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RESEARCH ARTICLE

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The rainy season in the Southern Peruvian Andes: A climatological analysis based on the new Climandes index

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Abstract

The rainy season is of high importance for livelihoods in the Southern Peruvian Andes (SPA), especially for agriculture, which is mainly rain fed and one of the main income sources in the region. Therefore, knowledge and predictions of the rainy season such as its onset and ending are crucial for planning purposes. However, such information is currently not readily available for the local population. Moreover, an evaluation of existing rainy season indices shows that they are not optimally suited for the SPA and may not be directly applicable in a forecasting context. Therefore, we develop a new index, named Climandes index, which is tailored to the SPA and designed to be of use for operational monitoring and forecasting purposes. Using this index, we analyse the climatology and trends of the rainy season in the SPA. We find that the rainy season starts roughly between September and January with durations between 3 and 8 months. Both onset and duration show a pronounced northeast-southwest gradient, regions closer to the Amazon Basin have a considerably longer rainy season. The inter-annual variability of the onset is very high, that is, 2–5 months depending on the station, while the end of the rainy season shows a much lower variability (i.e., 1.5–3 months). The spatial patterns of total precipitation amount and dry spells within the rainy season are only weakly related to its timing. Trends in rainy season characteristics since 1965 are mostly weak and not significant, but generally indicate a tendency towards a shortening of the rainy season in the whole study area due to a later onset and an increase in precipitation sums during the rainy season in the northwestern study area.

KEYWORDS

agrometeorology, application/context, geophysical sphere, mountain, observational data analysis, physical phenomenon, rainfall, rainy season, tools and methods

1 | INTRODUCTION

Precipitation in the Southern Peruvian Andes (further referred to as SPA), a plateau with mean elevations of about 3,800 m.a.s.l. (Figure 1a), is characterized by a pronounced annual cycle. It can be divided into a main dry season (roughly May to July) with very little precipitation and a main wet season (roughly December to March) when most of the annual precipitation falls (Figure 1b; e.g., Perry et al., 2014; Imfeld et al., 2020). The onset and cessation of the rainy season fall into the transition periods from dry to wet (August to December) and wet to dry (March to May). The seasonal cycle is strongly connected to the zonal winds in the middle and upper troposphere, more specifically to the Bolivian High, which forms in austral summer whereby its position is primarily determined in response to convection over the Amazon (Lenters and Cook, 1997; Vuille, 1999; Garreaud et al., 2003). These zonal winds can consequently be seen as a characteristic of the South American Monsoon System (SAMS, see for example, Silva and Kousky, 2012). In austral summer, often, easterly winds related to the Bolivian High transport moist air from the Amazon towards the plateau, whereas in austral winter, when the Bolivian High is absent, westerly winds prevail over the study area and hinder the moisture import from the Amazon (e.g., Garreaud, 2009; Segura et al., 2016).

Such weather and climate patterns are crucial for agriculture which is the main source of income in the SPA (Rossa et al., 2020). Since a large part of the farmers practice rain-fed farming with no means of irrigation, agricultural activities in the region are highly dependent on the rainy season (e.g., Sietz et al., 2012). In the SPA, the onset and the duration of the rainy season determine the sowing date and the length of the growing period. Climate information on the onset and duration of the rainy season along with the prediction thereof are thus of high interest. At present, decisions such as when to start sowing are based on longstanding traditional knowledge, which might be problematic in a changing climate if, for example, the frequency and temporal variations of rainfall are changing. In addition, the detection of changes in the characteristics of the rainy season are of high relevance for future planning purposes and mitigation strategies. However, precise meteorological and climatological information about the rainy season in the SPA is currently not readily available.

While various studies on characteristics of the rainy season exist for, for example, western Africa (e.g., Jolliffe and Dodd, 1994; Dodd and Jolliffe, 2001; Stern et al., 1981; Mupangwa et al., 2011), eastern Africa (e.g., Camberlin and Okoola, 2003; Camberlin et al., 2009) or in the Amazon basin (e.g., Marengo et al., 2001, 2017; Liebmann et al., 2007; Fu et al., 2013), literature on the rainy season in the Andean region is scarce. For the Bolivian Altiplano southeast of the SPA, Garcia et al. (2007) conducted an analysis of the rainy season showing a pronounced north–south gradient in onset dates and duration. The onset dates range

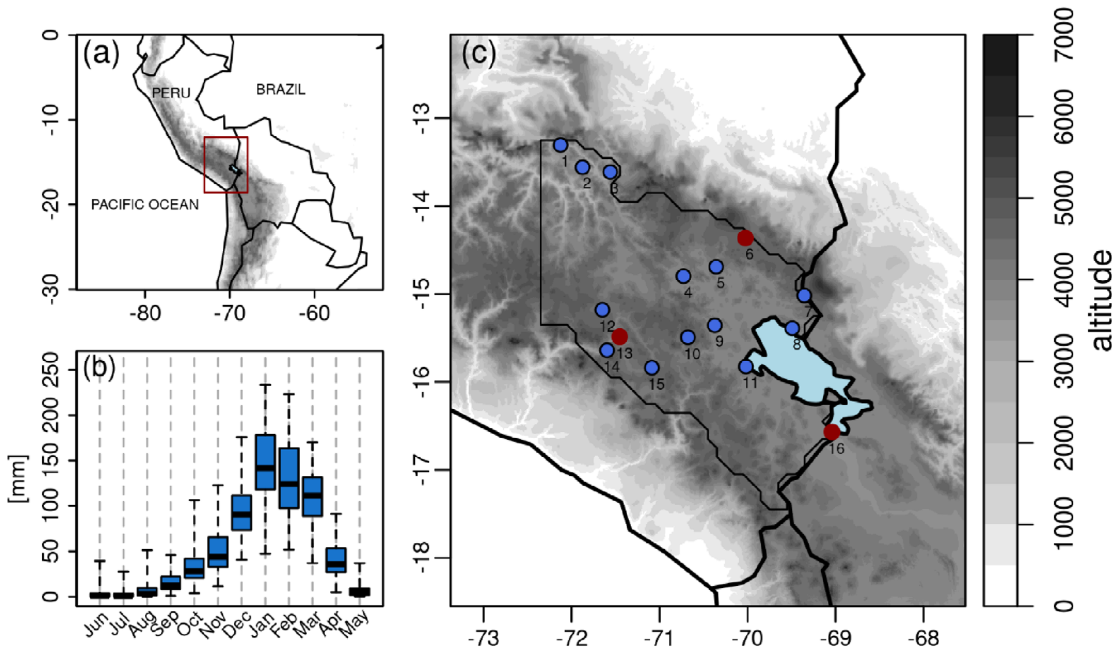

FIGURE 1 (a) Location of the study area in South America, (b) distribution of monthly precipitation derived from the stations in the study area for the period 1981/1982 to 2010/2011, (c) study area in the southern Peruvian Andes with topography and station location. The black line shows the border of the study area, the light blue area denotes Lake Titicaca. The three stations coloured in red are analysed in-depth in the course of the article (6: Crucero, 13: Sibayo, 16: Desaguadero) from early to late November, starting in the North, and the durations from 5 months in the North to 4 months in the South. They observed a high variability of the onset dates and a clear inverse relationship between onset dates and duration, that is, the earlier the onset the longer the duration. Further, Garcia et al. (2007) observed a frequent delay in sowing and a need to re-sow caused by the high probability of dry spells during and after the normal sowing period as well as the occurrence of prolonged dry spells during drought sensitive cultivation stages. For the Cordillera Blanca and Negra, two mountain chains to the north of the SPA, Gurgiser et al. (2016) analysed different characteristics of the rainy season such as onset, cessation and duration, and dry spells occurring within the rainy season as well as wet spells within the dry season. Similar to Garcia et al. (2007), they observed a high variability in onset dates and sometimes long dry spells occurring after several wet days at the beginning of the season, often resulting in too early sowing. In addition, Gurgiser et al. (2016) compared some characteristics of the rainy season to the farmers' perceptions of signs of a changing climate. The farmers perceived a delay, less rain overall and increasing variability of the onset dates of the rainy season as well as generally more intense rainfall events. Except for the generally high variability in onset dates, these perceptions could not be corroborated by the meteorological data. For instance, no significant trends in the onset of the rainy season were detected in the (relatively short) period of 1981–2010. However, it should be noted that Gurgiser et al. (2016) state that the quality and temporal aggregation of their data make it difficult to derive robust statements on trends. Giráldez et al. (2020) conducted a study on the rainy season in the Mantaro River Basin in the Central Peruvian Andes for the period 1965–2013. Their findings confirm the high variability in onset dates, which mainly modulate the duration of the rainy season. Further, they found a north–south gradient in the onset of the rainy season with earliest mean onsets at the end of September and latest mean cessation dates in early April. In the Mantaro River Basin, a delay of 3 days/decade in onset dates was observed for the studied period. However, the trend signal is not significant for high altitude stations and weak compared with the standard deviation, which ranges between one to five pentads. Trends in the cessation of the rainy season have not been found in the above studies.

In this study, we aim to find an index, which can be used for forecasting the onset of the rainy season in the SPA based on currently available forecast products. In a first step, we therefore qualitatively evaluate the ability of existing indices from the literature to determine the onset and cessation of the rainy season in the SPA. Since their performance is not satisfactory in our evaluation for this particular region, we adopt the concepts of existing indices but modify them to better represent the rainy season in the SPA and to be applicable in forecasting. Index parameters are derived by a combination of statistical analysis of precipitation in the region and expert judgement. As this work was part of the Climandes project (Gubler, Sedlmeier, et al., 2020), the new index is called the Climandes index.

Based on the Climandes index, we conduct a climatological analysis of the characteristics of the rainy season in the SPA in order to close the above-mentioned information gap. These findings serve as a basis for providing and further developing climate information for the agricultural sector in the region. The climatological analysis includes climatological mean values, inter-seasonal and -annual variability, trends and the characterization of regional differences. Furthermore, relationships between the different spatio-temporal precipitation characteristics with respect to the timing of the rainy season are analysed.

2 | DATA

2.1 | Station data

We use observations from 16 stations (Table 1 and Figure 1c) provided by the Peruvian weather service SENAMHI. The selection of the 16 stations is based on quality criteria and record length. The observations have been quality controlled and homogenized in the course of the projects Climandes 1 & 2 (Rosas et al., 2016) and DECADE (Hunziker et al., 2017) for the period 1965 to 2013. For this study, the time series are extended until 2018. Note that the authors are not aware of any changes in station locations after 2013 and a visual inspection did not reveal any major break points. The station records have not been gap-filled and thus missing values have to be taken into account when calculating the indices.

For the three stations Crucero (6), Sibayo (13) and Desaguadero (16) (red circles in Figure 1c), in-depth analyses are shown in Sections 4.3 and 4.4. These three stations are selected because they represent geographically distinct areas (see Figure 1) and contain few missing values.

2.2 | PISCO

The gridded dataset for daily precipitation PISCO (Peruvian Interpolated data of SENAMHI'S Climatological and Hydrological Observations) was developed by SENAMHI. The dataset is available for the years 1981–2016 at a resolution of ∼10 km.Aybar et al., 2019. Note

TABLE 1 Description of precipitation stations in the Southern Peruvian Andes

Number	Station name	Department	Longitude	Latitude	Altitude	% missing values
1	Urubamba	Cusco	−72.13	−13.3	3,071	3.5 (2.4)
2	Granja Kcayra	Cusco	−71.88	−13.56	3,219	1.5 (1.7)
3	Ccatcca	Cusco	−71.56	−13.61	3,693	8.9 (5.6)
4	Chuquibambilla	Puno	−70.73	−14.8	3,910	0.5 (17.3)
5	Progreso	Puno	−70.36	−14.69	3,965	5.8 (3.7)
6	**Crucero**	**Puno**	**−70.02**	**−14.36**	**4,136**	**0.0 (2.6)**
7	Cojata	Puno	−69.36	−15.02	4,351	1.8 (1.8)
8	Huaraya Moho	Puno	−69.49	−15.39	3,831	0.8 (3.4)
9	Lampa	Puno	−70.37	−15.36	3,900	0.8 (1.1)
10	Pampahuta	Puno	−70.68	−15.49	4,320	0 (1.3)
11	Puno	Puno	−70.02	−15.82	3,840	0.3 (0.9)
12	La Angostura	Arequipa	−71.65	−15.18	4,256	0.3 (13.7)
13	**Sibayo**	**Arequipa**	**−71.45**	**−15.49**	**3,827**	**0.6 (0.5)**
14	Chivay	Arequipa	−71.6	−15.64	3,661	3.7 (2.3)
15	Imata	Arequipa	−71.09	−15.84	4,445	0.2 (0.4)
16	**Desaguadero**	**Puno**	**−69.04**	**−16.57**	**3,860**	**0.0 (1.0)**

Note: For the stations marked in bold font, more in-depth analyses are shown throughout this paper. Missing values are shown for the climate normal 1981–2010, the value in brackets corresponds to the percentage of missing values for the whole available period 1965–2018.

that the dataset inherently has a problem with inhomogeneities, as the number of stations included in the data record varies depending on the period, and as the station distribution is not uniform. For this analysis, only grid points above 3,000 m.a.s.l. are used (see study area in Figure 1c).

The full dataset can be downloaded from: http://iridl.ldeo.columbia.edu/SOURCES/.SENAMHI/.HSR/.PISCO/

3 | METHODS

3.1 | Evaluation of selected indices from the literature

We first examine different indices from literature with respect to their ability to describe the rainy season in the SPA in the region We select four indices from literature describing the onset and two describing the cessation of the rainy season (Table 2). For reasons of data availability and quality, we use only threshold-based indices which rely solely on daily precipitation data and use a fixed absolute threshold (in contrast to percentile-based thresholds as, for example, used by Giráldez et al. (2020) or the definition using the SPI by Silva et al. (2008)). The first two indices are the onset and cessation indices developed by Garcia et al. (2007) and Gurgiser et al. (2016), described above. The third onset index stems from Jolliffe and Dodd (1994) and is originally based on Stern et al. (1981). Variants of the latter index have been widely applied in Africa (e.g., Stern et al., 1981; Jolliffe and Dodd, 1994; Dodd and Jolliffe, 2001; Laux and Bardossy, 2008). The fourth onset index is used by the

TABLE 2 Definition of the rainy season indices

	Onset of rainy season	Cessation of rainy season
Gurgiser (Gurgiser et al., 2016)	P(7 d) > 10 mm No. wet days >10 within next 31 days (dd_th = 1 mm)	P(1 d) < 1 mm P(46 d) < 10 mm
Garcia (Garcia et al., 2007)	P(3 d) > 20 mm CDD ≤ 10 within next 30 days (dd_th = 0.1 mm)	P(20 d) = 0
JD (Jolliffe and Dodd, 1994)	P(3 of 5 days) ≥ 0.1 mm P(5 d) > 25 mm CDD ≤ 7 within next 30 days (dd_th = 0.1 mm)	–
SOS (Frere and Popov, 1986)	P(10 d) = 25 mm P(11–20 d) = 20 mm P(21–30 d) = 20 mm	–

Note: $P(x)$ refers to the x-day precipitation sum, CDD stands for consecutive dry days and dd_th is the precipitation threshold used for defining a dry day.

Agrometeorological division of the Peruvian weather service SENAMHI as an input for the water requirement satisfaction index (WRSI, Frere and Popov, 1986), which is the basis for SENAMHI's agrometeorological drought monitoring. In the following, the indices are termed as Gurgiser, Garcia, JD (named after the authors of the publishing article, cf Table 2), and SOS (start-of-season).

The onset indices are based on a set of two to three different criteria that account for (1) the precipitation amount falling within several days and (2) the occurrence of subsequent dry or wet spells. The first criterion is designed to indicate the time when the soil contains enough moisture for sowing. The second criterion is relevant in order to ignore single precipitation events followed by long dry spells. This aims at avoiding too early sowing due to a false start of the rainy season. In contrast to the above indices, the SOS does not include a dry spell criterion explicitly, but requires precipitation to exceed considerably high thresholds over three consecutive 10-day periods. The overall required 30-day precipitation sum of 65 mm assures either the occurrence of only few dry days or the occurrence of heavy precipitation events (see Figure 1b for mean monthly precipitation sums). The studies by Garcia et al. (2007) and Gurgiser et al. (2016) also provide indices for the cessation of the rainy season (Table 2), defined by less than 10 mm precipitation within 46 days (Gurgiser) or occurrence of 20 consecutive dry days (CDD) (Garcia).

Our evaluation is based on the following requirements: The conditions of the onset indicators should be well met in the main rainy season of the SPA when most of the annual rain falls. If they are too strict (e.g., precipitation thresholds are too high), there are too many cases in which the rainy season onset cannot be determined making the index useless for a climatological analysis. On the other hand, the criteria should not be too lenient (e.g., very low precipitation thresholds) that they are already fulfilled during the dry season. Furthermore, as rain fed agriculture is of high importance in the region, "false starts", i.e., long dry periods directly after the onset should be avoided. Therefore, the indices are evaluated by checking how often the index criteria are met within the main dry and wet season. In this study, the main rainy season is defined as the period for which the 10-day running mean of the daily precipitation median of all PISCO grid points within the SPA region surpasses its annual 75th percentile. The main dry season is the period for which the median stays below its annual 25th percentile (Figure 2). Considering the climatology (10-day running mean of the daily precipitation median), this definition leads to a 91 days long main wet season and 86 days long main dry season, and thus coincides well with the length of approximately 3 months of the main dry and wet season in the SPA determined by Andrade et al. (2018).

The analysis is based solely on station data for reasons explained in Sections 2.2 and 3.3. For each index, the probability of fulfilling its criteria is determined for each Julian day throughout the climate normal period of 1981/1982 to 2010/2011. This probability is estimated at each station separately by counting the number of times the criteria is fulfilled at a specific day in the period divided by the length of available data in the period (at most 30 years).

3.2 | Adaptation of index criteria for the SPA

According to our evaluation criteria, none of the indices from literature capture the rainy season in the SPA sufficiently well (see Section 4.1). Thus, the index criteria need to be adapted for application in our study region.

The newly defined "Climandes index" is based on the same type of criteria as described above: (1) rain/no rain on the onset/cessation date itself, (2) precipitation sum P(d) of several days above (onset)/below (cessation) a threshold and (3) a maximum number of subsequent dry spells (CDD) after the onset date.

$$\text{Onset:}\quad P(1\,\mathrm{d}) > 1\,\mathrm{mm}\,\&\,P(x\,\mathrm{days}) \geq pth_{\mathrm{onset}}\ \& \\ \max(\mathrm{CDD}(y\mathrm{days})) \leq \max_{\mathrm{cdd}} \tag{1}$$

$$\text{Cessation:}\quad P(1\,\mathrm{d}) \leq 1\,\mathrm{mm}\,\&\,P(z\,\mathrm{days}) < pth_{\mathrm{cessation}} \tag{2}$$

In the following, we need to find adequate definitions for the period lengths x, y and z, the precipitation thresholds *pth_onset* and *pth_cessation* and the maximum number of allowed consecutive dry days after the onset *max_cdd*. The period lengths are defined argumentatively based on forecasting ranges of available forecast products. Precipitation and CDD thresholds are derived through a probability analysis of available station observations (described in detail below) using the climate normal period of 1981/1982 to 2010/2011.

The time span for calculating the onset is set to 5 days ($x = 5$) as the current SENAMHI weather forecast predicts the weather up to 5 days ahead. For y, a longer period has to be chosen in order to detect false starts (i.e., long-lasting dry spells after the onset date). The indices from literature use 30/31 days (see Table 2), a time span which is covered by the monthly forecast of, for example, the US National Oceanic and Atmospheric Administration (NOAA)'s Climate Prediction Center or

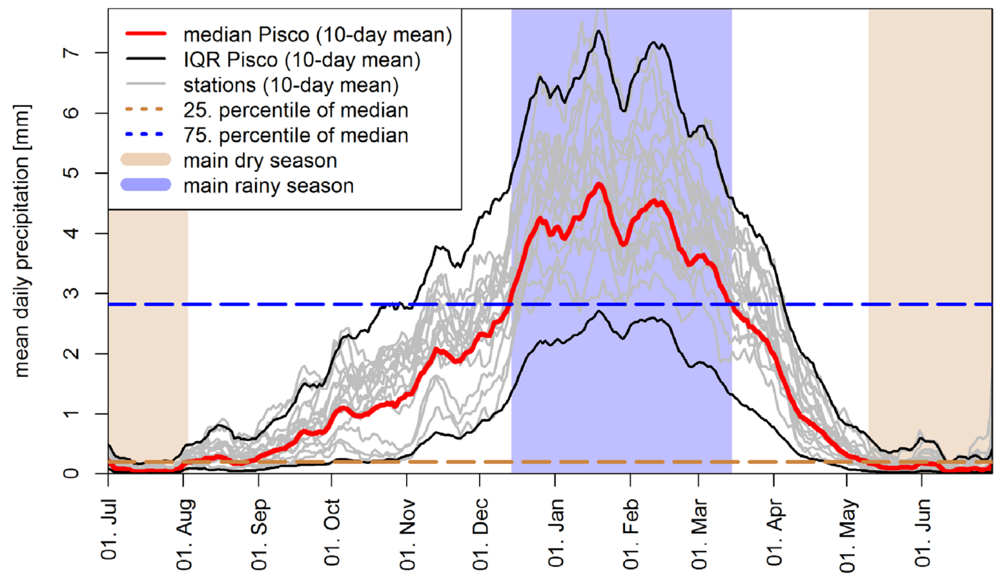

FIGURE 2 Mean yearly cycle of daily precipitation of PISCO gridpoints in the SPA (10-day running mean of median [red line] and IQR [black lines]) and of the 16 stations (10-day running mean [grey lines]). The dotted lines show the annual 25th (brown) and 75th (blue) percentile of the median of PISCO. The main rainy season is defined as the period for which the median is above the 75th percentile (blue shading), the main dry season as the period for which the median of PISCO is lower than the 25th percentile (brown shading)

the European Center for Medium Range Forecasting (ECMWF). We therefore use a time span of 30 days for both y and z. Forecasting the onset thus requires a two-step approach in which first, the surpassing of the precipitation threshold is forecast with the short-range weather forecast and, if the index criterion is fulfilled, the occurrence of consecutive dry spells is checked using a monthly forecast. Of course, this requires an a priori evaluation of forecast skill for the respective index criteria. While there are some studies on the seasonal forecast skill of rainy season precipitation for the region (e.g., Coelho et al., 2006; Gubler, Sedlmeier, et al., 2020; Vavrus et al., 2022), these mostly focus on mean precipitation. A skill assessment of monthly forecasts for our proposed index criteria was however beyond the scope of this study.

The thresholds are derived through the assumption that the two undefined parameters in the onset criteria (see Equation (1)) should each be very probable (>80%) in the main rainy season and very unlikely (<10%) in the main dry season for all stations. Further, the cessation criterion (Equation (2)) should be very unlikely (<10%) in the main rainy season and very probable (>80%) in the main dry season for all stations.For example, regarding the precipitation threshold *pth_onset*, this ensures that the threshold is not too high that it can only be met by single extreme precipitation events (i.e., a 5 day precipitation of 50 mm which almost never occurs is not a suitable onset threshold for this region). On the other hand, the threshold needs to be high enough to distinguish between the dry and the wet season. If a 5 day precipitation sum of 1 mm would be frequently met within the dry season, it would not be suitable for determining the onset.

The probability of a specific threshold being fulfilled is derived as a relative frequency, that is, by determining the relative frequency of days fulfilling the threshold criteria. In other words, we divide the total number of days within the main rainy/dry season, which fulfil the criteria for a given threshold, by the total number of days within the 30 seasons (omitting all days with missing values). This probability is calculated at each station separately. For *pth_onset*, 5-day precipitation sums between 1 and 30 mm, for *max_cdd*, dry spells of 1 to 10 days length, and for *pth_cessation*, values between 1 and 50 mm are tested.

Through our probability analysis, we thus obtain a range of meteorologically plausible parameter values. In a second step, the Climandes Index is defined by choosing the most suitable combination of parameter values based on the application (in our case agriculture).

3.3 | Methods of climatological analysis

For the climatological description of the rainy season, we investigate the timing of the rainy season using the newly defined Climandes Index (Section 4.3.1). Based on the onset and cessation of the rainy season, precipitation characteristics such as total precipitation sums, dry day percentages, and the maximum length of dry spells within the rainy season are determined (Section 4.3.2). In addition to the analyses of climatological mean values, the relations between the different rainy season parameters (onset, cessation, duration and precipitation characteristics) are assessed using Pearson correlation (Section 4.3.3). Strong connection between rainy season characteristics and onset dates would be especially interesting for planning purposes, as conclusions about for example, the expected precipitation amount or dry day percentages could be drawn, once the onset date is known. For the calculation of mean correlations over all stations, a Fisher transformation is applied (Wilks, 2011).

Finally, a trend analysis of the rainy season parameters is performed (Section 4.4) using a Theil-Sen slope estimator (Theil, 1950; Sen, 1968). Statistical significance is tested by the non-parametric Mann Kendall test (Mann, 1945; Kendall, 1975) at the 0.1 (10%) significance level. For calculation of the indices and their trends, the ClimIndVis R package is used. This package has been designed for the calculation and visualization of different climate indices within the CLIMANDES project (Gubler, Rossa, et al., 2020) and is freely available on GitHub (www.github.com/Climandes/ClimIndVis).

The spatial analyses performed in this study such as the calculation of climatological means are based on the 30-year reference normal 1981/1982 to 2010/2011, that is, starting with the rainy season in austral spring 1981. For this period, both homogenized station data and the gridded PISCO dataset are available. It is known that the general spatial patterns of the PISCO dataset match those of the station observations reasonably well (Imfeld et al., 2020). However, on individual days, the station observations and the gridded dataset can differ. This is mainly due to the mostly convective formation of precipitation and the complex topography of the region where individual precipitation events can be of small spatial extent. The temporal analyses such as climate variability, correlations, or trends are based on station data only. This is because the gridded dataset shows some problems with inhomogeneities (e.g., Section 2.2). For all temporal analyses, the full available 53-year period covering the rainy seasons 1965/1966 to 2017/2018 is analysed.

Note that the onset dates are restricted to the period 1st of July to 28th/29th of February and the cessation dates to 1st of March to 30th of June. These restrictions are chosen according to the main cultivation period in the region as well as in order to avoid that the onset takes place after the cessation. The latter can theoretically happen in years with very little precipitation and long dry spells during the austral summer months. In case where the index criteria are not met within these periods, the indices are not calculated.

In addition, missing values in the station observations result in some limitations regarding the calculation of the rainy season indices. In this study, onset and cessation are thus not calculated if a missing value in the time series occurs before the onset or cessation criteria are met within the restricted time periods described above. Otherwise, the uncertainty in onset or cessation is too high since the precipitation value of a single day can be decisive for whether the index criterion is met or not.

Further, the following rules apply with regard to the calculation of the rainy season characteristics:

- Precipitation sums and dry day percentages are only calculated if at least 90% of the daily observations within the rainy season are available.
- Dry days are given as a percentage of the duration of the rainy season for the respective year.
- Dry spell lengths are only calculated for years in which there are no missing values at all between onset and cessation dates.
- Climatological means are only considered if the index or precipitation characteristic can be calculated for at least 80% of the years.
- Trends are only calculated if <20% of the years are missing and if the first five as well as the last 5 years of the time series are all present.

4 | RESULTS

4.1 | Evaluation of existing indices

The probabilities of fulfilling the index criteria within the main rainy season are quite low for all, except for the Gurgiser index, which shows probabilities around 80% within the main rainy season for most stations (Figure 3a). JD and Garcia indices show probabilities below 50% (Figure 3b, d). The SOS index has probabilities of around 60% (Figure 3c). The Gurgiser index seems to work quite well for the region. However, an analysis of the maximum number of consecutive dry days within the 30 days following the onset date shows that it has the drawback of a high number of false starts, where the calculated onset is followed by long dry spells (see Figure 4a). For our evaluation period, dry spells of up to 16 days length are recorded after the onset date. The analysis of the wet day criterion by Gurgiser, which requires more than 10 wet days within 31 days of the onset, is too weak, as it still allows up to 20 consecutive dry days within the 31 days following the onset date. The probabilities of fulfilling the cessation criteria are quite high for both

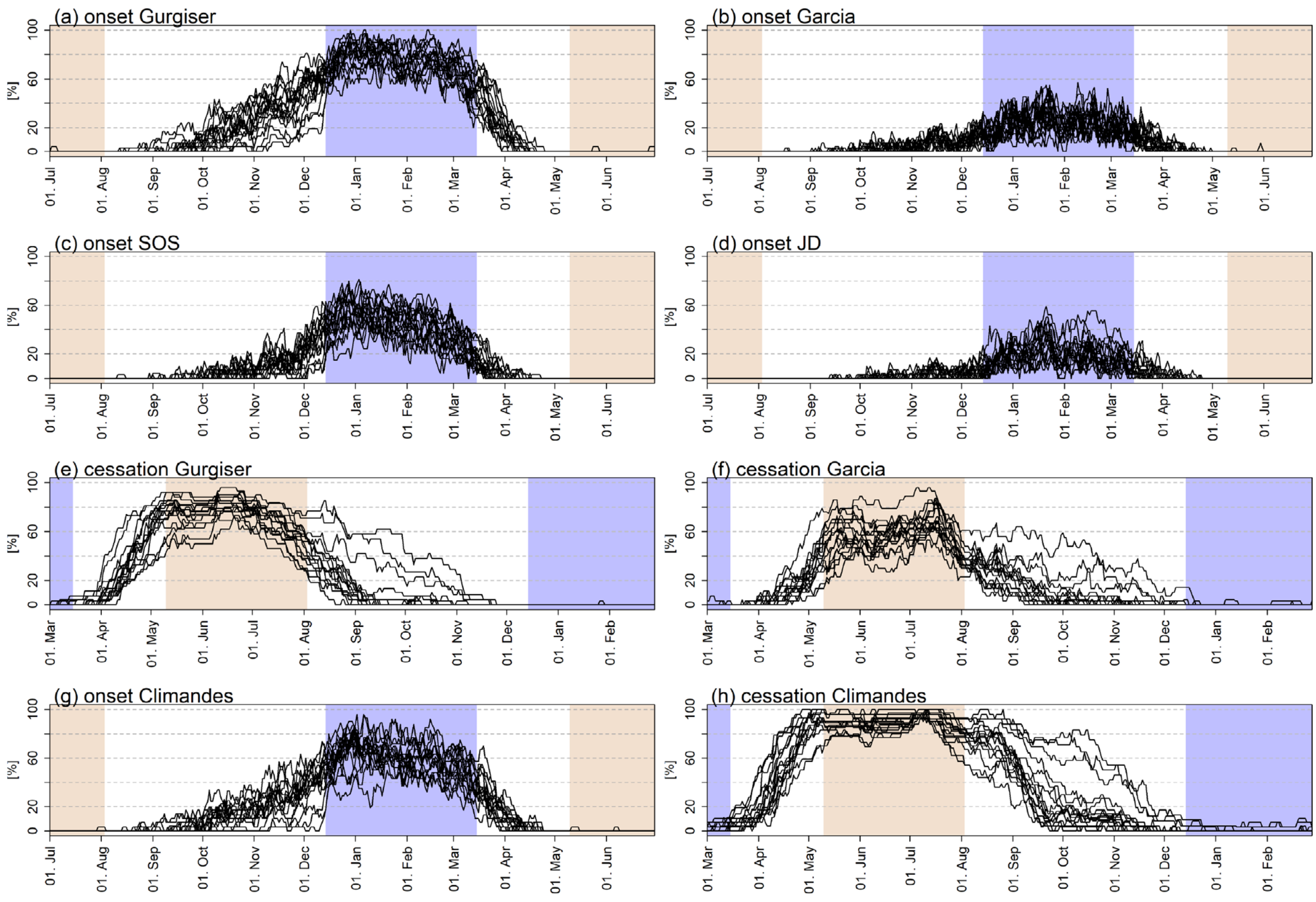

FIGURE 3 Probability of fulfilling the index criteria for four onset indices: (a) Gurgiser, (b) Garcia, (c) SOS and (d) JD; and two cessation indices: (e) Gurgiser, (f) Garcia. The figures at the bottom show the probabilities for the (g) onset and (h) cessation for the Climandes index. The probabilities are depicted for the 16 stations and the period 1981/1982 to 2010/2011. Shaded areas mark the evaluation periods within the main rainy/dry seasons (see Figure 2). Note the different time axis for onset and cessation

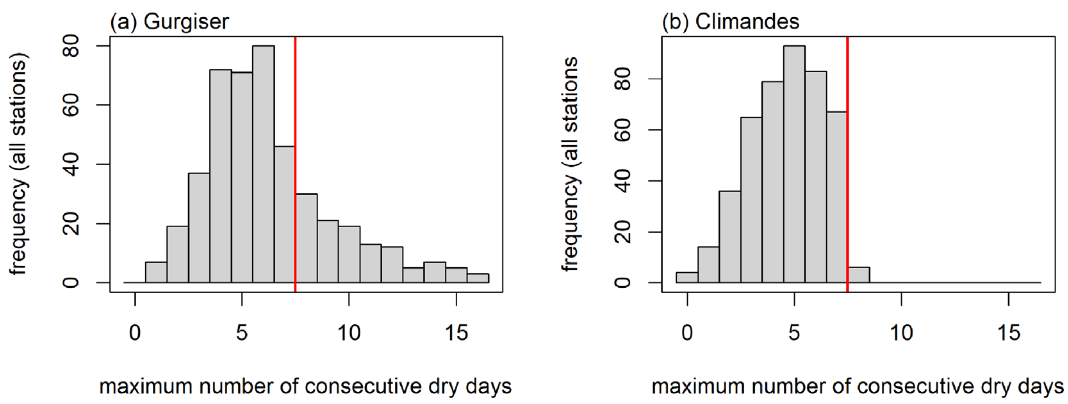

FIGURE 4 Maximum number of consecutive dry days in the 30 days following the rainy season onset for (a) the Gurgiser index, (b) the Climandes index. The histograms include values for all stations and all years where onset dates could be defined. The red line denotes the cdd threshold of 7 days which we have used for the index definition. The Gurgiser index shows dry spells of up to 16 in the 30 days after the onset

the Gurgiser and the Garcia indices (Figure 3e, f) with slightly higher values for the former. As in our evaluation none of the indices from literature capture the rainy season in the SPA as defined in our study sufficiently well, the index criteria need to be adapted for application in our study region.

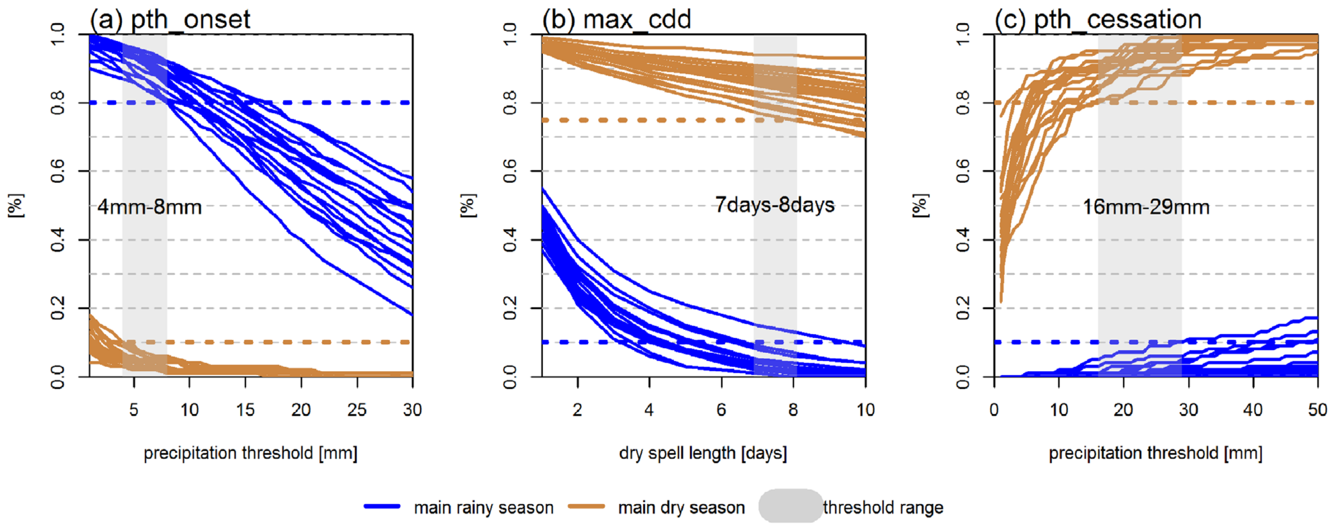

FIGURE 5 Derivation of parameter ranges for the adaptation of index for the SPA region (see Equations 1 and 2). (a) Derivation of pth_onset: probability (y-axis) of surpassing 5-day precipitation thresholds (x-axis) at the stations. (b) Derivation of max_cdd: probability (y-axis) of occurrence of a dry spell of specific lengths (x-axis). (c) Derivation of pth_cessation: probability (y-axis) of 30-day precipitation less than thresholds (x-axis) at the stations. Blue lines show the station probabilities for the main rainy season, brown lines show the station probabilities for the main dry season as defined in Figure 2. Horizontal lines highlight the probability chosen for selecting thresholds and grey shaded areas show the resulting range of possible thresholds for the SPA (see text). All analyses are based on the time span 1981/1982 to 2010/2011

4.2 | The Climandes index for the SPA

Our analysis yields a range of possible values for *pth_onset*, *max_cdd* and *pth_cessation* (Figure 5). The threshold *pth_onset* must lie between 4 and 8 mm for the SPA region (Figure 5a). As higher precipitation thresholds are better suited to ensure a sufficient precipitation amount for agricultural purposes, we set *pth_onset* to 8 mm. For *max_cdd*, no common threshold is yielded using the probability thresholds of 10% and 80%. Therefore, the probability threshold is lowered to 75% for the dry season. Further, we excluded one station (station 14) for the 10% threshold of the wet season. This station is located at the southwestern border of the study area in the transition region to the dry coast and shows comparatively low precipitation sums and a high number of dry days (see Imfeld et al., 2020). Finally, this results in a threshold range for *max_cdd* of 7–8 days. As dry spells after sowing are particularly harmful for new seedlings, the maximum number of allowed consecutive dry days *max_cdd* is set to 7. Note that Garcia et al. (2007) use the same threshold (see Table 2). The range of possible values for *pth_cessation* yielded by our analysis lies between 16 and 29 mm.

As lower precipitation thresholds lead to a lower number of false ends, the lowest value for *pth_cessation* for the different time spans of 16 mm is considered.

Based on the above discussions, the Climandes index is defined as follows:

$$\text{Onset}: \quad P(1\,\text{d}) > 1\,\text{mm}\ \&\ P(5\,\text{days}) \geq 8\,\text{mm}\ \&\ \max(\text{CDD}(30\,\text{days})) \leq 7\,\text{days} \tag{3}$$

$$\text{Cessation}: \quad P(1\,\text{d}) \leq 1\,mm\ \&\ P(30\,\text{days}) < 16\,\text{mm} \tag{4}$$

Conducting the same probability analysis as for the indices from literature (Figure 3a–f) yields a good applicability of our index for the SPA (Figure 3g, h). Due to our stricter CDD criterion, the onset probabilities are slightly lower than those of the Gurgiser index but this eliminates the danger of false starts after the onset date (see Figure 4b). The one station showing low probabilities of around 30–40% is station 14, which was excluded from the analysis determining the CDD thresholds. The probabilities of fulfilling the cessation criteria are around 80% for all stations and thus also very high.

4.3 | Climatology of the rainy season in the SPA

4.3.1 | Onset, cessation and duration

The mean onset dates of the rainy season in the SPA show a pronounced northeast-southwest gradient (Figure 6a). The rainy season starts at the end of September in the northeastern study area and then moves southwestward during the following 3 months with mean onset dates in December in the southwestern part of the study area.

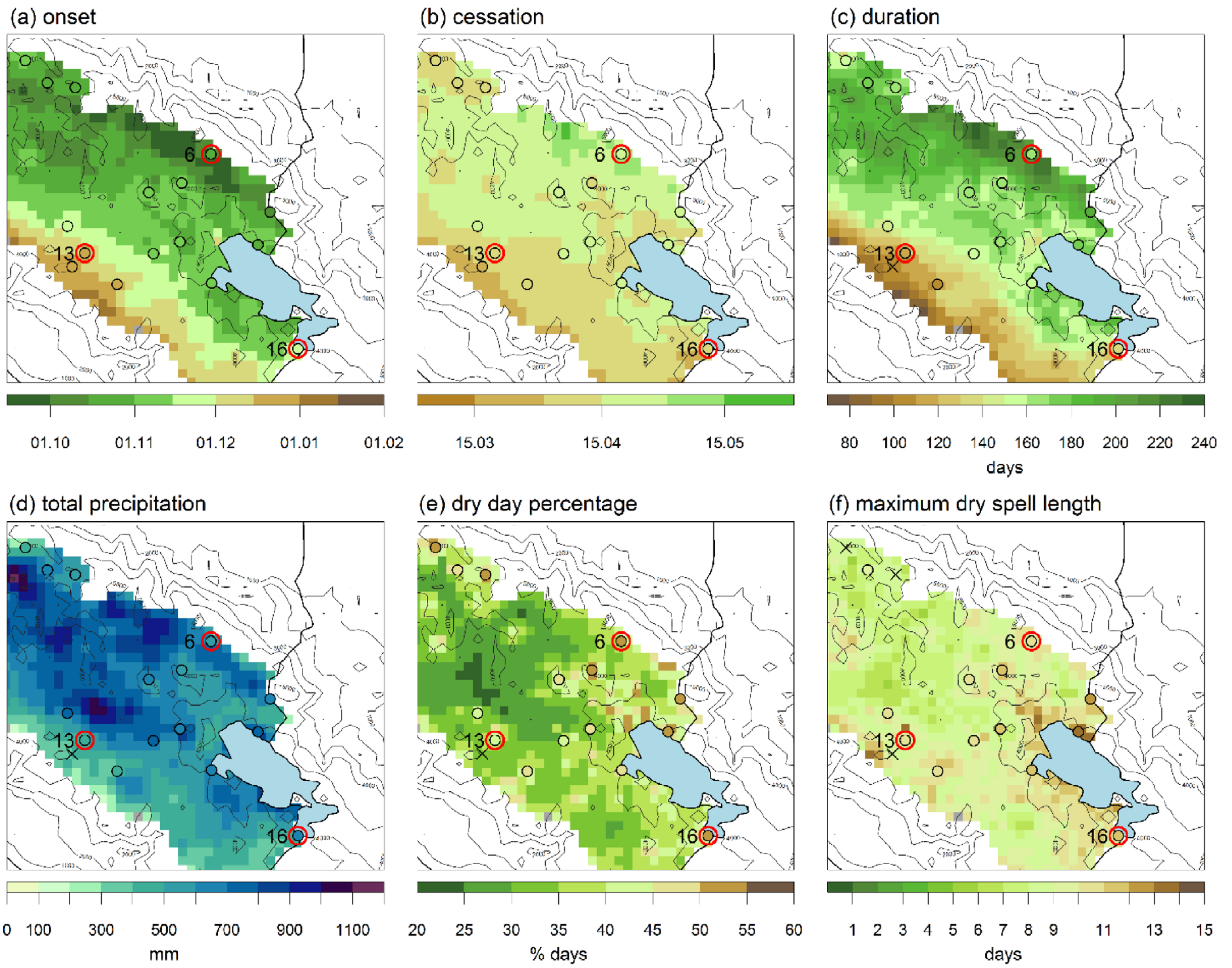

FIGURE 6 Climatological mean for the 30-year reference normal 1981/1982 to 2010/2011 calculated with the Climandes index for (a) onset date, (b) cessation date, (c) duration, (d) precipitation sum, (e) dry day percentage and (f) maximum length of dry spells. The latter three are calculated for the respective rainy season period of each grid cell, station and year. If more than 20% of the years are missing, the index is not calculated. In this case, a black cross marks the stations, while the grid cells are marked in grey. Contour lines show topography every 1,000 m. Stations for which time series are shown in Figure 7 are highlighted by red circles. The light blue area is Lake Titicaca

The onset dates show a large inter-annual variability (Figure 7a solid lines). The difference between the earliest and latest onset dates in the 53-year time period (1965/1966 to 2017/2018) ranges between 79 and 159 days depending on the station (i.e., ≈2 to 5 months). The variability is highest around Lake Titicaca (not shown).

For most of the area, the rainy season ends in April on average. The spatial pattern of the cessation of the rainy season is the opposite of the pattern of the onset dates and the regional variability is lower (Figure 6b, note the different order of the colour scale). The earliest mean cessation dates are found at the end of March at the southwestern border of the study area and the latest dates in the northeast around the middle of May. The cessation of the rainy season thus happens within approximately 2 months in the whole study area, and therefore in a narrower time window than the onset. This also becomes clear from the monthly precipitation sums, which drop quite abruptly between March and May (Figure 1a).

The year-to-year variability of the cessation dates is smaller compared with the onset (compare solid and dashed lines in Figure 7a for the three exemplary stations). The difference between the earliest and latest cessation range between 43 and 92 for the 16 stations analysed in this work (≈1.5 to 3 months). The earliest cessation dates are registered at the beginning of March, the latest in the middle of June.

Consistent with the above results for onset and cessation dates, the mean duration of the rainy season is

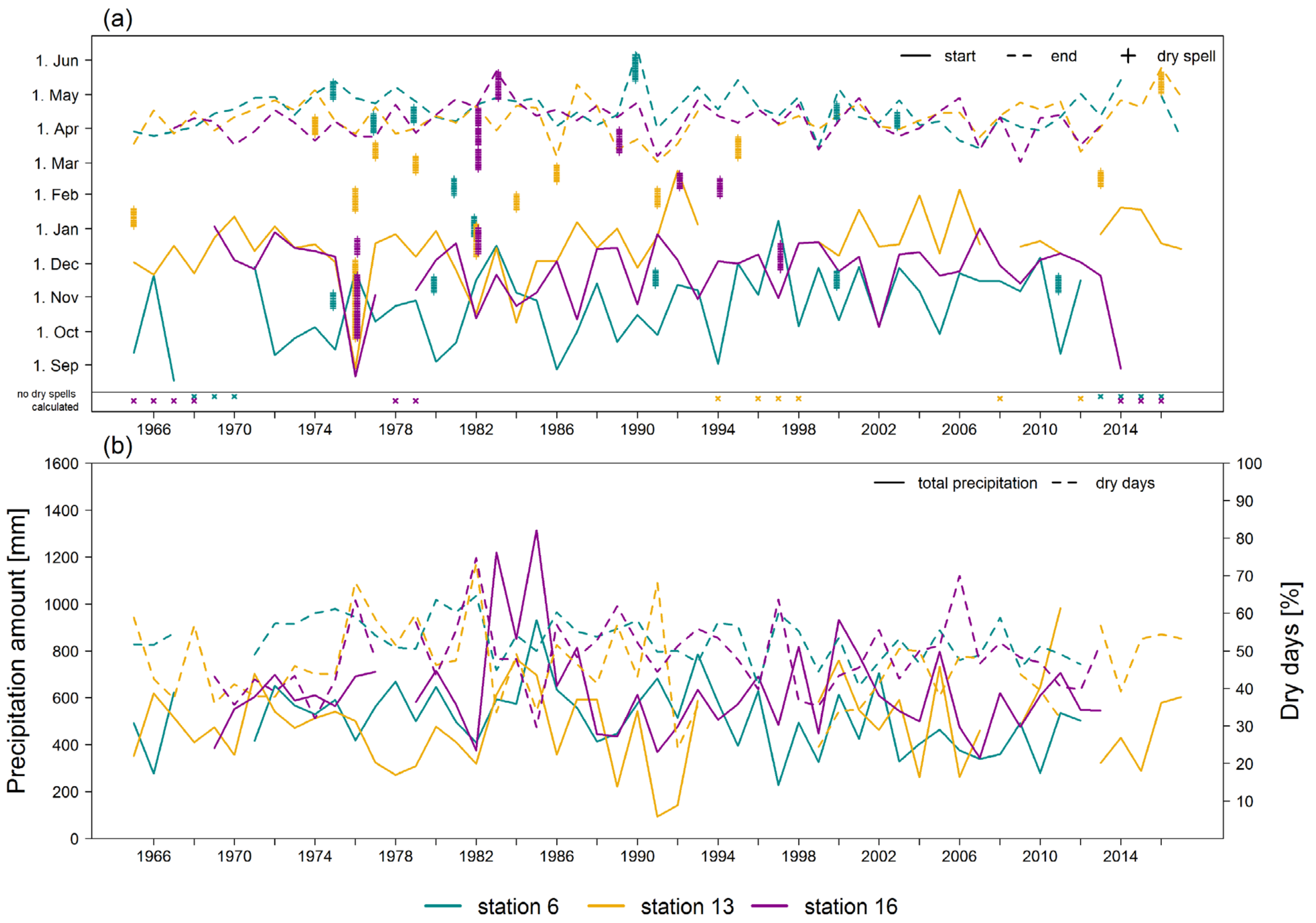

FIGURE 7 Time series for the full period 1965/1966 to 2017/2018 using the Climandes index for (a) onset (solid) and cessation (dashed) dates and (b) total precipitation (cf. left axis, solid lines) and dry day percentage (cf. right axis, dashed lines) for the three stations Crucero (station 6, see Figure 1c or Table 1), Sibayo (station 13) and Desaguadero (station 16). The vertical lines in a) depict the dry spells that last longer than 14 days. Years for which no dry spells can be calculated due to missing values during the rainy season are marked with a cross at the bottom of the plot in the respective colour

longest along the northeastern part of the study area (up to 230 days ≈8 months) and shortest in the southwestern part (around 90 days ≈3 months, see Figure 6c). Station values range between roughly 200 days in the northeast and 100 days in the southwest. The duration thus decreases with increasing distance to the moisture source of the Amazon in the adjacent lowlands to the east of the SPA.

4.3.2 | Precipitation characteristics

Precipitation sums within the rainy season show a different spatial pattern than onset and cessation. Most of the precipitation in the SPA falls between the months of December to March (Figure 1b) and therefore in the middle of the rainy season. Thus, higher total precipitation sums do not entirely coincide with longer durations but are linked more for instance to atmospheric circulation and topography. Largest mean precipitation sums of up to almost 1,200 mm are found in the northwest of the SPA. These high values probably stem from orographic precipitation at the eastern slopes of the mountain chain confining the plateau to the west. Lowest mean values of roughly 180 mm are registered in the southwestern part of the study area (Figure 6d). Mean precipitation sums vary between 424 and 730 mm for the different stations in the SPA, but with a considerable year-to-year variability (see solid lines in Figure 7b for exemplary time series). The standard deviation ranges between 116 and 242 mm (corresponding to 18–38% of mean values). Maximum values in single years range between 622 and 1,563 mm, whereas lowest measured rainy season precipitation sums vary between 93 and 448 mm, depending on the station.

The mean percentage of dry days within the rainy season for the 16 stations lies roughly between 40% and 55%. Dry day percentages in the gridded dataset show a similar but inverse pattern to the precipitation sums, with highest dry day percentages in regions with low precipitation sums and vice versa (compare Figure 6d, e). In general, stations with shorter rainy seasons (e.g., in the southwestern part of the study area) tend to have a lower percentage of dry days (compare Figure 6c, e). For example, dry day percentages are around 10% lower for Sibayo (station 13) in the southwest than for Crucero (station 6) in the northeast (see stations marked by red circles in Figure 6 and dashed lines in Figure 7b). The inter-annual variability however is quite low for all stations covering a range of 6–13%.

The mean maximum dry spell lengths at the different stations lie between 9 and 13 days in the SPA. Highest values are found around Lake Titicaca, shortest spells are observed in the northwestern part of the study area where the dry day percentages are also lowest (Figure 6e). The inter-annual variability is high, with standard deviations of maximum spells ranging between 3 and 10 days. The maximum dry spell lengths amount up to 40 days in the reference period, considering the whole 53-year time series, dry spells of up to 73 days have been recorded in the southwestern part of the study area. Furthermore, long dry episodes of more than 2 weeks are found in 7%–43% of the 53 years depending on the station (the spatial distribution is similar as for the mean maximum dry spell length in Figure 6f). They mostly occur at the end of the rainy season when they are not so critical for agriculture. However, long dry spells have also been registered in the months of January to March when more sensitive growing stages, such as flowering, take place (see vertical lines in Figure 7a for the three stations 6, 13 and 16).

4.3.3 | Relation between different rainy season characteristics

The correlation coefficients between onset and cessation dates is −0.07 and thus very low (Table 3). Considering the mean correlation of all stations, the duration largely depends on the onset dates (mean correlations of duration—onset: −0.9/duration—cessation 0.49, see Table 3). This is not surprising as the variability of the onset date is higher than that of the cessation and thus has a greater influence on the duration (see Section 4.3.1).

Precipitation sums show the highest correlation with the duration of the rainy season with a value of 0.59. For the cessation and onset dates, the correlations with precipitation sums are lower. The low correlations are expected when looking at the temporal distribution of precipitation in the region (Figure 1b), for example, most of the precipitation falls between the months of December to March and thus mostly well after the onset date and before the cessation date.

Maximum dry spell lengths show mean (anti-)correlations of −0.48/0.48 with onset and duration. Especially for stations in the southwestern part of the study area and around Lake Titicaca, early onset dates and longer duration seem to be related to longer maximum dry spell lengths (mean correlation for stations 8–16: maximum dry days—onset = −0.58, maximum dry days—duration 0.53, not shown in table). Correlations in the northwestern study area (stations 1–3) are below 0.25 (not shown in table). With a mean correlation of 0.14, no link is found between maximum dry spell length and the cessation of the rainy season. Correlations between the precipitation sum and the maximum dry spell lengths are even lower (mean correlation of 0.04, correlations at individual stations are all below ±0.25, not shown).

4.4 | Trends of the rainy season in the SPA

Only few stations show a significant trend in the rainy season indices and characteristics for the 53 years of data availability (Figure 8). Due to the high number of missing values, trends for rainy season parameters cannot be assessed for all stations (onset: 12 stations, cessations: 14 stations, duration and rainy season characteristics: 10–11 stations). Spatially consistent trends of onset are found in the center of the SPA at Lake Titicaca and to the west (stations 5 + 6 and 9–11). Here, a delay of onset dates of up to 7.8 days per decade is found, which is however only significant at two out of the five stations. Cessation trends are smaller than onset trends and mostly not

TABLE 3 Station mean of Pearson correlation for rainy season indices and characteristics within the rainy season (considering all stations)

Index	Cessation	Duration	Precipitation sum	Maximum dry spell length
Onset	−0.07	−0.90	−0.46	−0.48
Cessation	–	0.49	0.43	0.14
Duration	–	–	0.59	0.48
Precipitation sum	–	–	–	0.04

Note: Correlations are calculated for the whole available time period (1965/1966 to 2017/2018).

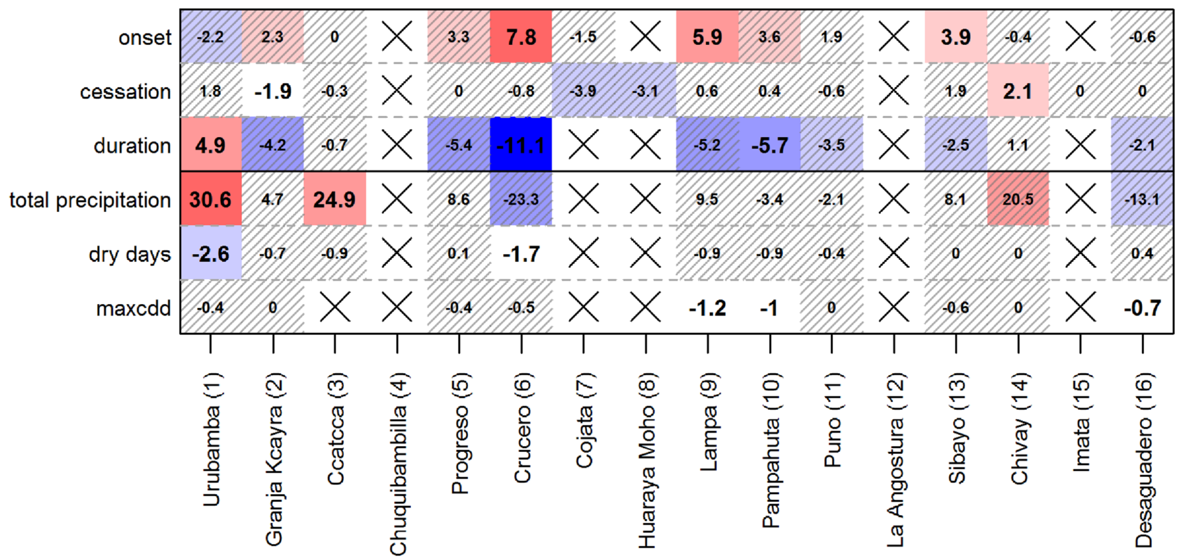

FIGURE 8 Overview of the trend values for all stations considering the rainy seasons 1965/1966 to 2017/2018 for onset, cessation and duration, total precipitation, dry day percentages and the maximum number of consecutive dry days (maxCDD). Red colours show positive trends, blue colours negative trends, non-significant trends at the 10% level are overlaid by a grey shading. Trends were only calculated if at least 20% of the values were non-missing and if the first five as well as the last 5 years of the time series are all not all missing, otherwise the respective field is marked by an X. Station numbers are shown in brackets

significant. As a consequence, the duration shows mostly decreasing tendencies, especially in regions where the onset is delayed. A shortening of the rainy season by up to 11.1 days/decade can be observed, however for most stations, the trend is not significant at the 10% level. Trends in precipitation characteristics are also mostly not significant. Precipitation sums mostly show a tendency towards an increase, especially in the northeastern part of the study area (stations 1–3) where the trend is significant for two out of the three stations. Alongside with these findings, the number of dry days and maximum dry spell lengths show a tendency towards a decrease, but significant trends are also only found for two out of 11 (dry days) and three out of 10 (max(CDD)) stations. Time series of selected stations also show this decrease of maximum dry spell length (see Figure 7a).

5 | SUMMARY AND DISCUSSION

5.1 | The Climandes index

The rainy season indices from literature we evaluated in this study are not suitable according to our evaluation criteria tailored to rain fed agriculture and for forecasting the rainy season in the Southern Peruvian Andes (SPA). Thus, we have adapted the existing indices to the region and these criteria. The analysis is based on daily precipitation data and the assumption that it should be very likely, that the index criteria for the onset are met in the main rainy season and very unlikely that they are met in the main dry season (and vice versa for the cessation criteria). From the resulting range of meteorologically plausible parameter values, we chose the final parameters based on expert judgement. Based on this, the Climandes index defines the onset as a precipitation sum of at least 8 mm within 5 days and the occurrence of not more than 7 consecutive dry days within the 30 days following the onset date. The cessation date is defined as the first day for which the following 30-day precipitation is below 16 mm. The time periods of 5 and 30 days were chosen based on available forecast products for Peru. Comparing our analysis of precipitation and dry days to the existing indices shows that the precipitation thresholds for the indices from literature are all too high for our study region except for the Gurgiser index. However, the Gurgiser index allows consecutive dry spells of up to 20 days in the 30 days following the onset date. For their study, detecting/defining dry spells after conditions that might have been interpreted by farmers as the onset of the rainy seasons was one of the interests and justifies this definition for their study. However, according to our evaluation criteria tailored more towards forecasting the wet season, this is seen to be far more than the 7 consecutive dry days yielded by our evaluation and is in our perspective the reason for many "false starts" of the Gurgiser index.

For cessation, the criteria used by the Gurgiser and Garcia indices are stricter than those of the Climandes index. Comparing the cessation dates of the Garcia and the Gurgiser indices yields a generally earlier cessation date for the Climandes index (not shown).

Of course, both onset and cessation indices largely depend on the stations considered for the derivation of the index. The aim of this study was to find an index to characterize the whole SPA in order to evaluate regional patterns and get a general overview of the rainy season in the region. For specific applications in smaller regions, the adaptation of thresholds using the proposed methodology might be useful to better fit the local climate and give more specific advice to farmers.

As the time spans of available forecast products has been taken into account for the index adaptation, the Climandes index is particularly suited for forecasting purposes. The onset index could be forecast in a two step process, first checking whether the precipitation criteria is fulfilled using the short range weather forecast and if so using the monthly forecast to assess the probability of fulfilling the dry spell criteria. This of course requires a prior skill analysis and a high enough predictability based on available forecast products.5.2 Climatology and Trends in the Southern Peruvian Andes.

The rainy season in the SPA shows a pronounced northeast-southwest pattern. While the mean onset dates of the rainy season are earliest in the northeast (~September) and latest in the southwest (~December/January), the spatial pattern of cessation is opposite, with earliest mean cessation dates in the southwest in March and latest in the northeast in May. This results in considerably shorter growing seasons in regions lying further away from the Amazon. On average, the rainy seasons last up to 8 months in the northeast and only 3 months in the southwest of our study area. This spatial pattern was also observed by Andrade et al. (2018) evaluating monthly precipitation sums and Segura et al. (2019), who conducted a study on precipitation variability in the whole tropical Andes. Segura et al. (2019) associate the precipitation pattern with development of the South American Monsoon System (SAMS). They found increasing precipitation in the northeastern region of the SPA during the early stages in the development of the SAMS, and high precipitation in the whole SPA as the SAMS reaches its mature phase and the Bolivian High is located near the Bolivian Andes. Giráldez et al. (2020) and Garcia et al. (2007) reported a similar north–south difference in the onset of the rainy season for their study regions in the Central and Bolivian Andes. Andrade et al. (2018) also noted a much faster transition from wet to dry than from dry to wet for the Peruvian and Bolivian Altiplano. Due to this, the definition of the cessation in this region is easier to determine, as has been noted by previous studies (Marengo et al., 2001; Segele and Lamb, 2005). The cessation dates for the northeastern part of our study area occur in mid-May and are similar to those that Gurgiser et al. (2016) found in their study area located further north. In the southwest, they occur mid-March to early-April and are similar to those that Garcia et al. (2007) found for their study area located further south. This highlights a general south–north gradient of cessation dates in the Andes, also noted by Garcia et al. (2007). For the Peruvian Andes north of our study area, Gurgiser et al. (2016) found rainy seasons of around 250 days (~8 months). For the central Andes, Giráldez et al. (2020) found a mean duration of 196 days (~6 months). For the Bolivian Altiplano, Garcia et al. (2007) reported duration of ~5 months in the northern part (close to our study area) and a shorter rainy season of ~4 months for southern stations. Thus, the findings on the timing of the rainy season found here compare well to those of previous studies.

The high inter-annual variability of the onset dates is remarkable. It ranges between 2 and 5 months depending on the region. Reasons for this could be the aforementioned convective nature of precipitation as well as the dependence of the onset index on the absolute threshold values. The high variability in onset dates has also been reported by previous studies (Gurgiser et al., 2016; Giráldez et al., 2020). It has been related to the strength and position of the Bolivian High, the propagation of the South Atlantic Convergence Zone (SACZ) and the convective activity over the equatorial Atlantic Ocean, which determines the moisture flux towards the Andes from the lowlands to the east. Giráldez et al. (2020) found that early/late onset dates are associated with a southward (northward) shift of the SACZ and weak (strong) convection over the equatorial Atlantic. In contrast, the inter-annual variability of cessation is not as pronounced as for the onset dates.

The spatial pattern of precipitation characteristics during the rainy season is different to the pattern of the timing of the rainy season. The precipitation sum at a particular location in the study area is determined by two main factors: by the distance to the moisture source in the adjacent lowlands to the east (leading to an east–west gradient) and by the tropical moisture influx that leads to orographic precipitation along the western slopes of the Andes (leading to a north–south gradient). Due to the convective nature of precipitation, topography additionally plays an important role (for a more detailed analysis of precipitation see for example, Lavado Casimiro et al., 2012, 2013; Imfeld et al., 2020). Highest/lowest precipitation sums/dry day percentages are recorded in the northwestern study area and lowest/highest values along the southern border at Lake Titicaca. Mean precipitation sums for the 16 stations lie between 420 and 730 mm. Dry day percentages during the wet season are between 40%

and 55%. The mean maximum dry spell length during the wet season ranges between roughly 9–14 days and is shortest in the northwest. Around Lake Titicaca, dry spells persisting longer than 2 weeks are found in more than one third of the 53 years. Previous studies have mostly focused on mean dry spell lengths, reporting mean spell lengths of 2–4 days (Imfeld et al., 2020) up to 1–2 weeks (Lenters and Cook, 1999; Garreaud and Aceituno, 2001). For agriculture, maximum spell lengths are of higher interest. While most plants can cope with a few dry days, long dry spells may have potentially damaging effects on plants if no means of irrigation are available, especially if they occur at critical stages of plant growth, as planting or anthesis. An interesting finding is that the precipitation characteristics within the rainy season only weakly depend on the onset/duration of the rainy season. Further, the relations between onset and cessation are weak.

The trend analysis yields a tendency towards later onset dates in conjunction with a shorter duration of the rainy season, especially in the region around Lake Titicaca. These findings agree with the results of Giráldez et al. (2020), who also found a delay in the onset of the rainy season. Further, the results indicate an increase in precipitation and decrease in dry day percentages and the maximum dry spell length within the rainy season. An increase of summer (DJF) precipitation has already been reported by Segura et al. (2020) and Imfeld et al. (2020) for our study region. However, the trend signals we found are mostly not significant. Due to the high inter-annual variability, longer time series would be needed for a robust trend analysis. Further, missing values might also influence the trend analysis. To analyse whether there are regionally consistent trends, either a higher and more representative number of homogenized station observations or a homogeneous gridded dataset covering a long time period would be needed. The inhomogeneities inherent in the PISCO dataset as well as its short time period of 35 years prevent a reliable trend analysis on a spatial level.

6 | CONCLUSION

In this study, we are proposing the Climandes Index, an index for defining the onset and end of the rainy season tailored to the Southern Peruvian Altiplano. The index may be used for a climatological analysis and is suitable for forecasting purposes.

Our findings form a basis for developing climate- and weather-based information for the agricultural sector. As such, they can be used to highlight the large inter-annual variability of the onset of the rainy season that (smallholder-) farmers have to reckon with. The potential for early and late rainy season onsets and the influence on the growing season length may require different cultivation decisions. In addition, the data shows that farmers need to prepare for dry spells that occur throughout the growing season. Eventually, based on the climatology described here, they may consider using an irrigation system. Further, the high inter-annual variability of the onset of the rainy season potentially masks underlying trends. Based on the available data, robust statements on trends are not possible, however our analysis shows indications of a shift to a shortening of the rainy season due to a later onset date in the central part of the SPA. For a more robust trend analysis, it is essential to ensure long-term homogeneous observations in the region.

In addition, we found that the date of the onset does not allow to draw conclusions about the total precipitation or the number of dry days in the following rainy season. This is also be good news in the sense that a late start of the rainy season does not necessarily imply insufficient water during the growing season.

In summary, the present analyses allow to draw co nclusions regarding the climatology of the rainy season in the Southern Peruvian Andes. This may be relevant for planning purposes in the agricultural sector, as this is one main income in the region which is highly climate sensitive.

Operationalizing the monitoring and forecast of the Climandes index could offer guidance for the planning of sowing activities. Using the proposed two-step process of first predicting the surpassing of the precipitation threshold with the operational SENAMHI forecast and then in a second step, using monthly precipitation forecasts to check for the occurrence of dry spells, asks for reliable precipitation predictions on both timescales. Long-range predictions are available from global forecasts issued by, for example, NOAA's Climate Prediction Center or the forecasts of ECMWF, but a specific analysis on predicting the index criteria is required before considering its use for practical applications. Especially the early prediction of dry spells would be of high value, not only for the onset but also for possible mitigation measures during the rainy season as our analysis shows that the occurrence of long dry spells is not unusual.

AUTHOR CONTRIBUTIONS

Katrin Sedlmeier: Conceptualization; formal analysis; investigation; methodology; project administration; software; visualization; writing – original draft; writing – review and editing. **Noemi Imfeld:** Conceptualization; formal analysis; investigation; methodology; software; visualization; writing – original draft; writing – review and editing. **Stefanie Gubler:** Conceptualization; funding acquisition; methodology; project administration; supervision; writing – original draft; writing – review and editing. **Christoph Spirig:** Conceptualization; supervision; writing – review and editing.

Karim Quevedo Caiña: Project administration; resources; supervision; writing – review and editing. **Yury Escajadillo:** Resources; writing – review and editing. **Mario Rohrer:** Supervision; writing – review and editing. **Cornelia Schwierz:** Supervision; writing – review and editing.

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DATA AVAILABILITY STATEMENT

Station data is currently not openly available. Details of the data and how to request access are available from SENAMHI Peru: https://www.senamhi.gob.pe/?&p=solicitud-servicio. The PISCO dataset analysed during the current study is available at http://iridl.ldeo.columbia.edu/SOURCES/.SENAMHI/.HSR/.PISCO/. The elevation data in Figure 1 stems from the GTOPO30 dataset: 10.5066/F7DF6PQS. The calculation of indices and trends is implemented in the ClimIndVis package freely available on GitHub (www.github.com/Climandes/ClimIndVis). DOI: https://www.zenodo.org/badge/latestdoi/140861804.

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