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Climate Forcings and Their Influence in the Cordillera Blanca, Perú, Deduced from Spectral Analysis Techniques †

Adrián Fernández-Sánchez [1,2,*], Jose Úbeda Palenque [1,2], Luis Miguel Tanarro García [1], Nuria Naranjo Fernández [3], José Antonio Álvarez Aldegunde [4] and Johan Chancafé [5]

1 Department of Geography, Geography and History School, University Complutense of Madrid, 28040 Madrid, Spain; joseubeda@ucm.es (J.Ú.P.); pace@ghis.ucm.es (L.M.T.G.)
2 Guías de Espeleología y Montaña, Casilla del Mortero, 28189 Madrid, Spain
3 Hydrogeology Center, Malaga University, 29590 Malaga, Spain; nuria.naranjo.phd@gmail.com
4 Civil Engineering Department, Universidad de Cartagena, Cartagena de Indias 130001, Colombia; jalvareza@unicartagena.edu.co
5 Servicio Nacional de Meteorología e Hidrología de Perú, Lima 15072, Peru; chancafe.clima@gmail.com
* Correspondence: adrferna@ucm.es; Tel.: +34-605843486
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Abstract: The Cordillera Blanca of Peru (Central Andes) has the highest elevation in the country, and is mostly affected by tropical and regional climate forcings. Spectral techniques are applied to temperature and precipitation records in order to discern the hidden periodicities and to correlate the influence of different climate forcing indexes that are also submitted to analysis. Similar periodicities are found for Madden–Julian oscillation (MJO) and intra- and interseasonal scale temperature events; the Humboldt Current and South American low-level jet (SALLJ) periodicities are close to annual meteorological events, and El Niño–Southern Oscillation (ENSO) and Intertropical Convergence Zone (ITCZ) displacements are correlated with interannual scale temperature and precipitation events.

Keywords: Peru climate; climate forcings; spectral analysis; climatology; ENSO; ITCZ; MJO; Cordillera Blanca

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1. Introduction

Determining the influence of climatic forcings on the climatic variability of a region is of special importance to forecasting the behavior of the regional climatic system as well as the natural and ecological processes derived from it. In the context of global warming [1], it is necessary to characterize the influence of the factors that regulate the regional climate due to the possibility of change in the mechanisms of action.

Spectral analysis techniques have been widely used in Earth sciences, especially in astrophysics [2], climatology [3], as well as in air quality assessment [4]. Few climatic studies have been carried out in the South American region using the spectral analysis technique, being mostly paleoclimatic analyses of sedimentary cores [5] or ice cores [6]. In Peru itself, this technique would only have been used to determine the probability of the change in the intensity of the El Niño–Southern Oscillation (ENSO) phenomenon [7].

These techniques are normally useful for the study and characterization of the climate, whereas their use in the comparison between climate forcings and meteorological records has been more limited. The aim of this work is to perform spectral analysis techniques in 34-year daily meteorological records for stations located in the vicinity of the Cordillera Blanca of Peru, in the Central Andes.

The Cordillera Blanca (7°9′ S–11°39′ S and 78°30′ W–76°11′ W) is one of the areas with the highest elevations in the country, with up to 30 peaks at an altitude greater than 6000 m. This mountain range is affected by a tropical climate framework and a strong influence of forcings such as the El Niño–Southern Oscillation (ENSO), the displacement of the Intertropical Convergence Zone (ITCZ), and the Madden–Julian oscillation (MJO).

2. Methodology

Precipitation, maximum, and minimum temperature records on a daily scale were chosen from up to 17 meteorological stations (Table 1) located in the Cordillera Blanca range. The meteorological data were provided by the Peruvian Meteorological and Hydrological Service (SENAMHI) and the Agro Ancash organization (Carhuaz station). The time range chosen was between 1 January 1986 and 31 December 2019, covering a period of 34 years. These data series have been previously standardized (completed and homogenized) and subjected to detrending techniques in Fernández–Sánchez et al. [8].

Table 1. Meteorological stations used in the present study.

Meteorological Stations	Chosen Period	Variable	Altitude (m.a.s.l)
Aija	1999–2019	P., Max. T, Min.T.	3478
Cachicadan	1986–2019	P., Max. T, Min.T.	2885
Cajamarca	1986–2019	P., Max. T, Min.T.	2686
Cajatambo	1990–2019	P., Max. T, Min.T.	3405
Casapalca	1987–2019	Precipitation	4924
Carhuaz	1986–2016	P., Max. T, Min.T.	2644
Chavín	2000–2019	P., Max. T, Min.T.	3132
Chiquián	1986–2019	P., Max. T, Min.T.	3412
Dos de Mayo	2000–2019	P., Max. T, Min.T.	3474
Huamachuco	1986–2019	P., Max. T, Min.T.	3178
Huánuco	1986–2019	P., Max. T, Min.T.	1918
Matucana	1986–2019	P., Max. T, Min.T.	2417
Oyón	1986–2019	P., Max. T, Min.T.	3663
Pomabamba	1989–2019	P., Max. T, Min.T.	2975
A. Weberbahuer	1986–2019	P., Max. T, Min.T.	2666
Huaraz	1998–2019	P., Max. T, Min.T.	3071
Recuay	1986–2019	P., Max. T, Min.T.	3417

Precipitation (P), Maximum Temperature (Max. T) and Minimum Temperature (Min. T).

Indices of the various climatic forcings that most frequently affect the Cordillera Blanca were obtained. These data, recorded at various time scales (daily, monthly, and annually), were also subjected to spectral analysis techniques. Table 2 collects the indices used in this study. The forcings of solar activity, the Pacific decadal oscillation (PDO), the Choco low-level jet, the Caribbean low-level jet, and the South American monsoon system were not subjected to spectral analysis due to the large number of recent studies that have determined their periodicity, although they were used for comparison in the discussion section.

Spectral analysis allows data series to be decomposed into cycles that may be superimposed on temporal variability and that would be difficult to recognize with the naked eye. The three meteorological variables treated in this study were evaluated with the spectral analysis technique using the PAST software [9]. PAST is based on the Lomb–Scargle periodogram algorithm [10].

Table 2. Indexes and description of the main climate forcings indexes used in the study comparison.

Index	Region	Period
ONI Index (ENSO) [11]	Equatorial Pacific	1950–2021
SST Index [12]	El Niño 1+2	1982–2021
Humboldt Current [13]	7–9° S latitude	1997–2017
Sun radiation [14]	Global	1978–2019
ITCZ displacement [15]	90–60° W longitude	1979–2005
Bolivian High [16]	Bolivia	1979–2014
SALLJ [17]	Eastern Andes	1979–2018
Chocó LLJ [18]	Colombia North	1978–2010
Caribbean LLJ [19]	Caribbean Sea	1979–2010
MJO Index [20]	40° W longitude	1979–2021

3. Results

Tables 3 and 4 summarize the periodicities identified in the meteorological records spectral analysis. Very clear spectral signatures are detected in the periods of 122, 182, and 365 days, and these three values can be determined as the main periodicities.

Table 3. Identified periodicities for each meteorological variable in an intraseason, interseason, and annual scales.

Variable	Intraseasonal	Intraseasonal	Intraseasonal	Interseasonal	Interseasonal	Annual
Maximum T.	27–30 days	46–52 days	90 days	122 days	182 days	365 days
Minimum T.	27–30 days	46–52 days	90 days	122 days	182 days	365 days
Precipitation	No period	46–52 days	90 days	122 days	182 days	365 days

Table 4. Identified periodicities for each meteorological variable in interannual and inter-decadal scales.

Variable	Interannual	Interannual	Interannual	Interannual	Interannual	Interannual	Interdec.	Interdec.
Maximum T.	1 yr 3 m.	1 yr 6 m.	1 yr 9 m.	3 yr	4 yr 6 m	5.6–7 yr	11–12 yr	14–18 yr
Minimum T.	1 yr 3 m.	1 yr 6 m.	1 yr 9 m.	3 yr	4 yr 6 m	5.6–7 yr	11–12 yr	No period
Precipitation	No period	1 yr 3 m.	1 yr 9 m.	No period	No period	5.6–7 yr	11–12 yr	14–18 yr

"T" means temperature, "m" means months, "yr" means year and "interdec" means interdecadal.

The secondary periods are much more distributed in all the data series and are not coincident for all the variables or all the seasons. Therefore, the discernible secondary cycles for this study is 27 to 30 days, 42 to 50 days, 90 days, 1.3 years, 1.6 years, 1.9 years, 3 years, 4.5 years, 5 to 7 years, and 11 to 12 years.

The results of the climatic forcings spectral analysis are shown in Tables 5 and 6. No discernible spectral cycles were found in the existing data for the Caribbean low-level jet, the Bolivian Alta and the Chocó low-level jet.

Table 5. Periodicities found for each climatic forcing in the Cordillera Blanca region in annual, interannual, and interdecadal scales.

Index	Annual	Interannual	Interannual	Interannual	Interdecadal
ONI Index	1 yr	1 yr 5 m	3 yr 3 m.	4.7–5.5 yr	11 yr 10 m
SST Index	1 yr	NP	NP	4 yr	NP
Humboldt Curr.	1 yr 1 m	2 yr 3 m	NP	4 yr 6 m.	NP
ITCZ displ.	NP	NP	3 yr	NP	NP
SALLJ	1 yr 2 m	2 yr 7 m	NP	5 yr 6 m	9 yr 3 m
MJO Index	NP	NP	NP	NP	NP
ENSO	1 year	NP	NP	4.7–5 y	11 years

Where "NP" means No Periodicities, "m" means months, and "yr" means year.

Table 6. Periodicities found for each climatic forcing in the Cordillera Blanca region in intraseasonal and interseasonal scales.

Index	Interseasonal	Interseasonal	Interseasonal	Interseasonal	Interseasonal	Interseasonal
ONI Index	NP	NP	NP	NP	NP	NP
SST Index	NP	NP	NP	NP	NP	NP
Humboldt Curr.	NP	NP	NP	NP	6 m	10 m
ITCZ displ.	NP	NP	NP	NP	NP	NP
SALLJ	25 days	NP	NP	NP	4.7 m	9 m
MJO Index	21 days	36 days	1.5 m	2.5 m	3 m	NP
ENSO	NP	NP	NP	NP	NP	NP

Where "NP" means No Periodicities, "m" means months, and "y" means year.

4. Discussion

High spectral power periods were detected (122 days–4 months, 182 days–6 months, and 365 days–1 year) and exist in most of the stations for all the variables.

The period of 182 days has a good correspondence with the forcing of the intensification and de-intensification of the Humboldt Current, which according to the spectral analysis carried out, has a biannual behavior (6 months). ITCZ also has a biannual behavior in its displacement southwards in latitude, as some investigations have defined [21]. Correspondences in cycles of 182 days were also detected in Amazonia and the highlands of Ecuador [22], as well as in the Natuna Islands [23]. It is quite possible that the displacement towards the South in the ITCZ is the common factor of the three locations.

The 365-day period is the most powerful and is present in all the variables of all the seasons. It is likely that this general periodicity in the Cordillera Blanca is being led by the forcing activity of the ENSO events, the intensification of the Humboldt Current, and the sea surface temperature (SST), which have similar periodicities. In the latter case, the SST has an indirect correlation by influencing the ENSO and Humboldt Current forcings. Recent research has found periodicities of 365 days on the coast, Amazonia, and highlands of Ecuador, as well as in Kenya, Hungary, and the Natuna Islands [22,23], indicating that the influence could be global.

The 122-day period (4 months) has a good correspondence with the cyclicity found in the intensification and de-intensification of the Humboldt Current, as well as in the variability found in the present work for the South American low-level jet (SALLJ). From a climatic point of view, the period of 122 days is more notable in the precipitation variable. The Humboldt Current has an influence on the precipitation of the meteorological stations faced westwards, whereas the SALLJ influences the precipitation of the stations oriented to the East [24,25]. This period of 4 months has also been found in the Ecuadorian Amazon [22], determining the regional influence of the SALLJ.

The secondary periods detected on a monthly scale are the periods of 90 days (3 months), 72 days (2 months and 15 days), 46 days (1 month and 15 days), and 27 days. These periods seem to have a correspondence with the MJO (periodicities of 27 days, 45 days, 72 days, and 91 days), influenced by the modification of Outgoing Long-wave Radiation by the displacement of cloudiness [26] from of the propagation of Rossby waves [27]. Therefore, the 27-day cycle is similar to the 21-day cycle found for the SALLJ forcing and in solar activity [19,28]. The 90-day period has also been observed off the coast of Ecuador [22].

The periodicity of the activity of the Humboldt Current (13 months) and the SALLJ (14 months) are in good agreement with the cycle revealed for the maximum and minimum temperature of 1 year and 3 months, although these forcings have a greater influence on precipitation, potentially affected by the modification of cloud cover.

The interannual secondary periods are mainly influenced by the ENSO phenomena. In the present study, the ENSO yielded periodicities of 3 years and 3 months, close to the 3-year cycle present in the meteorological data, as well as periodicities of 4.7–5 years, close to the 4.5-year cycle of both temperature variables. The displacement of the ITCZ is also associated with the 3-year cycle, as it has a revealed periodicity of 3 years and

3 months. Both forcings are associated with a greater or lesser cloud cover, creating an increase or decrease in the maximum temperature, a variable with a greater number of 3-year periodicities. Ilyes et al. [22] and Herho et al. [23] also observed a cycle of 4.7–5 years on the coast of Ecuador and on the Natuna Islands, respectively, relating it to the ENSO and Indian Ocean Dipole events.

The ENSO would also be the main forcing influencing the meteorological periodicity of 5.6–7 years, as there is literature that reveals a period of 5 to 7 years [29,30], which was not found in the present study. After this cycle, a direct solar influence was also found in the maximum temperature or indirectly on the ENSO, as there are defined solar cycles between 5, 5.5, and 7.8 years [2]. In the Bolivian Altiplano, certain periodicities have been found that cover up to 7 years [30], although they are attributed to the precipitation variable.

The meteorological periodicity of 11–12 years is associated with solar variability cycles defined in 11 years [31], which have a great influence on short-term temperatures [32]. The existence of a "cascade" phenomenon from the triple Solar–SST–ENSO phenomenon is very likely, since periodicities of 11 years have been found in the SST [33] and in the ENSO in the present study.

The last cycle detected in the spectral analysis of the meteorological variables is the double cycle of 16 and 17 years, which corresponds to the variability of the PDO between 12 and 20 years [34].

It has not been possible to find the periodicity associated with the Bolivian High and the low-level Caribbean and Chocó jets, given that the data records on an annual scale prevent the revealing of cycles with spectral powers greater than significance. It is necessary to have data on a monthly or daily scale.

5. Conclusions

Spectral techniques have proven to be a good tool when assessing the periodicities associated with meteorological data and climate forcing data, allowing comparisons to be made on the influence of these forces on regional climate variability.

The present study has revealed that the main periodicities of 122, 182, and 365 days are associated with the influence of the SALLJ and the Humboldt current for the first cycle, the displacement of the ITCZ for the second, and a joint influence of ENSO and the SST in the last cycle.

Possible direct and indirect relationships between the MJO (and to a lesser extent the SALLJ) and the intra- and interseasonal scale periodicities of precipitation and temperature variables have also been revealed. Therefore, it has been possible to relate the joint influence of the activity of the Humboldt Current and the SALLJ in cycles close to the annual periodicity. In periodicities with an interannual scale, the main influences could be the ENSO phenomena in conjunction with solar activity, as well as the displacement of the ITCZ in the meteorological periodicity of 3 years. Interdecadal cycles are influenced by solar activity and PDO.

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