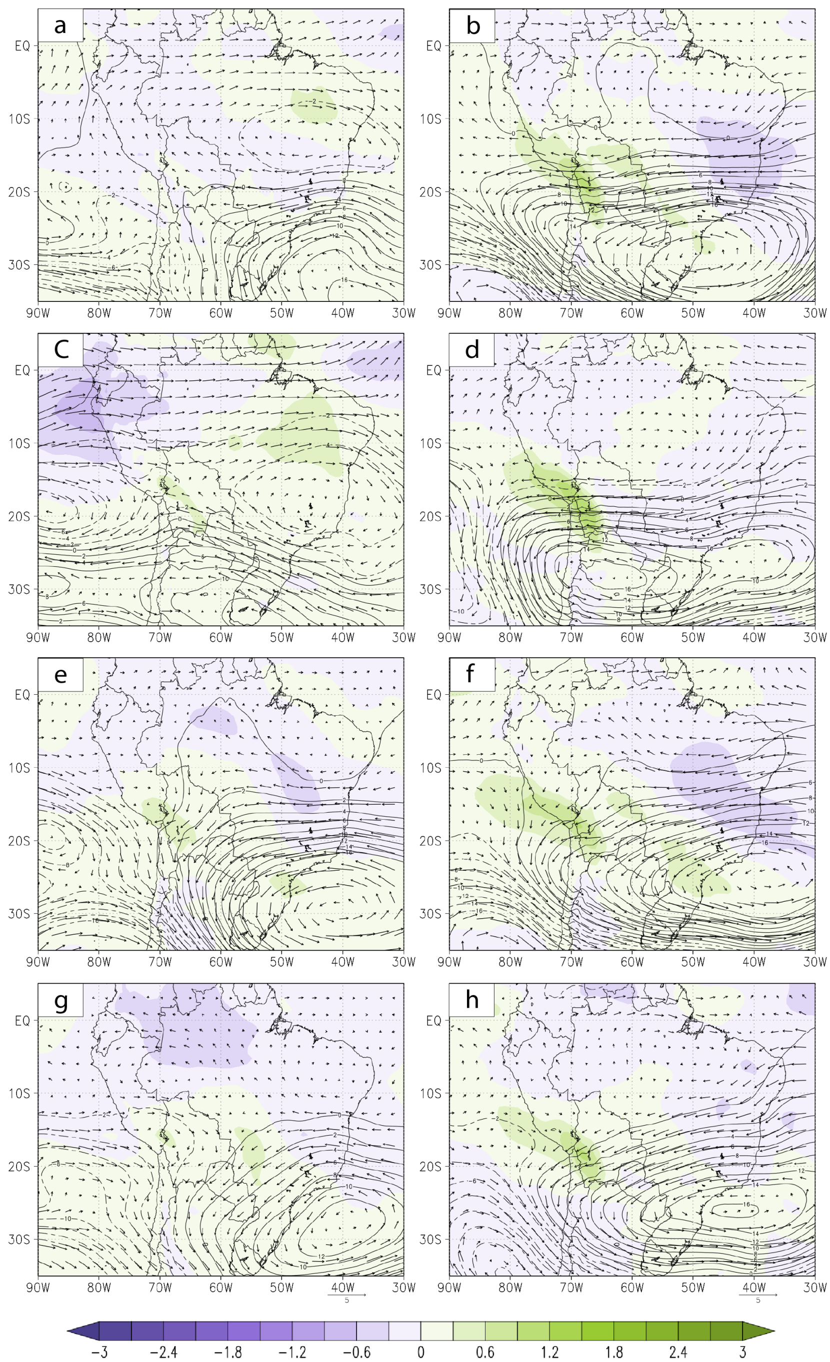


FIG. 13. Monthly differences in 500 hPa between early and late wet season onset among the four groups 1 (a and b), 2 (c and d), 3 (e and f), and 4 (g and h) in October (left panels) and November (right panels). Wind in vectors (ms^{-1}), specific humidity in shaded (gkg^{-1}), and geopotential height in contour ($gpdm$) with solid line showing positive differences and dotted lines, negative differences.

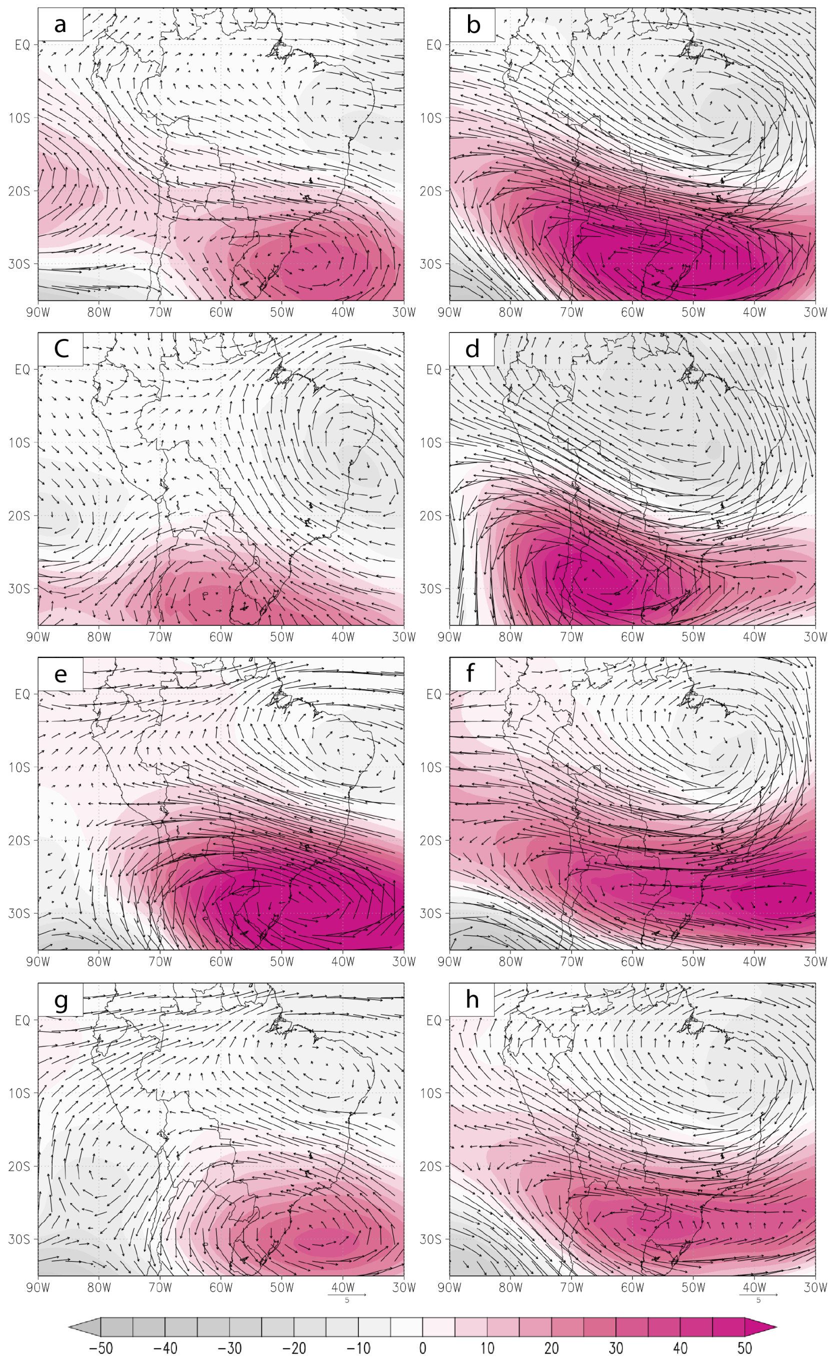


FIG. 14. Monthly differences in 200 hPa between early and late wet season onset among the four groups 1 (a nad b), 2 (c and d), 3 (e and f), and 4 (g and h) in October (left panels) and November (right panels). Wind in vectors (ms^{-1}) and geopotential height in shaded ($gpdm$).

Vita

Tania K. Ita Vargas was born and raised in Carhuaz, a little town located in Cordillera Blanca in the northern Peruvian Mountains. After graduating from high school in 2005 and begging a career in Management, she moved to Lima to study Meteorology at the Agrarian National University, eventually graduating with honors in April of 2013. Soon After, Tania joined the SENAMHI Peru where she work for 5 years. During that time, she had the opportunity to attend the International Desk Meteorology at NOAA in College Park, Maryland, USA, where she was trained in weather forecast in South America. Tania moved to Boone, NC, in January 2018 to work as a graduate research assistant with Dr. Baker Perry at Appalachian State University to improve her understanding of precipitation in the tropical high Andes of Peru and its implications for tropical glaciers. As part of this work, she has had the opportunity to return to Peru for summer course and fieldwork in one occasion, gaining valuable experience in mountaineering and interacting closer with Andean partners of Dr. Perry.

After graduation with a M.A. in Geography in May 2019, Tania plans to return to Peru to continue study the weather and climate of the Andes. She also hope to work in deep with Andean communities in weather and climate forecasting, for which she also plan to study Quechua as soon as come back to Peru.