

Position of the Bolivian High system: climatology and its relationship with precipitation and streamflow in the southern highlands of Peru

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Abstract

The Bolivian High (BH) is an upper-tropospheric anticyclonic circulation associated with the South American Monsoon System, exerting a significant influence on the seasonal hydroclimate of the Andes. However, its short-term (daily and monthly) relationship with Andean hydrology remains understudied due to challenges in long-term detection of BH. An automatic method for tracking the BH applied to the ERA5 reanalysis was used to examine its short-term position (latitude, longitude, and altitude) in relation to precipitation and streamflow in the Southern Highlands of Peru (SHP), with emphasis on droughts during ENSO phases. Climatologically, the BH centre lies at 16.5°S, 65.2°W, and 12448.6 m_gp at 200 hPa during December–February (1981–2020). Daily positions vary more in longitude than in latitude. A seasonal migration pattern is observed between November–April, with the BH shifting from northeast Bolivia to the south-southwest and returning northeast. A south-westward (north-eastward) BH shift usually brings wetter (drier) SPH conditions, especially along the western Andes. These shifts enable or inhibit the moisture transport from the Amazon basin to the Andes. Droughts in the SHP are linked to El Niño's northeastward shift since January. Conversely, during La Niña, the BH shifts southward, favouring above-average precipitation and streamflow, particularly on the western slope. This study improves understanding of the short-term relationship between the BH and hydroclimatic conditions in the SHP. It provides a tool for BH monitoring in the context of weather and climate prediction and climate change scenarios.

1. INTRODUCTION

The climate of South America is significantly influenced by large-scale atmospheric circulations. The Bolivian High (BH) is a warm-core anticyclonic circulation in the upper troposphere located at the centre of South America (approximately 15°S, 65°W). This is observed during the austral spring-summer with maximum temperature and geopotential height around 300 and 150 hPa, respectively (Lenters and Cook 1997; Espinoza et al. 2020). Early studies hypothesized that the BH has a thermal origin, primarily due to latent heat, and to a lesser degree, sensible heat release over the Altiplano and tropical Andes (Schwerdtfeger 1961; Gutman and Schwerdtfeger 1965). However, subsequent experiments indicated that its formation, position, and intensity are primarily determined by tropospheric warming induced by intense convective activity over the Amazon during the South American Monsoon (Silva Dias et al. 1983; DeMaria 1985; Kleeman 1989; Figueroa et al. 1995; Lenters and Cook 1997; Rodwell and Hoskins 2001). Furthermore, the Andean topography exerts an indirect influence on the BH through the reorganization of low-level circulations, which in turn affects the configuration of convection (Garreaud and Aceituno 2007). The BH is one of the main features of the South American Monsoon System. This interacts with synoptic and large-scale features, such as the South Atlantic Convergence Zone, reinforcing the BH circulation through vorticity advection (Figueroa et al. 1995). Conversely, the BH's position and intensity are modified through a hydrostatic balance with warm low-level air, linked to frontal activity (Silva Dias et al. 1983; Lenters and Cook 1999). Moreover, the BH is related to a cyclonic circulation observed in northeast Brazil, known as the upper tropospheric cyclonic vortex (Kousky and Gan 1981), with coupling locally maintained by Amazonian convection and remotely by condensational heating in Africa and the

western tropical Pacific (Lenters and Cook 1997; Chen et al. 1999). The BH also exhibits intraseasonal fluctuations associated with the activity of Rossby wave trains, the South American rainfall Dipole and the Madden-Julian Oscillation, which modulate convective activity in South America (Suarez 2021).

Several studies indicate that the position and magnitude of upper-tropospheric circulation are determinants of hydroclimatic variability in the Andes. In this context, the position of the BH is particularly relevant, due to its prevalence at the upper-levels of the troposphere during the Central Andes rainy season. The relationship between the BH position and precipitation has been studied across a range of time scales. This includes diurnal (as identified indirectly in Junquas et al., 2018), intraseasonal (Garreaud 2000; Ferreira et al. 2004; Suarez 2021), seasonal (Segura et al. 2019), interannual (Vuille and Keimig 2004; Sulca et al. 2017; Segura et al. 2019), decadal (Segura et al. 2016; Sulca et al. 2022) and paleoclimatic (Garreaud et al. 2003; Martin et al. 2018). Additionally, the relationship between precipitation and upper troposphere winds are also associated with extreme events in the region (Vuille et al. 1998; Sulca et al. 2016, 2018; Castino et al. 2020; Flores-Rojas et al. 2021); as well as with low-frequency variability modes like the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (Imfeld et al. 2019; Rojas-Murillo et al. 2022; Gutierrez-Villarreal et al. 2024). Specifically, the BH modulates moist air transport from the Amazon to the southern tropical Andes (8°-20°S) during the rainy season, a mechanism essential for convective activity in the Altiplano (Garreaud et al. 2003; Espinoza et al. 2020), with more relevance before the 2000s at a seasonal scale (Segura et al. 2020). The precipitation in the southern tropical Andes is amplified when the BH is situated to the south of its climatological position, with the northern branch intensified. Conversely, dry conditions are prevalent when the system is weakened or absent (Garreaud 1999; Vuille and Keimig 2004; Segura et al. 2019). These findings emphasize the crucial influence of the BH on the hydroclimatology of the Andes.

The Andes region is highly vulnerable to the impacts of climatic variability and faces unique challenges in addressing climate change. These challenges include the limited capacity of atmospheric models to accurately simulate the intricate atmospheric dynamics of the Andes and the constrained adaptive capacity to extreme events due to insufficient weather observation data (Condom et al. 2020; Cazorla et al. 2022; Cavazos et al. 2024; Huerta et al. 2025). In particular, the population of the Southern Highlands of Peru (SHP) is especially vulnerable to the effects of dry conditions during the rainy season. This vulnerability arises from limited available resources and a strong dependence on rainfed agriculture, as well as extensive and mixed livestock systems (Alonso et al. 2022). Despite the robust relationship between the warm (cold) phases of ENSO and dry (wet) conditions in the SHP (Lavado-Casimiro et al. 2013; Lavado-Casimiro and Espinoza 2014; Sulca et al. 2017; Jonaitis et al. 2021), recent studies indicate that the presence of El Niño (La Niña) does not necessarily lead to drought (flood conditions) in this region (Imfeld et al. 2019; Gutierrez-Villarreal et al. 2024). This suggests a potential limitation in the predictability of climate conditions, and consequently, in the quality of decision-making. Moreover, projections indicate a decline in agricultural productivity in the SHP of up to 20% by 2050 (compared to 2012), the highest in the country (Anríquez and Toledo 2019). Considering these issues, using the BH behaviour as an indicator of potential hydroclimatic conditions could improve the capacity to manage climate risks and adapt to future scenarios.

However, the detection of BH remains predominantly manual, based on visual analysis of mid-upper-level meteorological fields, outgoing longwave radiation, and satellite imagery (Ferreira et al. 2004; Garreaud and Aceituno 2007; Marengo et al. 2012; Espinoza et al. 2020; Satyamurty and Rosa 2020). The manual approach presents a challenge to the analysis and monitoring of BH for high temporal resolutions and over extended periods. In light of these limitations, the development of automated detection methods for synoptic-scale systems offers a robust alternative for the study of these systems and their impacts on the climate system. In general, tracking algorithms indices are calculated from anomalies or threshold values in certain variables associated with the system (e.g. Flaounas et al., 2014; Gilliland and Keim, 2018; Pinheiro et al., 2019; Díaz et al., 2020), as well as from the application of statistical, numerical, or machine learning techniques (e.g. Murray and Simmonds, 1991; Wheeler and Hendon, 2004; Da Silva and De Carvalho, 2007; Biard and Kunkel, 2019). To authors' knowledge, Reason (2016) was the first to apply this approach to the BH. These measured its seasonal magnitude using standardised anomalies of geopotential height at 500 hPa over central South America. Subsequent studies have used this approach to evaluate the influence of BH activity on the South American climate (Fernández-Sánchez et al. 2022; Arias et al. 2025). Recently, Suarez (2021) adapted the vortex detection algorithm by Holmén (2012) to track the centre of the anticyclonic circulation (200 hPa) on a daily timescale, based on wind components. This enabled an examination of the relationship between the position of the BH at sub-seasonal scales, the passage of Rossby waves and the phases of the Madden-Julian Oscillation. A review of the literature revealed no further applications of tracking methods to the BH, highlighting a potential for enhancement of these techniques and the development of climate monitoring tools associated with one of South America's most critical circulation systems.

Previous studies on BH that employed automatic detection of atmospheric systems did not explicitly address the inherent limitations of this approach. These include the dependence on the characteristics observed in the reanalysis, the spatio-temporal representativeness of the established criteria, and the design of the implemented algorithm (Rudeva et al. 2014; Grieger et al. 2018; Pinheiro et al. 2020). Furthermore, the presence of multiple candidate regions to be identified as the system and the efficiency of the solutions to this problem (Flaounas et al. 2014) must be considered. Aspects related to the temporal and spatial variability of BH, such as its fluctuations during ENSO phases, and its influence on South American hydroclimatology at high temporal frequencies over long periods remains limited. The lack of information is relevant given the uncertainty of the impact of projected changes in this system on precipitation patterns in the SHP (Barreto Schuler, 2016; Minvielle & Garreaud, 2011; Thibeault et al., 2012). In light of the above, this study proposes the development of daily indicators for the BH position to describe its short-term relationship (both daily and monthly) with precipitation and streamflow in the SHP, with particular emphasis on the incidence of droughts during ENSO phases. To this aim, the following science questions are proposed:

- How does the choice of tracking method affect the resulting daily BH position?
- What are the characteristics of the short-term variability of the BH, and how is this variability linked to the hydroclimate of the SHP?

- How does the relationship between the BH and the hydroclimate of the SHP vary under different ENSO phases?

2. STUDY AREA

In this study, the SHP was defined as the region with an elevation greater than 3000 m.a.s.l. between 12°-18.5°S 74°-68°W (Fig. 1). This delineation was consistent with hydroclimatological studies that focused on the Peruvian high Andes (e.g. Imfeld et al., 2019; Segura et al., 2020; Sedlmeier et al., 2023). The SHP exhibited pronounced seasonality in precipitation, with the rainy season (November-April) accumulating approximately 88% of the annual precipitation (441–837 mm per year), mainly during summer (51.3–60.8%); in contrast, winter was characterized by a high frequency of dry days (~ 95%), with occasional unusual wet events (Huerta and Lavado-Casimiro 2021; Imfeld et al. 2021; Segura et al. 2022).

On the other hand, the SHP included drainages to the Pacific Ocean, the Amazon basin and the endorheic basin of Lake Titicaca. The region also showed a strong seasonality in streamflow, which tended to be highly correlated with precipitation, with streamflow peaking on average one month after rainfall reaches its maximum rates, and exhibiting significant inter-annual streamflow variability in the Pacific drainages (Lavado Casimiro et al. 2012). Recent studies indicate that both streamflow and precipitation exhibited no significant interannual trends which are negatively related to tropical Pacific Ocean surface temperature (Lavado Casimiro et al. 2012; Heidinger et al. 2018; Huerta and Lavado-Casimiro 2021; Imfeld et al. 2021). Indeed, El Niño (La Niña) was associated with drought (flood conditions) during the rainy season, particularly to the west of the SHP (Lavado-Casimiro et al. 2013; Lavado-Casimiro and Espinoza 2014; Jonaitis et al. 2021).

3. DATA AND METHODS

3.1. Data

The atmospheric features of the BH were represented by the European Centre for Medium-Range Weather Forecast Re-Analysis version 5 (ERA5; Hersbach et al., 2020). This was selected for its higher spatial resolution (0.25°x0.25°) and superior data assimilation scheme in comparison to the previous reanalyses.

The hydrometeorological database, prepared by the Servicio Nacional de Meteorología e Hidrología del Perú (SENAMHI) and known as Peruvian Interpolated data of the SENAMHI's Climatological and hydrological Observations (PISCO) was employed. This includes gridded precipitation data (PISCOp; 0.1°x0.1°; 1981–2016; Aybar et al., 2020) and simulated streamflow series (PISCO_HyD_ARNOVIC; 1981–2022; Llauca et al., 2023). PISCOp was constructed from satellite estimates and observed precipitation data that underwent quality control, gap-filling and spatial interpolation to create an extensive database of high temporal and spatial resolution for the entire Peruvian territory. Meanwhile,

PISCO_HyD_ARNOVIC uses information from PISCOp to estimate daily streamflow series using a hybrid modelling framework that integrates sub-basin rainfall-runoff and river-routing models, calibrated with observed hydrological data. Due to the relatively small magnitude and variation of streamflow in rivers of first order, only those of second order or higher are considered.

The choice of the ERA5 and PISCO datasets is supported by their application in recent regional hydroclimatological studies (e.g. Imfeld et al., 2019; Gutierrez-Villarreal et al., 2024), and needed by the scarcity and low quality of climate data available in the SHP (Rosas et al. 2016; Hunziker et al. 2017; Gubler et al. 2017; Huerta et al. 2025). The period from 1981 to 2020 (1981 to 2016) is selected based on the temporal availability of PISCO_HyD_ARNOVIC (PISCOp) datasets utilized in the study. Anomalies were computed regarding the climatology of the entire period.

To evaluate the influence of datasets selection on the algorithms performing, the results obtained with ERA5 and PISCOp data are contrasted with other datasets. For atmospheric fields, the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR R1; 2.5°x2.5°; Kalnay et al., 1996) and NCEP-Department of Energy (NCEP-DOE R2; 1.875°x1.875°; Kanamitsu et al., 2002) were considered. For precipitation, the Rain for Peru and Ecuador gridded product (RAIN4PE; 0.1°x0.1°; 1981–2015; Fernandez-Palomino et al., 2022) was used. Finally, Oceanic Niño Index (ONI) based on Extended Reconstructed Sea Surface Temperature version 5 data (Huang et al. 2017) was employed to identify ENSO phases.

3.2. Methodology

To examine the short-term relationship between the BH position and the hydroclimate in the SHP, a methodological framework is developed in three main stages (Fig. 2). First, algorithms are designed and evaluated to identify the daily position of the BH, accounting for its spatial and temporal variability. The best-performing algorithm is then selected for application in subsequent stages. Second, the relationship between the BH's position with the precipitation and streamflow in the study region is assessed. This relationship is ultimately examined during the ENSO phases.

3.2.1. Identifying the position of BH

The reference domain 0°-30°S 80°-47.5°W is selected to encompass the main features of the BH and its spatial variations, as well as to minimise the interference from other anticyclonic circulations outside this domain (Ferreira et al. 2004; Barreto 2016; Suarez 2021). The analysis is focused on the November-April period, when the BH is typically observed and coincides with the rainy season over the SHP (Espinoza et al. 2020; Suarez 2021). To define daily indicators, the observations at 0, 6, 12, and 18 UTC of the day of analysis were averaged for the selected variable.

Preliminary algorithms. Four algorithms were tested to determine the BH position in terms of latitude, longitude, and altitude. These were adapted from previous studies and applied to identify and track the BH. Most are based on atmospheric circulation, where the non-divergent component of the wind was

isolated using the Helmholtz decomposition (Lindborg 2015). Such a method isolates the rotational component of the wind, which is associated with anticyclonic vortex centres (Suarez 2021). No other data pre-processing, such as transformations to spherical coordinates, was applied.

Wind-based algorithms aim to detect Closed Anticyclonic Circulations (CAC) at 200 hPa, which may correspond to the BH centre. A CAC is a grid point surrounded by adjacent grids, forming a closed circulation in an anticyclonic direction. The reference grid point may be located to the north, west, south and east of the analysed grid. These positions correspond to angular offsets of 0°, 90°, 180°, and 270° relative to the North, respectively. The adjacent grids are separated by 0.25° in latitude or longitude. This offset reflects with the spatial resolution of the reanalysis dataset, which is 0.25° in ERA5

Depending on the specific criteria, a CAC may be designated as the BH centre. In algorithms where such criteria are not explicitly defined, the BH centre is estimated as the mean latitude, longitude, and geopotential height at 200 hPa of all identified CACs. Each algorithm relies on distinct criteria (Table 1), as detailed below:

Table 1
Differences between the implemented algorithms for the BH position.

Algorithm	Variable	Maximum regions criterion	Points needed to define closed circulation	Reference
GK2018	hgt	Yes	—	Gilliland and Keim (2018)
S2021	u,v	No	Four	Suarez (2021)
P2019 relaxed	u,v	Yes	One	Pinheiro et al. (2019)
P2019 strict	u,v	Yes	Four	Pinheiro et al. (2019)
BH index	u,v	No	Four	This study
Abbreviations: geopotential height (hgt), meridional (v) and zonal (u) components of non-divergent component of wind.				

- GK2018: The algorithm proposed by Gilliland and Keim (2018) serves as a basis for tracking regions of maxima in the geopotential height at 200 hPa. This may indicate the BH centre at monthly and seasonal scale observations (Lenters and Cook 1997; Barreto 2016). On each analysis day, regions are identified iteratively using spatial filtering steps. In the first iteration, grid points exceeding the daily mean geopotential height across the domain are selected. In the second iteration, only those exceeding the mean of the previous iteration are retained. This process is repeated up to seven iterations. The mean latitude, longitude and geopotential height of grids retained indicate the latitude, longitude, and altitude of the BH centre, respectively. Before applying GK2018, spatio-temporal smoothing reduced high-frequency noise. A moving average with a 5x5 grid and two-day

window was applied to mitigate abrupt fluctuations in geopotential height caused by topographic features.

- S2021: It was implemented by Suarez (2021) to detect CAC associated with the BH centre at 200 hPa based on the zonal (u) and meridional (v) components of the non-divergent wind. In his study, the original algorithm proposed by Holmén (2012) was adapted to identify anticyclonic vortices in the ERA Interim reanalysis. According to the author, four reference grid points are necessary to identify a CAC, located at the north, west, south and east of the analysed grid. These grids satisfy equations that demonstrate the presence of a closed vortex, their anticyclonic orientation and the exclusion of wind shear conditions.
- P2019-relaxed version: This algorithm was initially proposed by Pinheiro et al. (2019) and is adapted here to identify CAC associated with regions of maximum geopotential height at 200 hPa. This condition is denominated maximum region criterion, and is indicated by the final (seventh) step of the GK2018 algorithm. This criterion filters candidate grids, for which adjacent grids are then analysed to define CAC. The algorithm employs a single reference point for the definition of a closed circulation ($u > 0$), located to the south of the analysed grid (at 180° relative to North). This approach aims to identify the BH based on a local maximum in geopotential height, accompanied by westerly winds to the south, consistent with the southern branch of the system.
- P2019-strict version: This is analogous to the P2019 relaxed algorithm, but with a more rigorous criterion that employs four reference points. In each grid that satisfies the maximum region criterion, a CAC is identified when the non-divergent wind components of the adjacent grid cells form a closed circulation: north ($u < 0$), east ($v > 0$), south ($u > 0$) and west ($v < 0$).

While the algorithms were previously used successfully for their stated objectives, there are potential limitations to their utilisation for BH detection. One major limitation is their sensitivity to atmospheric phenomena that may generate geopotential height maxima or CACs outside the BH, such as frontal activity, tropical air masses, or spurious circulations. The latter are observed as circulations produced by the general movement of the atmosphere flow, not linked to any specific system. These spurious features are more likely to appear in high-resolution reanalyses. Notably, the S2021 and P2019 algorithms (in both relaxed and strict versions) lack explicit criteria to distinguish CAC associated with the BH from others. Therefore, a good correspondence between the average CAC position and the actual BH centre would suggest a relatively low impact of spurious circulations.

An enhanced algorithm: Bolivian High index. In this study, an enhanced algorithm (hereafter referred to as the BH index) is proposed to detect the BH position while minimizing the influence of other meteorological systems and preserving coherence across different time scales. The BH index is based on P2019 (strict version), but omits the maximum region criterion; that is, CACs are not required to coincide with geopotential height maxima (defined by GK2018). This referential algorithm was chosen due to its superior capability in representing the BH position, as observed in the mean non-divergent wind field climatology (Fig. S1). Furthermore, an algorithm based on atmospheric circulation could better

represent one of the main precipitation triggering mechanisms over the Andes: moisture advection (Garreaud, 1999).

The BH can be distinguished from other anticyclonic circulations over South America by several features. It shows a predominant frequency during austral summer, which is also evident in the monthly wind averages (Barreto 2016; Satyamurty and Rosa 2020). It is typically located over the central Andes (Lenters and Cook 1997; Espinoza et al. 2020), and is modulated by large-scale climate drivers (Lenters and Cook 1997; Gutierrez-Villarreal et al. 2024). Other atmospheric systems or phenomena can also generate CACs through different mechanisms. For instance, the thermal reorganizing of the ridge-trough patterns associated with frontal system activity may produce CACs over the southwestern Atlantic (Ramírez et al. 1999; Ferreira et al. 2004).

To further refine the detection, a climatological consistent criterion was added to select the CAC representing the daily BH centre. This criterion selects the CAC most consistent with the monthly climatological position and daily variability. The calculation of the BH index is as follows:

- First, the climatological position of the BH (in terms of latitude and longitude) is determined by the mean position of the CACs identified in the monthly non-divergent wind field climatologies (1981 – 2020). In these mean monthly climatologies, not CACs unrelated to BH were observed.
- Next, CAC are identified from the monthly mean non-divergent wind at 200 hPa. The monthly BH centre position is represented by the CAC closest to the monthly climatological position determined in the previous step. This is considered the BH index at the monthly scale.
- The monthly position is then converted to a daily reference position using a mean-preserving spline interpolation approach (Ruiz-Arias 2022). Such as method preserve coherence across timescales with low computational cost.
- For each day, the horizontal position of the BH centre is indicated by the CAC closest to the arithmetic mean between the previous day's position and its daily reference position. This approach reduces the probability of selecting CACs not associated with the BH, while leveraging the improved delineation of the system at coarse time scales. Finally, the altitude of the system is represented by the geopotential height at 200 hPa at the identified centre.

Algorithm selection. Algorithm performance was evaluated by comparing the estimated and observed daily positions (latitude and longitude) using visual inspection of the non-divergent wind at 200 hPa. Due to the simultaneity of the observations, the compared positions are considered paired samples and require tests designed under this criterion to obtain reliable results (Wilks 2019). A minimum of 616 days was analysed to ensure 90% statistical power, based on a pilot study assuming extra-small standardised differences (Cohen 1988; Whitehead et al. 2016). Days were selected by stratified random sampling according to the frequency of the ENSO-drought categories (Table 2). The precision errors were described using Mean Absolute Error, Mean BIAS Error and Spearman's Rank Correlation coefficient. Meanwhile, the capacity to discern days without BH was evaluated using the Matthews Correlation Coefficient (MCC). MCC is a balanced classification performance measure, particularly suitable for

binary classification (days with and without BH) with imbalanced classes (Chicco and Jurman 2020, 2023). The MCC values range from – 1 (total disagreement) to + 1 (perfect agreement), with 0 indicating no better than random classification.

Table 2
Categorization of rainy seasons in the SHP [1982–2016]

Category	Years	Relative frequency
EN with drought	1983, 1987, 1992, 2016	11.4%
EN without drought	1988, 1995, 1998, 2003, 2005, 2007, 2010, 2015	22.9%
La Niña	1984, 1985, 1989, 1996, 1999, 2000, 2001, 2006, 2008, 2009, 2011, 2012	34.3%
Normal	1982, 1986, 1990, 1991, 1993, 1994, 1997, 2002, 2004, 2013, 2014	31.4%
<i>Note.</i> In the table, each year identifies the year in which the rainy season ends. For example, “1982” indicates the period from 1981-11 to 1982-04. EN: El Niño.		

3.2.2. Relationship with precipitation and streamflow

The Spearman's rank correlation test (Spearman 1904) is used to provide evidence of any relationship between the BH position and the hydroclimate over the SHP. This is applied to daily and monthly rainfall (1982–2016) and daily mean streamflow (1982–2020), with time lags of up to three-time steps to account for potential delayed responses. Furthermore, the false discovery rate control procedure (FDR, Benjamini and Hochberg, 1995) is employed to control the probability of false positives in the multiple hypothesis tests. The FDR adjusts the significance threshold of each test performed based on a desired global significance level (0.05), reducing the possibility of considering spurious correlations as significant (Ventura et al. 2004; Hu et al. 2017).

3.2.3. Behaviour during ENSO phases and droughts

To assess the influence of ENSO on the BH position and its relationship with the hydroclimatic conditions over the SHP, a composite analysis is performed for the rainy seasons (November-April). This is conducted across different ENSO phases, considering both meteorological drought and non-drought periods. Drought events are identified using the 3-monthly Standardised Precipitation Index (SPI-3; McKee et al., 1993). Table 2 presents the categorisation of rainy seasons in the SHP (1982–2016) according to the predominance of El Niño ($ONI \geq 0.5^{\circ}C$), La Niña ($ONI \leq -0.5^{\circ}C$) or neutral conditions. It also includes the presence of moderate or higher droughts ($SPI-3 \leq -0.8$) affecting at least one-third of the region. These indicators have compatible time scales. As they are defined quarterly (Nov-Jan, Dec-Feb, Jan-Mar, Feb-Apr), it was sufficient to observe these conditions in two of the four quarters to cover the majority of the rainy season. This categorisation and its criteria are consistent with those used in related regional studies (e.g. Imfeld et al., 2019; Alonso et al., 2022). The moisture fluxes for each ENSO-drought phase were characterised using the vertically integrated moisture flux in the upper troposphere

(300 – 100 hPa). This analysis captures the dominant pathways of moisture transport in the tropical upper troposphere, which are particularly relevant due to the seasonal evolution and spatial displacement of the BH. Significant differences relative to neutral non-drought conditions are assessed using the Mood's median test (Mood et al. 1974) and two-sided Student's test (Wilks 2019). Given the spatial dependence of precipitation patterns over the SHP (Huerta and Lavado-Casimiro 2021), the FDR described above is applied as a field significance test. This is necessary to reduce possible increases in the number of tests significant due to this dependency (Douglas et al. 2000).

4. RESULTS AND DISCUSSION

4.1. Evaluation of Bolivian High indices

The performance of the BH index was evaluated by comparing its estimated daily positions with observed BH locations on selected days. Overall, the BH index closely reproduces the observed positions, especially in latitude, showing high correlation and low error (Table 3) based on the random dates selected between 1981 and 2020 (616 days). Among all tested algorithms, the BH index performs best in consistently identifying the BH, even on days with multiple anticyclonic circulations, a condition where the other algorithms often fail (Fig. 3). For instance, the S2021 and P2019 (relaxed version) algorithms present the highest error rates. Their less strict CAC definitions make them prone to spurious circulations. The maximum region criterion partially mitigates this issue in the P2019 (relaxed version), though it is less effective than the stricter four-point approach used in S2021 (Fig. 3a). However, applying a strict criterion to define the CAC, as in P2019 (strict version), leads to frequent BH detection failures. The days without BH reported by this algorithm is 66.1%, compared to only 7.3% in observations. This is because the closed circulation does not always align with the regions of maximum geopotential height (Fig. 3b,c).

Table 3
Metrics for assessing BH position during the evaluation period

Index name	Longitude [°]			Latitude [°]			Days without BH	
	MAE	MBE	r	MAE	MBE	r	%	MCC
GK2018	5.30	1.89	0.48	2.28	0.42	0.84	0.0	0.00
S2021	8.96	4.02	-0.14	3.57	2.45	0.51	51.0	0.09
P2019 relaxed	5.59	1.61	0.40	2.39	0.23	0.80	5.2	-0.04
P2019 strict	2.63	1.12	0.70	0.98	-0.14	0.89	66.1	0.14
BH index	1.28	-0.03	0.90	0.49	0.15	0.97	4.5	0.51
<i>Note.</i> During the evaluation period (random dates selected between 1981 and 2020), the % of days observed without BH presence is 7.3%. Bold values indicate the best performance for each metric. Abbreviation: Mean Absolute Error (MAE), Mean BIAS Error (MBE), Spearman's Rank correlation coefficient (r) and Matthews correlation coefficient (MCC).								

Conversely, GK2018 indicates that the BH persisted throughout the entire evaluation period, which is inaccurate. Certain weather patterns weaken the BH even in the most active months, such as, extratropical Rossby wave equatorward propagation (Sulca et al., 2016) and cold air intrusion (Satyamurty and Rosa 2020). Although GK2018 applies spatio-temporal smoothing to geopotential height (Fig. S2a,b), this method links the BH location with areas of higher geopotential height. These are not considered its actual presence or the influence of nearby atmospheric patterns, such as incoming air masses or other circulations (Fig. 3b,d).

The BH index enables rigorous delimitation of the CACs without relying on the maximum region criterion, while maintaining coherence with the behaviour of the system. Therefore, the BH index is used as a reference to determine the position of the BH in the subsequent analyses. It should be noted that the BH index has missing values in some months due to the absence of a reference position of the system in months when the mean circulation did not show the BH (Table S1). Comparison between non-divergent and total wind fields of the ERA5 and alternative reanalyses confirmed the system's absence, except for November 1983 (Fig. S2c,d). Differences in that case are attributed to reanalysis uncertainties. ERA5 is preferred due to its recent technical advancements (Hersbach et al. 2020).

4.2. Bolivian High climatology

The mean (median) position of the monthly BH centre during December-February is 16.5°S, 65.2°W and 12448.6 mgp at 200 hPa (16.5°S, 65.5°W and 12446.2 mgp) for the period 1981–2020. In contrast, the climatology derived from daily BH positions is 17.0°S, 64.9°W and 12453.6 mgp. Due to higher noise at daily scale, the monthly-based climatological values as recommended as a reference for future studies. This climatology differs from previous studies (e.g. Garreaud and Aceituno, 2007; Barreto Schuler, 2016; Sulca et al., 2016; Espinoza et al., 2020; Suarez, 2021), possibly due to the longer study period and the

use of ERA5, which provides improved spatial resolution compared to earlier reanalyses. The monthly BH position shows a clear seasonal migration (Fig. 4a,b,c and Table S2). From 12.1°S 63.7°W in November, it shifts southward to reach its southernmost extent (17.4°S 65.6°W) in January, before returning northeast to 10.3°S 62.6°W in April. This displacement pattern is consistent with the movement of convective activity, which is associated with the seasonal variability of the South American Monsoon System (Espinoza et al. 2021).

Figure 4d illustrates the spatial distribution of all daily BH positions identified by the tracking algorithm using ERA5 data for November-April during 1981–2020. This analysis reveals that the BH centre spans a broader range of longitudes than latitudes. Although some atypical positions (far from its climatology) are observed, these mostly occur when the system is not weakly defined (e.g. November or April; Fig. S3); or under the influence of its intraseasonal modulators (e.g. Sulca et al., 2016). Detection errors may also occur due to limitations of daily-scale tracking, as reported in Suarez (2021) and corroborated by other databases with different grid resolutions (Fig. S4).

4.3. Relationship with precipitation and streamflow

Daily and monthly BH positions are analysed and correlated with rainfall and streamflow over the SHP for the November-April period (Fig. 5). Spearman's rank correlation is used to assess the relationships. Both daily and monthly BH indices show statistically significant associations with rainfall and streamflow (Figs. 5 and S5). The negative relationship between the latitudinal position and both precipitation and streamflow is notably stronger than for the other coordinates, both in magnitude and spatial extent. This suggests that wetter conditions occur when the BH shifts southwards from its normal position. The median significant correlation coefficient between the latitudinal position of the BH and daily precipitation (streamflow) over the SHP during November-April is 0.37 (0.38), with stronger correlations on the western slope of the Andes and at the monthly scale. This pattern varies across the months and is more pronounced at the beginning and in the second half of the rainy season (Fig. 6). The magnitude and extent are particularly lower in January, especially on the eastern slopes of the Andes, where Amazonian convection dominates (Segura et al. 2020). In contrast, the BH altitude at 200 hPa shows a slight positive relationship with higher magnitude during the first months of the rainy season (Fig. S6). This may reflect the atmospheric warming by the latent heat release from convective activity over the Amazon basin and the Andes, associated with the South American Monsoon System (Lenters and Cook 1997). Meanwhile, the longitudinal position shows a less homogeneous relationship, with negative values dominating over the SHP, except in its eastern region (Fig. S7). Aside from this exception, the results observed for precipitation and streamflow are generally analogous. Similar results are obtained using the Rain4PE data (Fig. S8), reinforcing the robustness of the findings. Additionally, correlations tend to be more significant in high-altitude areas, suggesting a modulation by topography.

The relationship between precipitation in the SHP and the horizontal position (latitude and longitude) of the BH is consistent with its observed seasonal displacement. Between November-January, the southwestward displacement of the BH places its northern branch over the central and southern tropical Andes, pushing moisture from the Amazon towards the SHP. This enhances moist convection and

increases precipitation and streamflow (Horel et al. 1989; Marengo et al. 2012; Segura et al. 2019). Since February, the relationship tends to decrease in magnitude and extent as the system shifts to the northeast. Although this mechanism has been widely documented, this is the first time that the short-term relationship between the daily position of the BH with precipitation and streamflow in the SHP is quantified.

Figure 7 shows that the correlation between the latitudinal and longitudinal variations of the BH and precipitation in SHP decreases when considering lags of up to three days. In the spatial extent of the statistical significance (indicated by the colour of the boxes), the longitudinal and altitudinal relationships weaken over time, while the latitudinal relationship persists. This indicates that variations in the BH position have both immediate and persistent effects on precipitation events, but the most pronounced effects occur in the very short period (less than three days). This highlights the need for automated tools for day-to-day monitoring of the BH and its forecast variations, especially during the period of peak activity.

Although previous studies have documented the daily relationship between upper-tropospheric circulation and precipitation anomalies (e.g. Sulca et al. 2016), this is the first to quantify their magnitude and persistence. The highest daily precipitation rates occur when the BH is between 21–17.5°S 70.5–65°W, which is more frequent between December and March (Figs. S3 and S9). These results are consistent with previous research (e.g. Segura et al., 2019) that identified favourable BH for moisture inflow into the SHP and the occurrence of extreme precipitation events.

Recently, Segura et al. (2020) observed that since the early 2000s, the relationship between easterly winds at 200 hPa (linked to the BH) and the interannual variability of summer precipitation in the southern tropical Andes has weakened. Instead, convective activity in the western Amazon has become the main driver of precipitation over the last 20 years. In this context, a comparison of the BH-precipitation relationship between 1982–2001 and 2002–2016 (Figs. S10 and S11) shows a decrease in significantly correlation magnitude and spatial extent. The changes in the position of the BH were also calculated, revealing that in January, the average position shifts from 18°S, 66°W for the older period to 17.3°S, 64.2°W for the recent period. This is an overall modest northward shift that masks a more pronounced northeastward displacement, linked to reduced rainfall in the SHP (Fig. 5). Moreover, Fig. S10 shows the emergence of positive correlations northeast of the SHP, consistent with increased January instability documented by Segura et al. (2020). This pattern suggests that enhanced convective activity in the western Amazon may contribute to the BH's northward shift (Lenters and Cook 1997), leading to a decrease in moisture advection to the Andes. Nevertheless, when daily-scale variations of the BH position are considered, the influence of the BH on precipitation in the SHP becomes more significant after 2000s. Further research is needed to corroborate this hypothesis and the possible late onset and shorter duration effects of the observed and projected South American Monsoon System (Correa et al. 2021; Espinoza et al. 2021; Reboita et al. 2023), as it is beyond the scope of this study.

4.4. Behaviour during ENSO phases and droughts

The Figs. 8 and S12 illustrate the daily variations in the BH position across different ENSO-droughts phases. During El Niño events, the horizontal position of the BH is closer to normal at the beginning of the rainy season, with a subsequent east-northeastward shift (Fig. 8a,b). This shift positions the southwestern edge of the BH over the Altiplano and is associated with reduced moisture available over SHP (Fig. 9). These shifts limit the large-scale seasonal inflow of Amazonian moisture and draining moisture away from the Altiplano (Segura et al. 2019). Consequently, drier conditions prevail over the SHP region during El Niño (Figs. 10 and 11). The persistence of this pattern could be a decisive factor in the development of meteorological droughts, especially from January onwards. In agreement with Jonaitis et al. (2021), the greatest dryness associated with El Niño occurs on the western slope between January and March, but their impact persists in river flows until April (Fig. 11).

This El Niño pattern is likely driven by anomalous upper-level winds from the southeast Pacific, linked to an increased thermal gradient between tropics and mid-latitudes (Sulca et al. 2017; Imfeld et al. 2019). Positive sea surface temperature anomalies in the tropical central-eastern Pacific enhance convection, generating seasonal Rossby waves with anticyclonic circulations north and south of the equator (Gill 1980). This causes an upper-level anticyclonic circulation over central-western South America, shifting the BH northeastward from its typical position and resulting in a low delimitation during March-April, which is typical of drought conditions over SHP (Figs. 9 and S12). For December-February, the BH shifts northeastward (15.5°S 62.5°W) compared to its normal category conditions of 17.3°S 66.0°W (Table S3). Although different El Niño types (Kao and Yu 2009) are not explored here, the pattern described above is more clearly defined during the Eastern-Pacific El Niño (or canonical El Niño) than Central-Pacific El Niño or mixed El Niño (Imfeld et al. 2019). Therefore, the largest deviations in the position of the BH with potential impacts on the SHP may occur during the former.

Conversely, the pattern described is reversed during La Niña, during which the southern tropical Andes are dominated by strong northeasterly winds. During La Niña, the BH starts the rainy season further north than normal and moves southwards, increasing the inflow of moisture from the Amazon into the SHP (Figs. 8 and 9). This leads to positive rainfall and streamflow anomalies from February to April (Figs. 10 and 11). On the other hand, altitudinal anomalies could be related to tropospheric warming (cooling) caused by warm (cold) sea surface temperature anomalies in the central-eastern Pacific during El Niño (La Niña) (Fig. 8c).

The findings align with expected ENSO-driven hydroclimatic impacts in the SHP (Lavado-Casimiro et al. 2013; Lavado-Casimiro and Espinoza 2014) and underscore the importance of monitoring the sub-seasonal BH evolution as a predictive tool. However, data availability limited the period analysed to 1982–2016, excluding disturbances characteristic of more recent events. For instance, during the severe 2022–2023 drought, notable upper-level perturbations were observed (especially in November) that included weaker BH development. According to Gutierrez-Villarreal et al. (2024), these were driven by extratropical Rossby wave trains modulated by thermal conditions in the southwest Pacific and tropical Atlantic under La Niña conditions. Among their results, they showed that the position of the BH (around 11°S 62°W) matched what was described in this study (Fig. 8a,b). That is a north displacement relative

to position during normal conditions (13.7°S 62.9°W in November), except for the significant negative geopotential height anomaly at 200 hPa (Fig. 8c), which indicates the weakening of the BH.

5. CONCLUSIONS

This study aimed to analyse the short-term relationship between the Bolivian high (BH) position and the hydroclimate over the Southern Highlands of Peru (SHP). To this end, an algorithm was developed and statistically validated to determine the daily position of the BH centre, selecting the closed anticyclonic circulation most consistent with its climatological position. The results were analysed for the rainy seasons (November-April) between 1981 and 2020. The main results can be summarised as follows:

- The daily estimated position of the BH showed a reasonable accuracy, especially in the latitudinal position. The performance of the BH index is robust to most of the constraints associated with the automatic detection of atmospheric patterns, but could show deficiencies on days when the system is not fully defined.
- The climatological position of the BH during December-February is 16.5°S, 65.2°W and at an altitude of 12448.6 mgp (200 hPa), with a marked monthly shift from northeastern Bolivia to the south-southwest and then back to the northeast.
- The latitudinal and longitudinal position of the BH is inversely related to precipitation and streamflow in the SHP, particularly along the western Andes during austral summer. The position southwest of Bolivia being the most favourable for precipitation in the SHP. This relationship remains significant until the recent period, but further analysis is needed.
- During El Niño, the higher daily frequency of the BH north-northeast of its climatological position is associated with droughts over the SHP, especially from January onwards. In contrast, La Niña promotes a southward BH displacement and is linked to positive precipitation and streamflow anomalies, especially over the western slope of the Peruvian Andes. These contrasting configurations are driven by changes in the strength of the seasonal Rossby wave, which responds to modifications in the tropical–mid-latitude thermal gradient.

This study contributes to a deeper understanding of the short-term relationships of the BH position and its relationship with hydroclimatic conditions over the SHP. In addition, it provides tools for daily climate monitoring of the BH, which can be applied to upper-tropospheric anticyclonic systems in other monsoon systems, such as the Botswana High (Reason 2016). Recurrent monitoring of these systems is essential for operational weather and climate forecasting, especially during ENSO phases, and for studying the climate system under climate change scenarios, deforestation scenarios and other modes of variability (e.g. PDO). Future work could focus on improving the tracking algorithm by calculating the intensity, size, and duration of the BH, as well as other relevant characteristics (formation, dissipation and lifetime, among others). And, while the alternative algorithms tested showed lower performance compared to the BH index (due to possible influences from other features), they remain valuable options due to their lower latency and computational simplicity.

Declarations

Ethical Approval.

Not applicable.

Competing Interests.

The authors have no relevant financial or non-financial interest to disclose.

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A.H. conceived the methodology and experimental design with support from L.S.S. and K.C.; K.C. conducted the experiment and developed the figures and tables. K.C., A.H., and L.S.S. analysed the results and wrote the majority of the manuscript. H.P. provided the theoretical framework and contributed to reviewing and editing the manuscript. W.L.C. supervised the project and contributed to reviewing and editing the manuscript. All authors discussed the results and contributed to and commented on intermediate versions of the manuscript.

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Figures and Tables

Data availability.

The reanalysis datasets used in this study are publicly available through their respective institutional repositories: ERA5 from the European Centre for Medium-Range Weather Forecasts (<https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5>), NCEP-NCAR Reanalysis 1 (R1) (<https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html>), and NCEP-DOE Reanalysis 2 (R2) (<https://psl.noaa.gov/data/gridded/data.ncep.reanalysis2.html>). Precipitation and streamflow datasets are also accessible via their respective repositories: PISCOp (<https://piscoprec.github.io/>), PISCO_HyD_ARNOVIC (<http://www.hydroshare.org/resource/f723d6c762ca45b6936dd9489bc44842>), and RAIN4PE (<https://doi.org/10.5880/pik.2020.010>). Additionally, the Oceanic Niño Index (ONI) time

series was obtained from the NOAA Climate Prediction Center
(https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php).

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Figures

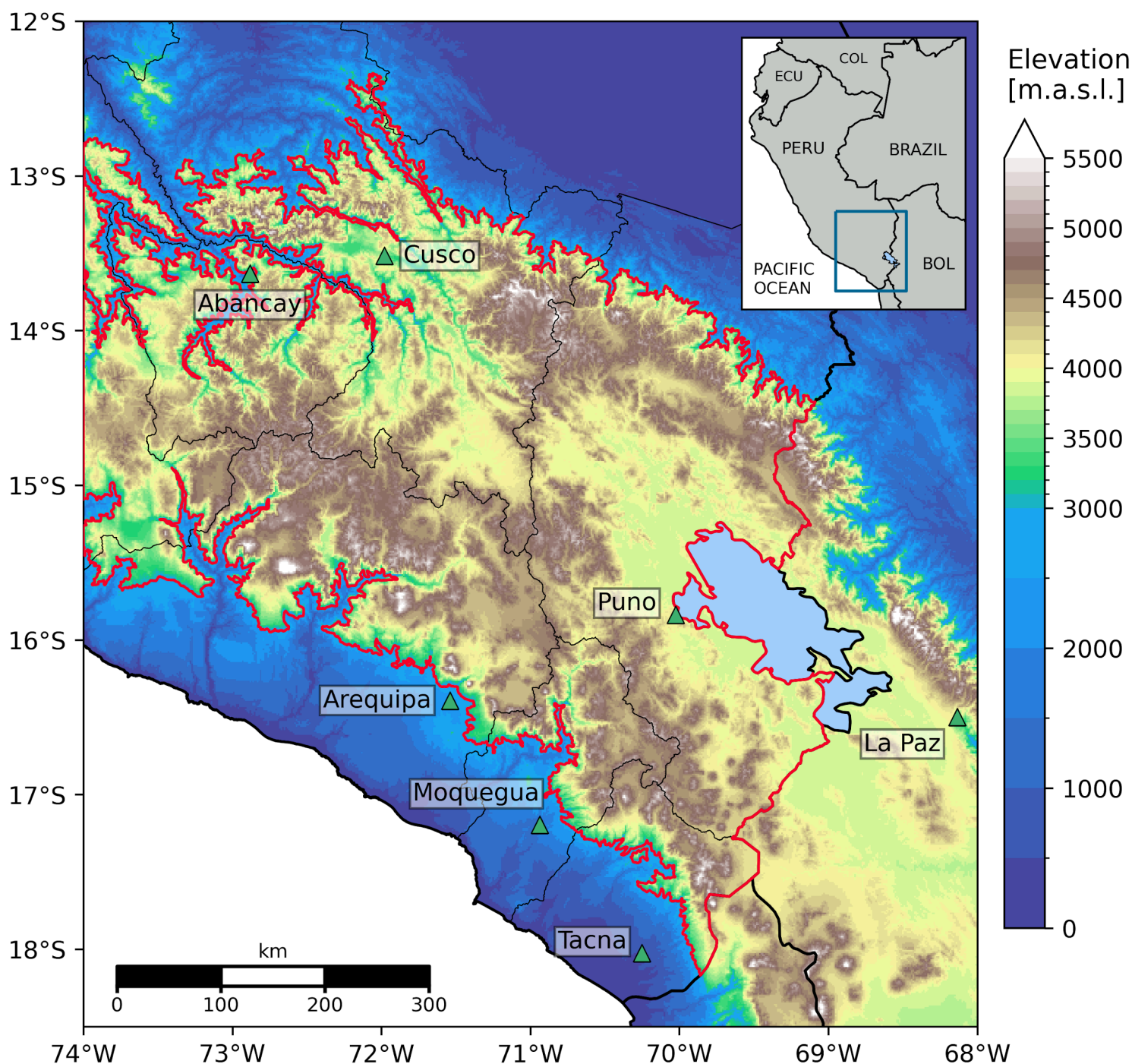


Figure 1

Topographic map of the south of Peru (12°-18.5°S, 74°-68°W). The red contour lines represent an isoline of 3000 m.a.s.l. within Peru and delineate the Southern Highlands of Peru (SHP). The thick (thin) black lines indicate the boundaries between countries (regions of Peru). The locations of cities and Lake Titicaca are indicated by green triangles and a light blue filled area, respectively.

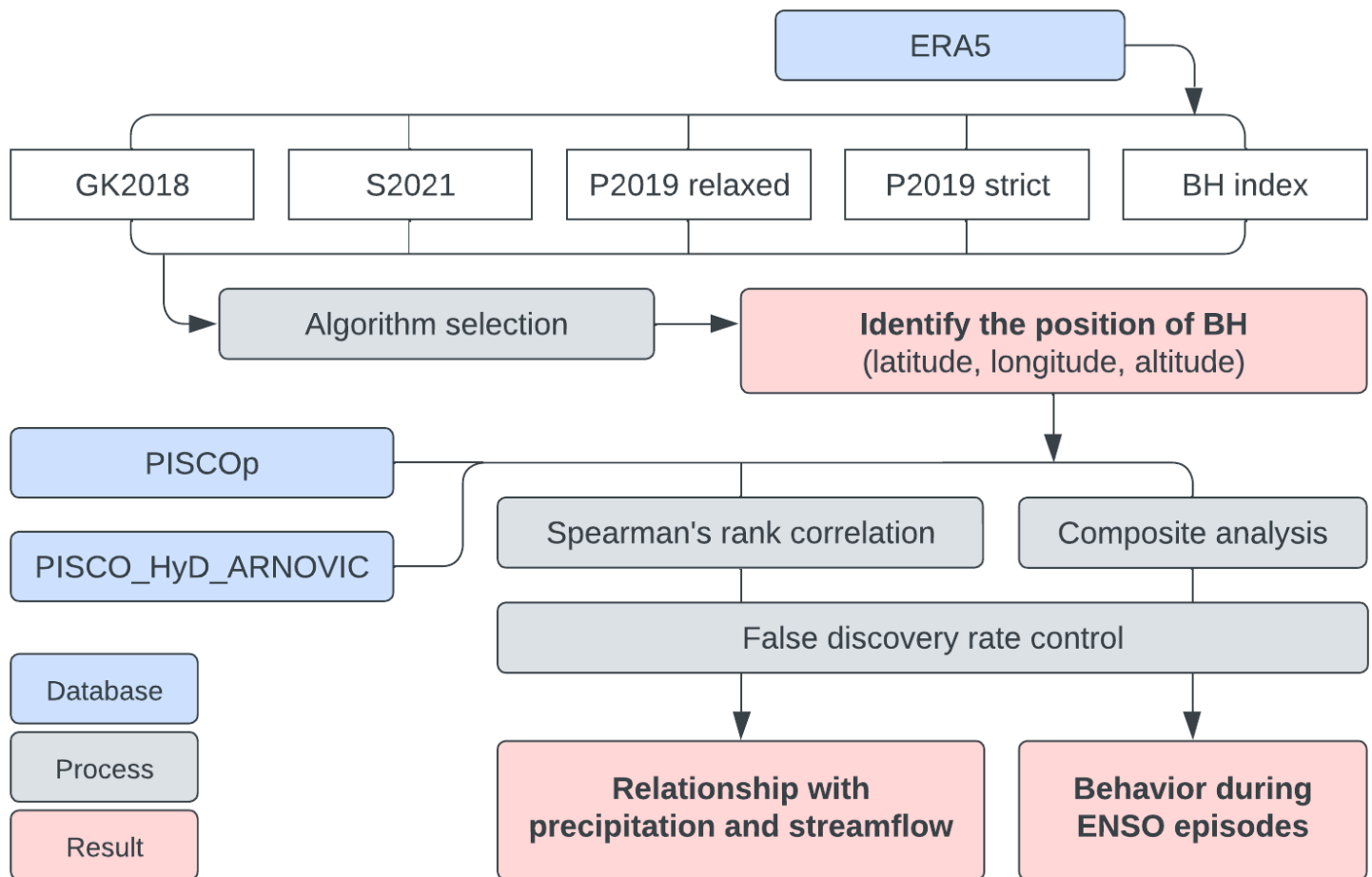


Figure 2

Schematic overview of the study.

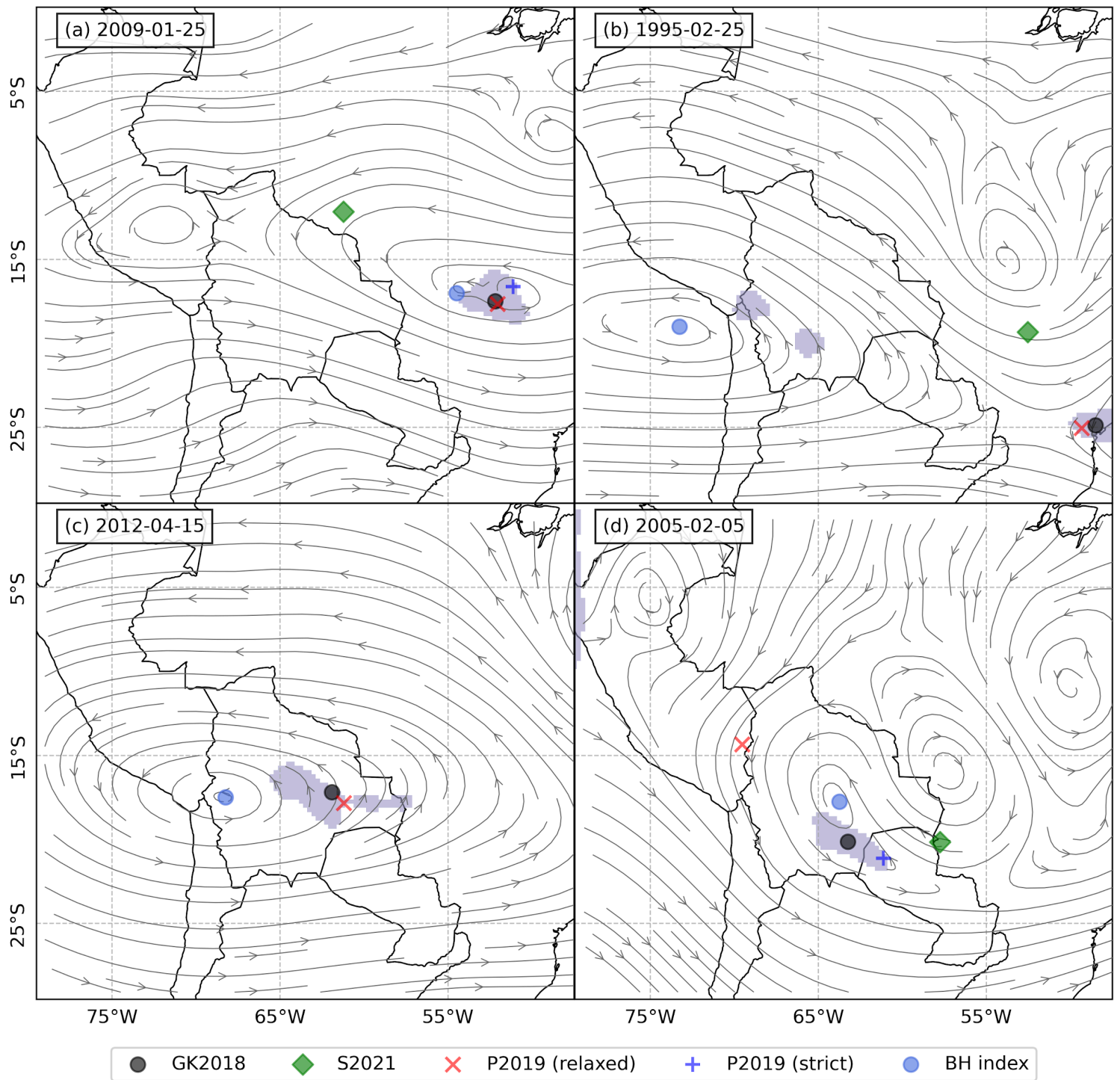


Figure 3

Examples of the tested BH algorithms for some specific days. Non-divergent wind at 200 hPa (streamlines) and regions of maximum geopotential height (shaded) are shown.

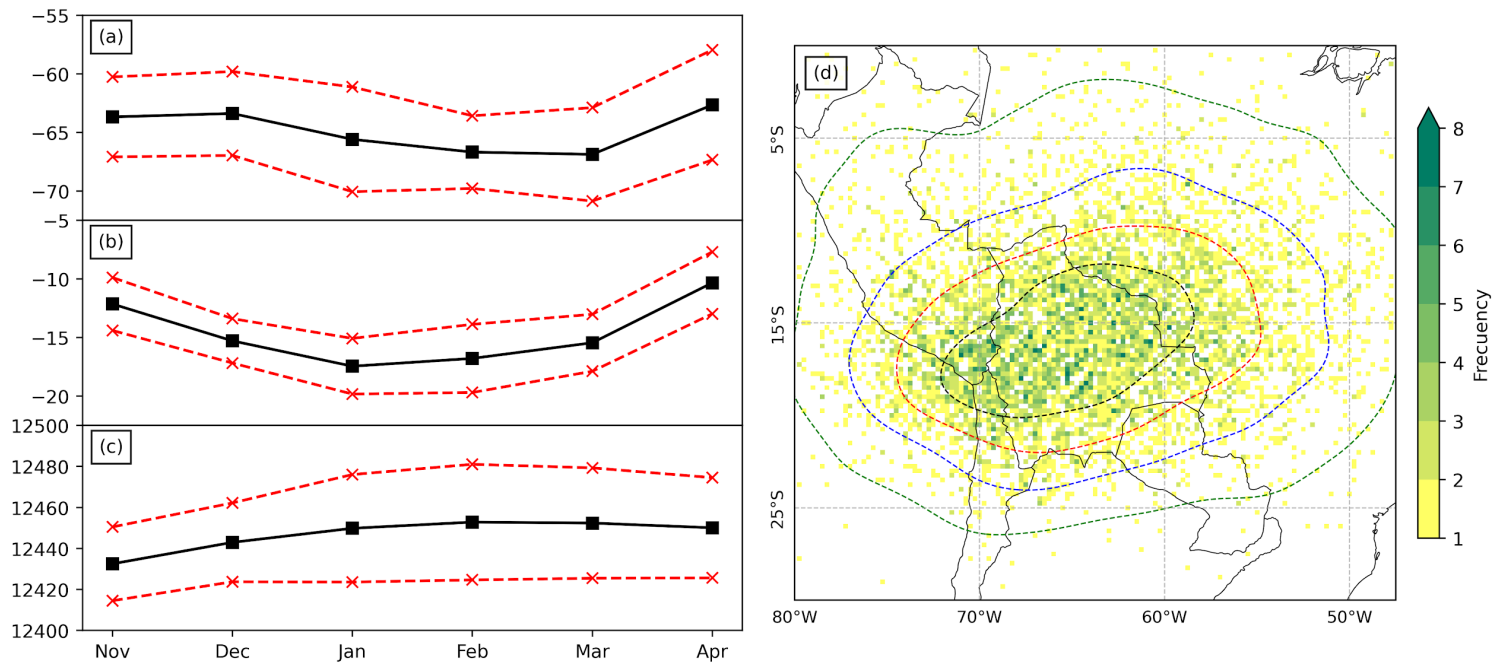


Figure 4

(a,b,c) Monthly climatological position of BH (1981-2020). The black line represents the average position in the month, while the red lines represent the interval of $\pm$ one standard deviation. (d) Daily frequency of the centre of BH [November-April, 1981-2020]. Segmented contours represent the regions that concentrate 25% (black), 50% (red), 75% (blue) and 90% (green) of the total. The region's concentration was delimited at the kernel density estimation.

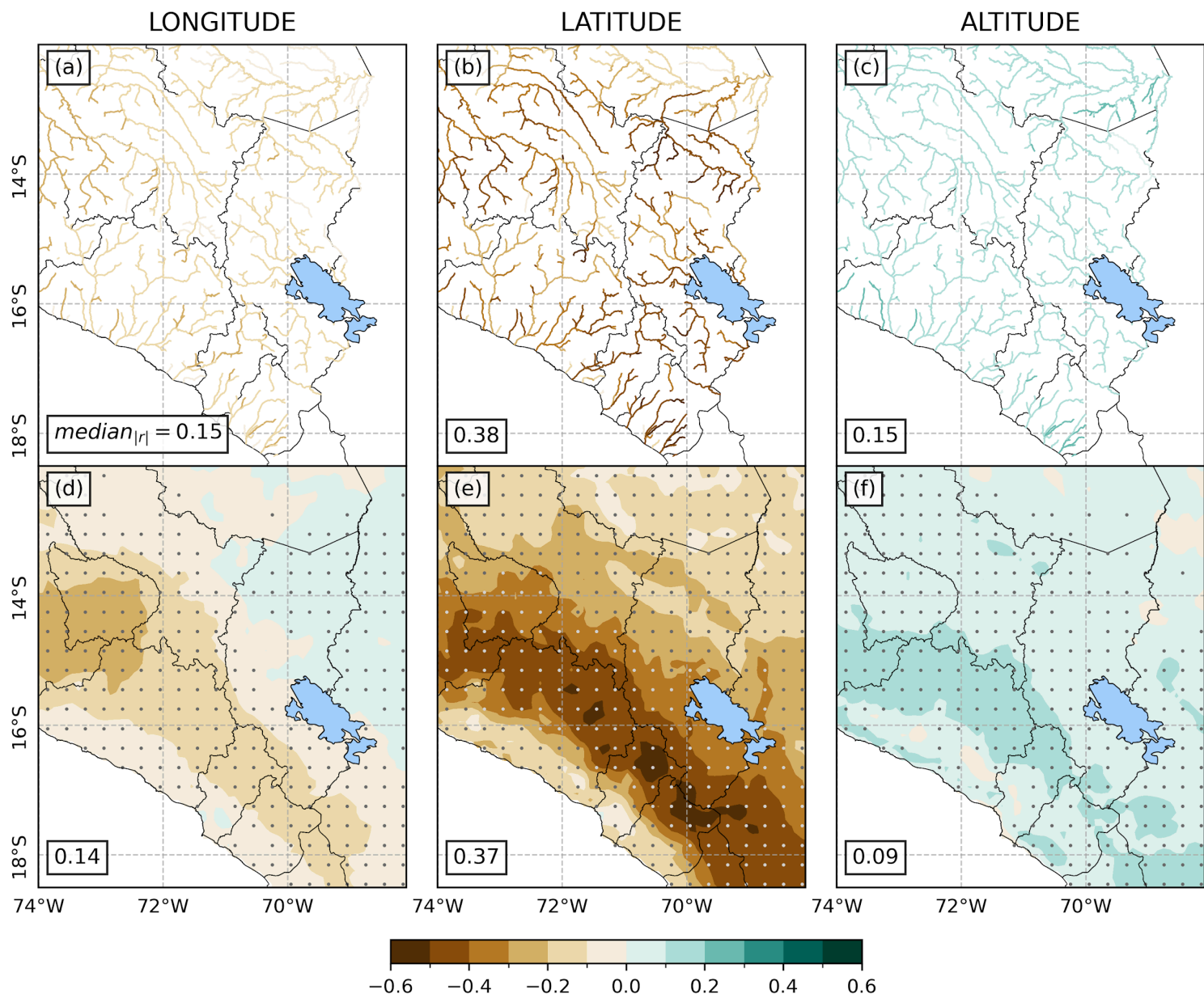


Figure 5

Correlation of daily BH position with streamflow (a,b,c) and precipitation (d,e,f) during the rainy season (November-April). In (a,b,c) only rivers with significant correlation are shown, while in (d,e,f) the dots indicate the regions of global statistical significance. The median correlation magnitude (absolute value) in the significant grids or lines on the SHP (delineation in Fig. 1) is shown in each panel.

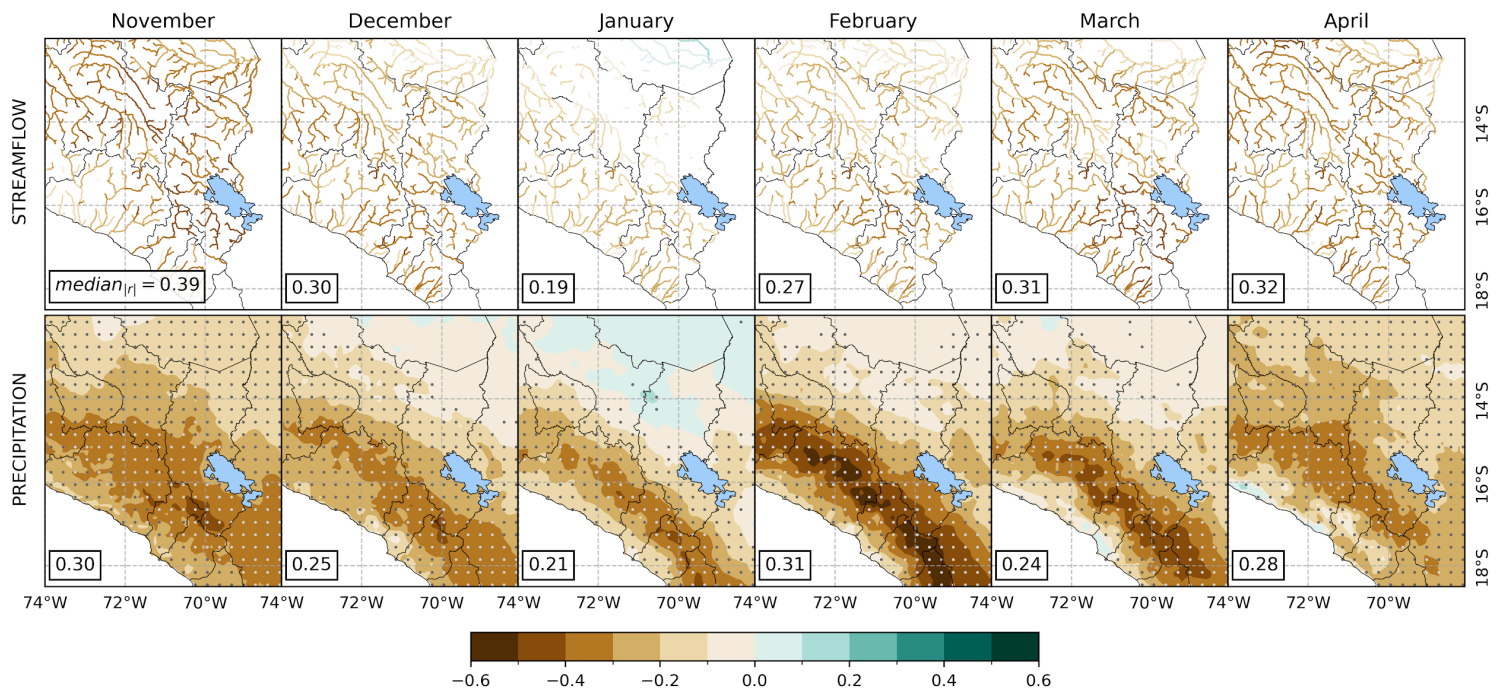


Figure 6

Correlation of daily latitudinal position of the BH with streamflow and precipitation in each month of the rainy season (November-April). In the first row, only rivers with significant correlation are shown, while in the second row, the dots indicate the regions of global statistical significance. The median correlation magnitude (absolute value) in the significant grids or lines on the SHP (delineation in Fig. 1) is shown in each panel.

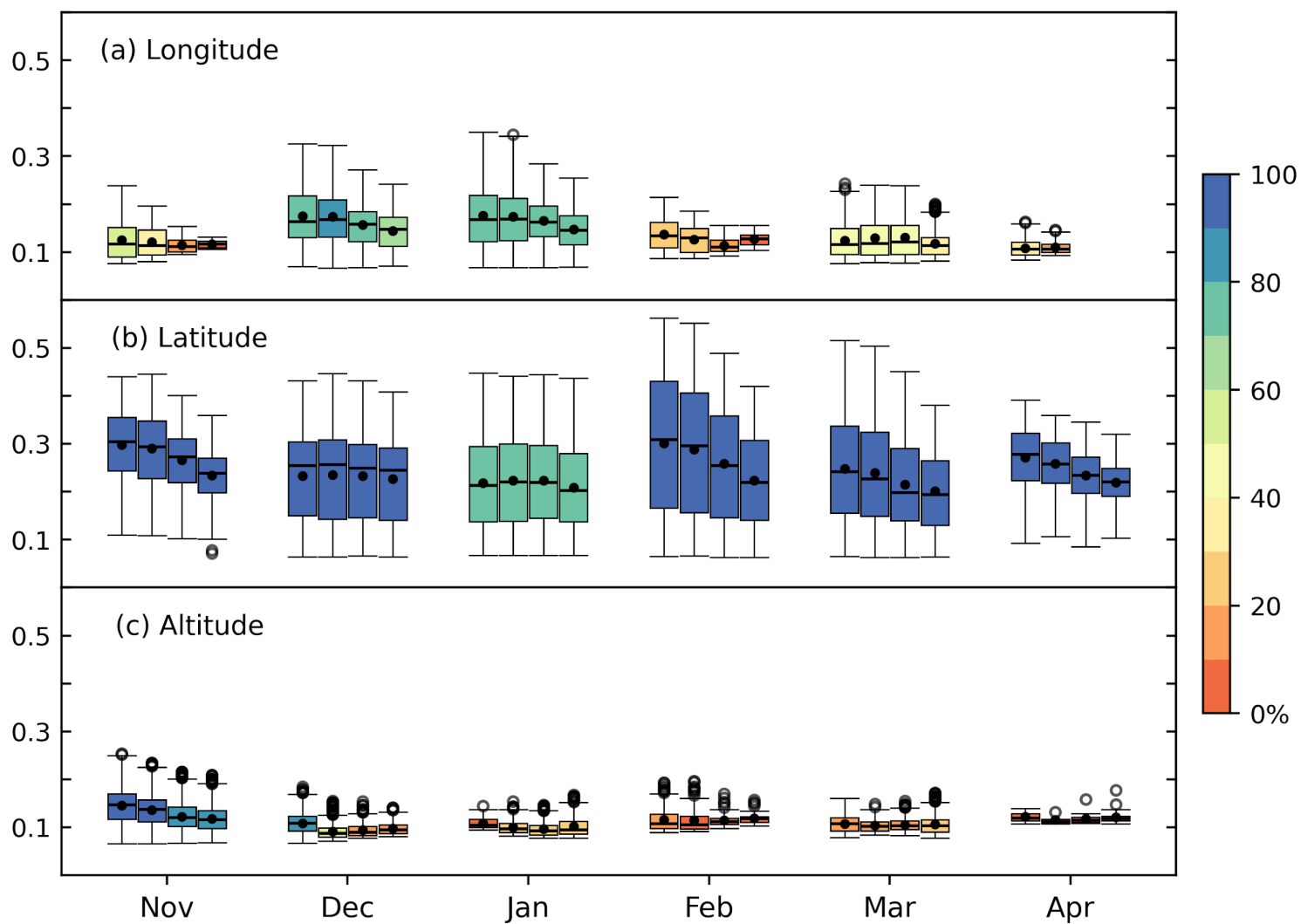


Figure 7

Magnitude of daily correlations (absolute value) with lags of up to three days (starting from the left box to the right of each month) for **(a)** longitudinal, **(b)** latitudinal, and **(c)** altitudinal position of the BH. Only the significant values in the SHP are shown. The colour of the box indicates the % of grids with statistical significance in the area.

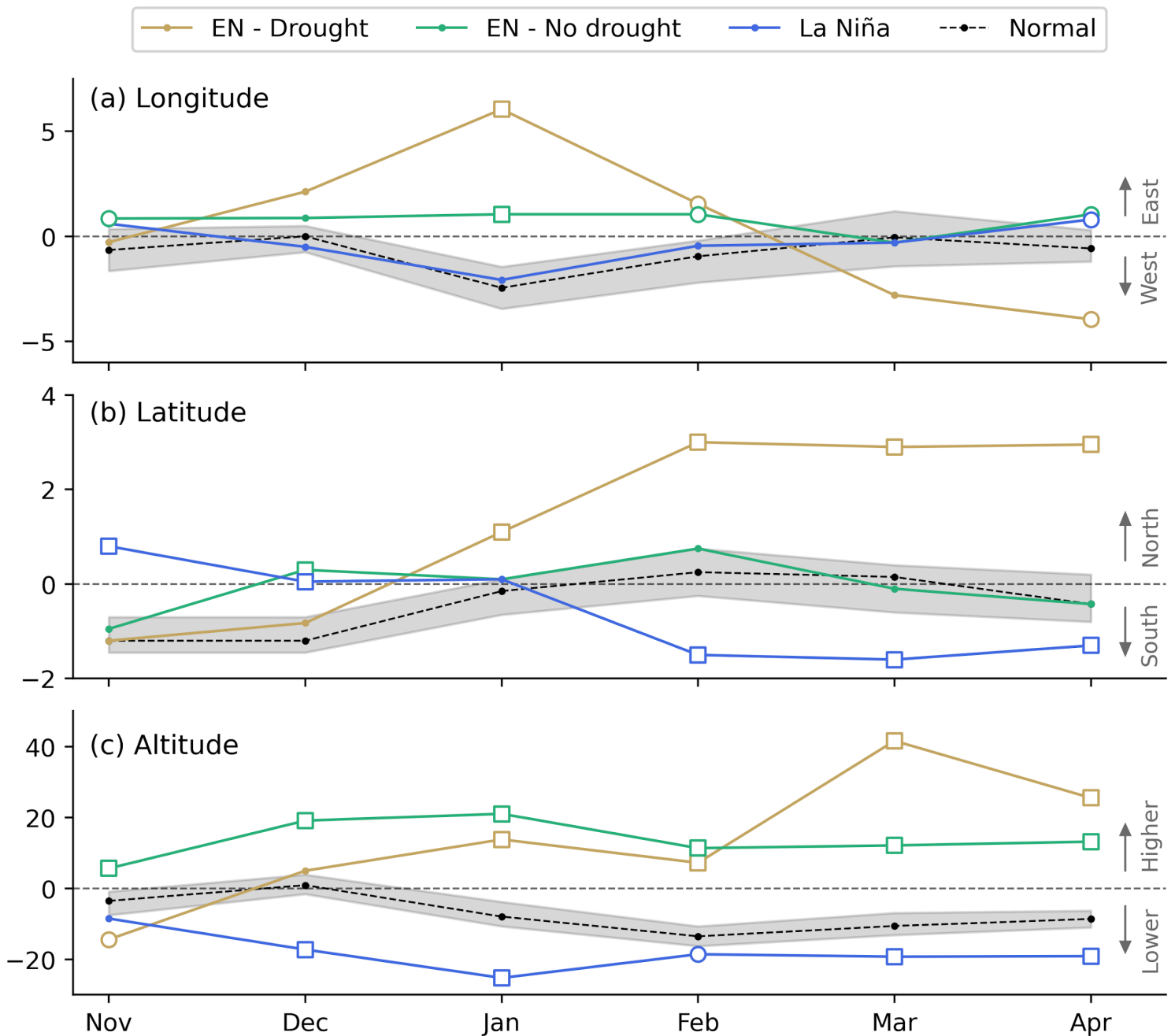


Figure 8

Median daily BH anomaly during ENSO-drought phases. The statistical significance of the differences from the normal category at the 95% (99%) confidence level is indicated by a circle (square). The shading indicates the confidence interval of the median in the normal category, obtained by bootstrapping at a 95% confidence level.

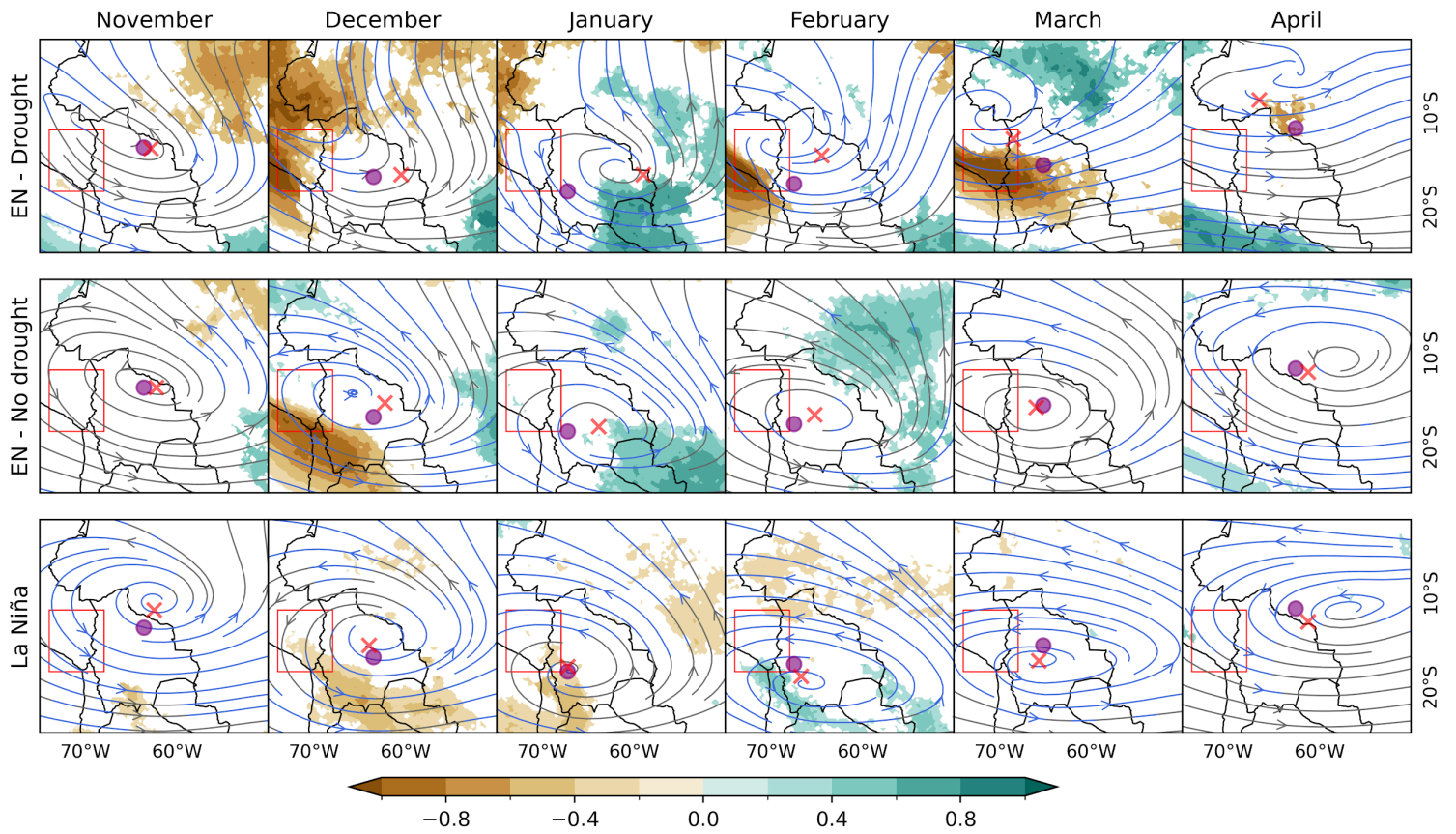


Figure 9

Vertically integrated moisture flux ($\text{kg.m}^{-1}.\text{s}^{-1}$, streamlines) and standardised specific humidity anomalies (shaded) at upper levels (300-100 hPa) during ENSO-drought phases. The median values of daily variables during each phase was shown. The purple dot and red x indicate the median values of the BH index under normal conditions and the analysed phase, respectively. Blue lines indicate statistically significant differences in moisture flux compared to normal conditions. The shaded only show regions with significant differences from normal conditions.

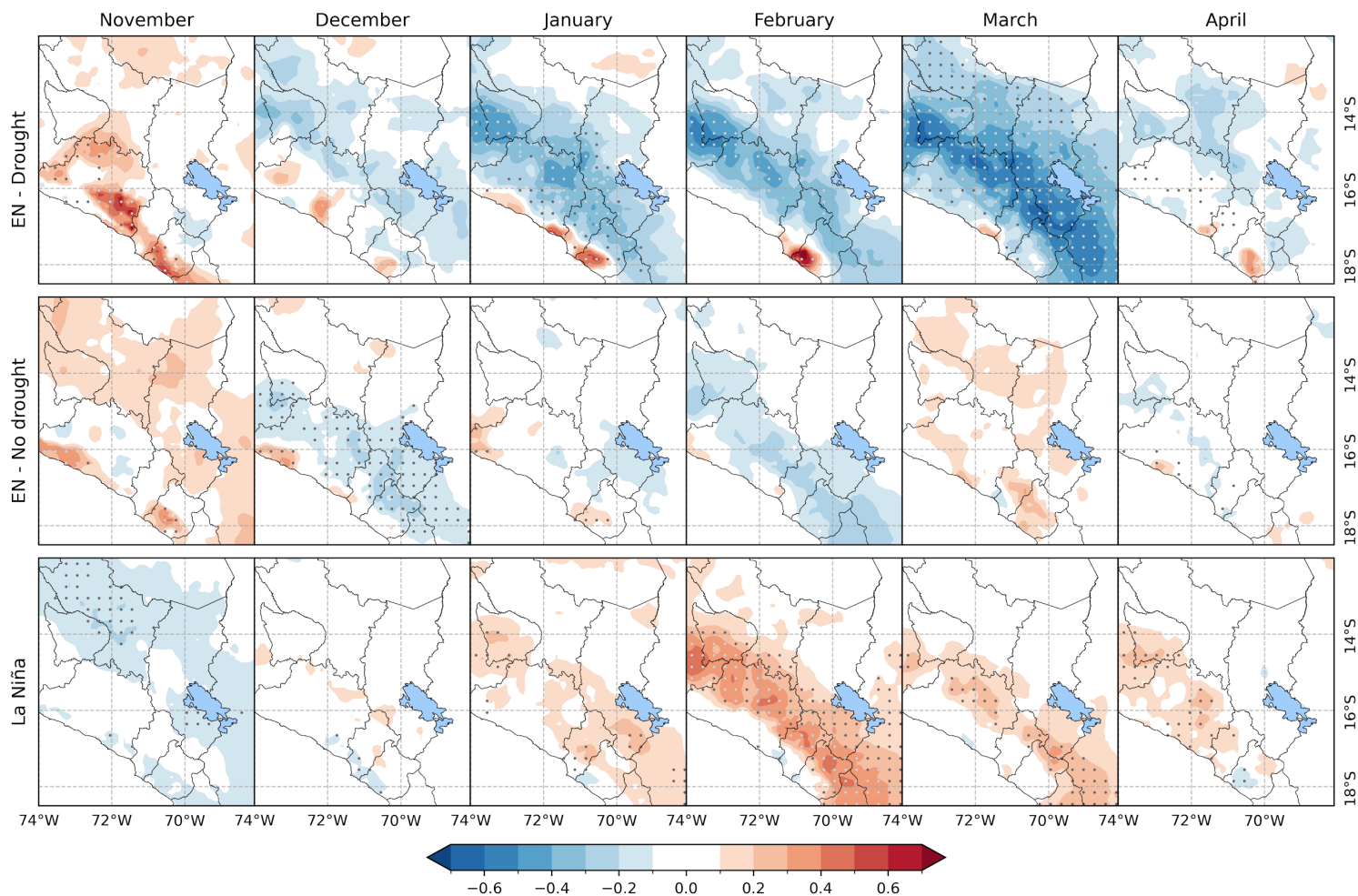


Figure 10

Mean standardised daily precipitation anomalies during ENSO-drought phases. Dots indicate regions with significant differences from normal conditions.

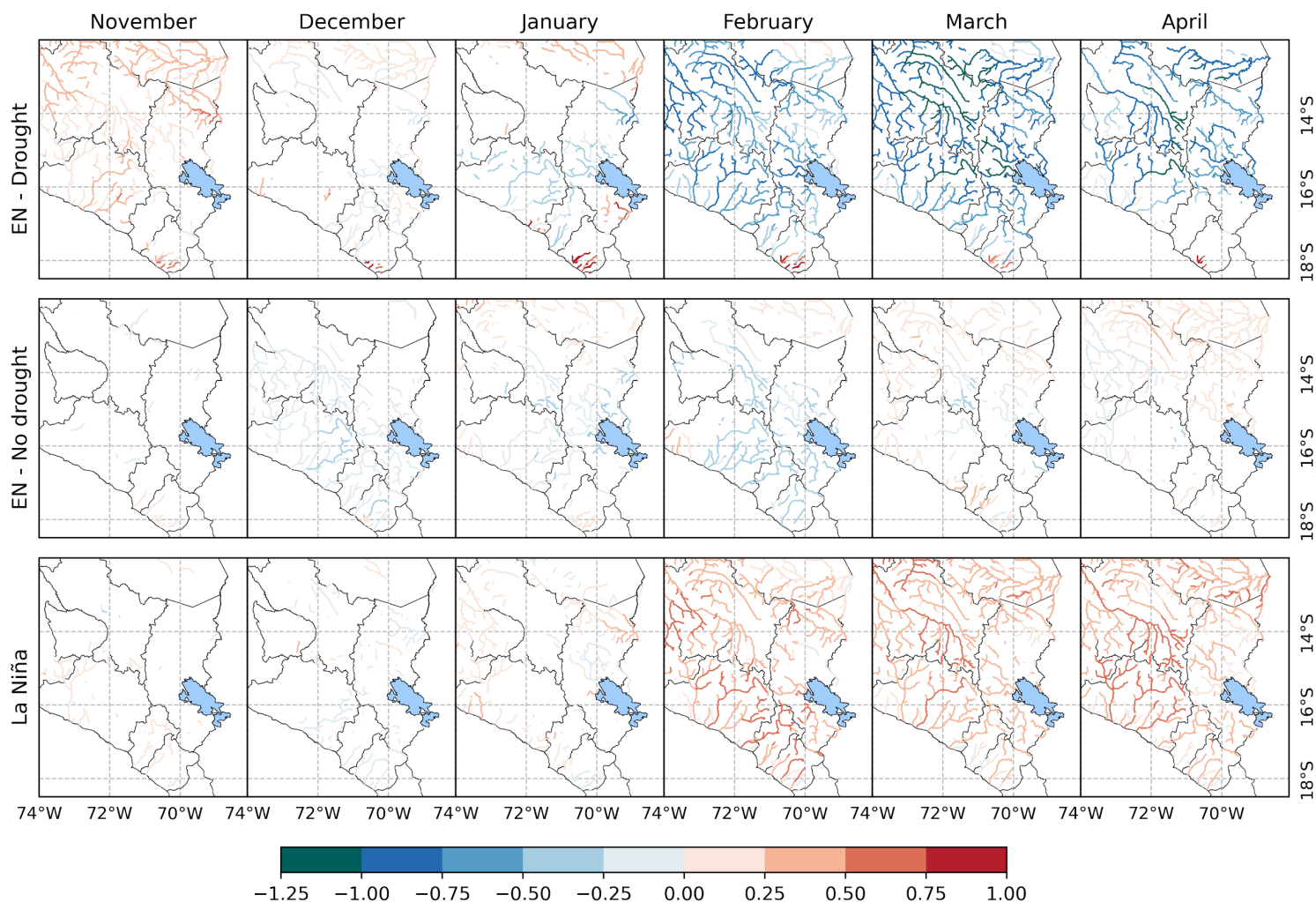


Figure 11

Standardised daily streamflow anomalies during ENSO-drought phases. Only show lines with significant differences from normal conditions.

Supplementary Files

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