Lightning activity over Chilean territory

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Key Points:

- Spatial and temporal distribution of thunderstorm days is presented for the entire Chilean territory, based on data from WWLLN between years 2012 and 2018.

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Abstract

This work presents the spatial distribution and temporal variability of lightning activity over the continental territory of Chile by means of Thunderstorms days (Td), on the basis of 7 years (2012-2018) of lightning measurement from World Wide Lightning Location Network (WWLLN). Td are obtained separately for the 15 geopolitical regions of Chile, reporting the higher lightning activity in the northeastern region of the country with 85 thunderstorms days per year. These values are mainly located in the mountains between 2000 and 5000 m.a.s.l. where extensive mining activity is located and there are electrical facilities of great importance for Chile. The Td values obtained in this study update the information presented by the World Meteorological Organization (WMO) in 1953, so far the only one available for the entire Chilean territory. From the diurnal cycle analysis, there is a marked mono-modal behaviour of lightning activity in the afternoon for latitudes between 17°S and 26°S (regions XV, I and II) and a different behavior of lightning activity over the region between 40°S and 56°S (regions X, XI and XII) known as Chilean Patagonia, due to special weather conditions in that area. Furthermore, the seasonal analysis showed that the highest lightning activity occurs in January and February and the lowest activity takes place between June and August. Once again, the Chilean Patagonia showed a different behavior because the highest activity is presented in May and August, and the lowest in September. The analysis and results presented here contribute to the knowledge of lightning activity in the region that has not been characterized before and can serve as a basis for future research to determine the behavior of this natural phenomenon.

1 Introduction

Chile is located in the southern hemisphere in South America between 17.5°S and 56°S and 66°W and 76°W. The country has varied topographic characteristics and a climate that is strongly influenced by factors such as latitude, altitude, atmospheric dynamics and oceanic influence, which control some of the basic climatic variables such as temperature, pressure, wind, humidity and precipitation (Fuenzalida et al., 2005; R. Garreaud et al., 2013; Viale & Garreaud, 2015). From the 4270 km of length (from north to south), only 15% of the 4270 km is located in the tropical region, where the major lightning activity over the globe occurs - north of South America and the center of Africa - (R. Bürgesser et al., 2012; Burgesser et al., 2013; Avila et al., 2015; Torres et al., 2015; Herrera et al., 2017; Albrecht et al., 2016). Although most of the territory is in the subtropical region, high failure rates of overhead power lines of the transmission system (Montaña et al., 2019), deaths and tragedies due to lightning have been reported recently in local media.

The general perception is that lightning activity in Chile is non-existent, and as a result, unfortunately it has not been monitored as a meteorological variable in recent years by the Chilean meteorological service. Although the studies of electrical activity in South America by Nicora (2014) demonstrated atmospheric electrical activity in southern Chilean Patagonia, at first, these results were ruled out because it was believed that the microphysical and dynamic conditions were not appropriate for the generation of this level of activity. However, the joint work among climatologists, geophysicists and physicists (R. D. Garreaud et al., 2014) demonstrated the presence of atmospheric electrical activity for that region too.

Given its long latitudinal span (17.5°-56°S), Chile exhibits a wide variety of climate conditions, from hyper arid in the north, semi-arid Mediterranean in the center and temperate humid in the south. These climate regimes are influenced by some of the large-scale circulation systems in the Southern Hemisphere, namely the semi-permanent surface anticyclone over the subtropical southeast Pacific creating stable, dry conditions- and the westerly wind belt at middle latitudes steering rain-producing weather systems from the South Pacific. This general pattern is profoundly modified by the Andes cordillera running along the whole country and with its crest level just 150-200 km from the Pacific coast. Between 18°-35°S the Andes height surpasses 5000 m.a.s.l.; farther south the mean height decreases to about 1500 m.a.s.l., but many peaks are still over 3000 m.a.s.l. In the northern part of Chile, precipitation only falls over the high Andes during summer in connection with the South American monsoon (R. Garreaud et al., 2003). South of 30°S, forced ascent of the westerly flow over the Andes produce a marked precipitation enhancement increasing by a factor of 2-3 the mean precipitation from the coast to the top of the mountain (Viale & Garreaud, 2015).

The central part of Chile (30°-38°S) exhibits a Mediterranean climate with an annual average precipitation between 100 and 2000 mm depending on latitude and altitude (Viale & Garreaud, 2015), concentrated in the austral winter (May-September) and produced by cold fronts (Falvey & Garreaud, 2007) and atmospheric rivers (Viale et al., 2018). Lightning activity is present in this area, only during the passage of cold-core, cut-off lows in the upper troposphere (Fuenzalida et al., 2005) and atop the Andes during episodic summer storms fueled by moisture coming from the Atlantic (Viale & Garreaud, 2014). Farther south, the Midlatitude Storm track brings precipitation year round and generate accumulations from 2000 to more than 5000 mm/year over the windward slope of the Austral Andes. Notably, significant lighting activity has been reported over western Patagonia, especially during cold, post-frontal conditions when the tropospheric column can be slightly unstable (R. D. Garreaud et al., 2014). Likewise, convective activity during summer over the Altiplano, the high level plateau of the central Andes, brings thunderstorms to the high terrain of northern Chile (Falvey & Garreaud, 2006).

Based on this description of Chilean topographic and climate characteristics, it can be noted that the variability of the parameters, due to the great extension of the territory, yields different behaviors of meteorological variables, one of them being the atmospheric electrical activity. In (R. D. Garreaud et al., 2014; M. G. Nicora et al., 2014) the spatial distribution and temporal variability of lightning activity over the region extending from $\sim$ 40°S to 55°S along the west coast of South America (Western Patagonia) is presented. The analysis focused on this area because there is important electrical activity, despite the fact that the weather conditions are not suitable for cloud electrification (cool and hyper-humid maritime climate). The activity is not distributed over the Austral Andes or over the dry lowlands of Argentina where the precipitation achieves a maximum, but instead, it is located on the southern coast of Chile. In (Avila et al., 2015) the diurnal cycle of lightning activity over tropical and subtropical regions of South America is analyzed, taking into consideration only north of Chile because the lightning database is restricted between 35°N and 35°S. According to that study, the main lightning activity occurs between 14:00 and 18:00 local time which is associated with diurnal heating, but in the areas limited by 25°S-35°S of latitude and 50°W-70°W of longitude (North of Argentina), the maximum lightning activity occurs from midnight to early morning hours caused by cold outflows from earlier convection crossing the Andes mountain range. Due to the strongly latitudinal structure of the country, it is very important to take into account the influence of the Andes mountain range for this study. The prominent Andes mountain range induces significant differences in climates between its eastern (Argentine territory) and western (Chilean territory) slopes. (Viale et al., 2019) documented in a denoted way, the abrupt changes in precipitation and cloud properties at both sides of the Andes south of 20°S.

There are not many published studies of lightning activity, due to the reduced number of measurements available in Chile. Nonetheless, in the last two decades more measurements have become available. For instance, there is the World Wide Lightning Location Network (WWLLN) that started in 2003 (Lay et al., 2004) and has sensors in Chile since 2014 (Montaña et al., 2019), the GLD360 from Vaisala (Said et al., 2010), and the more continental network Sferics Timing and Ranging Network (STARNET) that has measured lightning in South America since 2006 (Morales et al., 2015). Moreover, satellite measurements from the Optical Transient Detector (OTD) and the Lightning Imaging sensor (LIS) (Christian et al., 1999, 2003), enable a worldwide climatology since 1995. Recently, the ISS LIS is available since 2017 (Blakeslee et al., 2020), and from 2018, the Geostationary Lightning Mapper (GLM) on board the GOES-16 satellite (S. Rudlosky et al., 2017) that captures the lightning optical emission every 20 seconds over North and South America, has been available.

The objective of this work is to correct the lack of data regarding lightning activity in Chile, updating the available information that comes from the WMO publications of 1953 and that, in many cases, has values close to zero. The information is presented in detail for each of the geopolitical regions in which Chile is divided, which is important for climatological analysis and engineering applications of the energy sector, because Td values are used to compute the Ground Flash Density (Ng) for regions without lightning measurements, as it is the case of Chile. In addition, a methodology is presented for calculating thunderstorm days for a terrestrial network which can be used with another lightning technology such as GLM on GOES-16 and 17. Furthermore, these results respond to the request of the WMO to consider lightning as an essential climate variable, in order to know parameters' variation and its relationship with climate change. A seasonal and temporal analysis of lightning activity over entire Chilean territory is presented, with a specific attention in the Chilean Patagonia. The analysis includes a comparison at both sides of the Andes mountain, eastern side (Argentina) and western side (Chile). The description of the WWLLN location system, the number of sensors, the detection efficiency and general remarks are presented in section II. Section III and IV present the lightning parameters obtained from lightning location systems (LLS), and the analysis of results, finally, concluding remarks are presented in section V.

2 Lightning Location System

Since the WWLLN has sensors in Chile and provides data for the entire Chilean territory, this lightning location system will be utilized for the purposes of this study. WWLLN is a lightning detection network that started in 2003 with 11 sensors. Nowadays, it has more than 70 sensors installed in all five continents and few islands. WWLLN uses sensors that measure the vertical electrical field emitted by lightning discharges in the very low frequency (VLF) range of 6 to 22 kHz (Dowden et al., 2002). At least five sensor signals are required to locate a discharge (Abarca et al., 2010). The lightning signals are analyzed in terms of the phase slope to compute the Time of Group Arrival (TOGA) for every lightning stroke identified. Each sensor sends the TOGA information to the central station that combines the different arrival times to locate the discharges.

According to a validation study conducted in the United States during the period of 2006-2009 (Abarca et al., 2010), the WWLLN initially showed a cloud-to-ground flashes detection efficiency (DE) of 3.88% in 2006-2007 and in the period of 2008-2009 DE increased to 10.3%, compared to the National Lightning Detection Network (NLDN). Moreover, this study also showed that the DE was strongly dependent on peak current and polarity. For instance, when the peak current is higher than ± 35 kA the DE is above 10%. When it is between 0 and -10 kA, the DE is less than 2%. Using the TRMM/LIS as a reference (S. D. Rudlosky & Shea, 2013) observed that the DE of WWLLN improved from 6% to 9.2% during the period of 2009 to 2012. Also, WWLLN was approximately three times more likely to detect LIS flashes that occurred over the oceans (17.3%) compared to those occurring over land (6.4%). Later, using the stroke detected energy, (Hutchins et al., 2012) showed that the global average relative detection efficiency[1] increased from 35% in 2009 to 50% in 2011 due to the addition of new VLF stations along this period. Moreover, the corrected global absolute detection efficiency for cloud to ground and in-cloud flashes was 13.7% for 2010 and 13.0% for 2011. Later, (R. E. Bürgesser, 2017) compared WWLLN against TRMM/LIS during the period of 2012-2014 and found that despite the low WWLLN stroke detection efficiency, its performance was good enough to detect the main features of the tropical lightning (i.e., thunderstorms). Moreover, both lightning density maps (WWLLN-strokes and TRMM/LIS-flashes) showed similar spatial distribution with high time correlation. Finally, it was shown that the WWLLN had a mean flash multiplicity of 1.5.

3 Thunderstorm days (Td)

Over the years, the main climatological variable related to thunderstorm activity has been the thunderstorm day (Td). This standard meteorological parameter was defined by the International Meteorological Committee (IMO), the predecessor of the WMO, as any day in which the observer heard thunder without discriminating if the discharge was cloud-cloud or cloud-ground and regardless of the intensity of the storm and the occurrence of precipitation (Scott & Everett, 1878). This definition depends on the possibility of hearing thunder which, according to (Fleagle, 1949) is likely in a radius of approximately 25 km if thunder originates 4 km above the surface.

The human observation threshold was an intrinsic and subjective parameter in the data obtained from meteorological stations, but when the information comes from lightning location systems, the analysis has to define the size of grid cell for lightning thunder audibility in order to compute the Td values. In (Rakov & Uman, 2007) was mentioned that a possible range of audibility of thunder is about 15 km; additionally, it mentioned that the maximum range of audibility is typically about 25 km. In (M. Nicora, 2014), an analysis of the information from meteorological stations in Argentina for the period of 2005-2011 was carried out, to define a better range for thunder audibility (50 km, 25 km, 20 km or 15 km) in order to obtain the Td values based on WWLLN data. Data from 15 meteorological stations spread over the Argentinian territory were used. This analysis concluded that among 50, 25, 20 and 15 km, the 25 km grid size showed similar Td values compared with human observation for the stations under analysis. In (Czernecki et al., 2016), the authors made a comparison between a local lightning detection network in Poland and human observation. The conclusion was that the threshold value of the human average observational thunderstorm detection range is between 16.9 km to 18.3 km. In order to define the threshold value of the human observation to obtain the Td values for Chilean territory, the first step was to find information of thunderstorms days at local meteorological stations. The information is available from 1941 until 2011 for 59 land stations, but unfortunately, the truthfulness of the information is not verifiable because many stations have zero or no values because they were unattended for a long time.

For this study, the threshold value of 15 km for the human observation was considered, based on previous results (Rakov & Uman, 2007). The entire area of the Chilean territory was divided into equally spaced gridded cells of 30 km x 30 km, using the Universal Transverse Mercator coordinate system (UTM). For this study, Td represents the number of days with at least one WWLLN stroke detected in equally spaced gridded box defined before. The results of thunderstorm days are presented in Figure 1 for WWLLN data. The maximum values of Td are located in the northeastern region of the country

[1] "The relative detection efficiency is a measure of how well a given location in the network is being observed relative to the best region in the network. In a given grid cell the network MDE is compared to the total WWLLN energy distribution of the past seven days" (Hutchins et al., 2012)

Station	LAT.	LONG.	Td(WMO)	Td (WWLLN)
Arica	18°28’S	70°20’W	0	14
Iquique	20°12’S	70°11’W	*	10
Canchones	20°25’S	69°35’W	1	10
Colonia Pintados	20°37’S	69°39’W	1	8
Antofagasta	23°39’S	70°25’W	*	6
Refresco	25°19’S	69°52’W	*	6
Taltal	25°25’S	70°34’W	1	4
Potrerillos	26°30’S	69°27’W	1	11
Caldera	27°03’S	70°58’W	1	5
Copiapo	27°21’S	70°21’W	*	5
Vallenar	28°34’S	70°47’W	*	5
La Serena	28°54’S	71°15’W	*	3
Punta Tortuga	29°55’S	71°22’W	1	3
Vicuña	30°02’S	70°44’W	0	3
Ovalle	30°36’S	71°12’W	*	4
Zapallar	32°33’S	71°30’W	1	2
Jahuel	32°41’S	70°29’W	*	6
Los Andes	32°50’S	70°37’W	2	6
Llay Llay	32°50’S	70°59’W	*	3
Juncal	32°52’S	70°10’W	*	17
Quillota	32°53’S	71°16’W	1	4
Valparaiso	33°01’S	71°38’W	1	4
Peña Blanca	33°03’S	71°23’W	*	4
Santiago	33°27’S	70°42’W	3	6
San Jose de Maipo	33°38’S	70°22’W	2	8
El Teniente	34°06’S	70°22’W	1	12
Rancagua	34°10’S	70°45’W	4	5
Peuco	34°24’S	71°11’W	1	4
Rengo	34°24’S	70°52’W	4	5
San Fernando	34°35’S	71°00’W	2	5
Curico	34°59’S	71°14’W	1	4
Molina	35°05’S	71°16’W	1	5
Constitucion	35°20’S	72°26’W	2	3
Talca	35°26’S	71°40’W	1	4
Puente Carranza	35°36’S	72°38’W	1	5
Panimavida	35°45’S	71°24’W	3	5
Linares	35°51’S	71°36’W	*	5
Cauquenes	35°59’S	72°22’W	*	4

Table 1: Thunderstorm days in the north of Chile. Comparison between WMO (1953) and WWLLN data. Symbol $*$ means less than half a day.

(Arica region), near the border between Chile and Bolivia, with a value of 85 thunderstorm days per year. In the center of the country, around the metropolitan region of Santiago (32°S), the maximum value is 17. This figure shows high values of Td over the Andean mountain chain and low values near the sea shore. This behavior occurs for latitudes between -16°up to -45°, however the behavior is the opposite between -45°up to -56°, where the high values are presented in the sea shore, reaching up to 20 thunderstorm days per year. Tables 1 and 2 compare Td values obtained from the WWLLN with the previous keraunic level presented by (WMO, 1953). The Td values from WWLLN show higher values than the previously reported by WMO. Note that the WMO data were created in 1953, but it is the only information available for the entire Chilean territory. These comparisons show that the values reported by the WMO were highly dependent on the veracity of the information provided by each country, for example how many hours a day and how often the meteorological stations were attended. For the Chilean territory, the values reported by WMO were often zero or very close to zero, which probably did not reflect the real behavior of electrical activity in the country for that period.

Station	LAT.	LONG.	Td(WMO)	Td (WWLLN)
Tumbes	36°37'S	73°06'W	2	7
Talcahuano	36°43'S	73°07'W	1	5
Concepcion	36°50'S	73°03'W	2	4
Isla S. Maria	36°59'S	73°32'W	2	5
Punta Lavapie	37°08'S	73°35'W	2	5
Los Angeles	37°28'S	72°21'W	1	6
Lebu	37°37'S	73°40'W	3	6
Angol	37°49'S	72°39'W	*	5
Contulmo	38°02'S	73°13'W	3	7
Traiguen	38°15'S	72°40'W	1	7
Isla Mocha	38°22'S	73°54'W	1	7
Lonquimay	38°26'S	71°15'W	7	10
Puerto Dominguez	38°54'S	73°14'W	3	6
Valdivia	39°48'S	73°14'W	8	7
Punta Galera	40°01'S	73°44'W	4	7
Rio Bueno	40°20'S	72°55'W	3	6
Puerto Montt	41°28'S	72°57'W	3	5
Maullin	41°37'S	73°35'W	2	7
Punta Corona	41°47'S	73°52'W	4	7
Morro Lobos	42°03'S	73°24'W	6	8
Isla Gualo	43°34'S	74°45'W	3	4
Isla Falsa Melinka	43°54'S	73°46'W	6	5
Puerto Aysen	45°24'S	72°42'W	1	4
Cabo Raper	46°50'S	75°35'W	4	6
San Pedro	47°43'S	74°55'W	7	8
Puerto Consuelo	51°38'S	72°41'W	1	2
Punta Dungenes	52°24'S	68°26'W	1	3
Islote Evangelistas	52°24'S	75°06'W	2	5
Punta Arenas	53°10'S	70°54'W	*	2
Cabo San Isidro	53°47'S	70°58'W	1	2
Isla Navarino	55°10'S	67°30'W	*	2

Table 2: Thunderstorm days in the south of Chile. Comparison between WMO (1953) and WWLLN data. Symbol $*$ means less than half a day.

Figure 1: Maps of mean annual thunderstorm days for the Chilean territory for years 2012-2018 in the north part of the country (left) and in the south part of the country (right). The geopolitical divisions of Chile in white color.

Figure 2: Statistical values of mean annual thunderstorm days estimated for each geopolitical region of Chile shown earlier in Figure 1 and ordered by latitude.

As a complement, Figure 2 shows the inferred annual Td values ordered by latitude for Chilean territory, showing minimum, mean and maximum values for each of the 15 geopolitics regions of Chile. The DE over the Chilean territory has not been yet computed for years 2012-2018, but this will not considerably affect the retrieved Td values since we are not considering the lightning density in this study. The DE values for this period have to be analysed in future studies.

Chilean Patagonia has been analyzed separately because its weather conditions are not suitable for cloud electrification (cool and hyper-humid maritime climate) (R. D. Garreaud et al., 2014), however, concentrated lightning can still be present in this area. Chilean Patagonia extends from 40°to 56°S along the west coast of South America, see Figure 1. Its maximum Td value is 20 (see Figure 2), which is located in [47.5°S, 74.3°W], even this value is greater than those registered for the central Chilean territory. According to (R. D. Garreaud et al., 2014), the Coast of Golfo de Peneas (47.5°S) presents the local maxima for lightning flash density and number of thunderstorm days (in (R. D. Garreaud et al., 2014) used the term: "Lightning-days"), which coincides with our analysis. Moreover, lightning activity in this area is located over the sea shore, far from the Austral Andes and the massive Northern and Southern Patagonia Ice Field (R. D. Garreaud et al., 2014) as shown in Figure 1. That study (R. D. Garreaud et al., 2014) attributes this behavior to the surface boundary condition over the adjacent Pacific with waters warmer than those over open ocean, generating the conditions for instability buildup, favorable for cloud electrification.

4 Seasonal and Daily Variation

In order to determine how the lightning activity is distributed over Chilean territory, the inferred Td mean values (presented in Figure 2) were disaggregated for 15 geopolitical regions during the 12 months of the year based on the same data from WWLLN. The distribution of the Td mean values during the year is presented in Table 3. The maximum and minimum vales are highlighted for every geopolitical region in order to compare the behaviour for different latitudes. These results show that the regions from Arica (XV) (18°S) to Araucania (IX) (39°S) follow the same behaviour; the thunderstorms days are higher during the summer (December to February) and lower during the winter (June to August). On the other hand, the behavior in Chilean Patagonia (40°- 56°S) does not follow the same tendency, because the maximum values of thunderstorm days take place in August (Los Rios(XIV) and Los Lagos(X)) and May (Aysen(XI) and Magallanes(XII)) and minimum values take place in September (first month of the spring season). The monthly Td values in Chilean Patagonia do not show significant variation during the year (see Table 3).

On earlier analysis of lightning activity over South America based on LIS data, (Avila et al., 2015) showed that the maximum lightning activity (across all seasons) was predominantly between 14:00 and 18:00 LT, which can be associated to local diurnal heating that is more effective in land masses. Unfortunately, these results did not cover the entire Chilean territory due to LIS coverage limitation (± 38°N/S). Therefore, we presented a daily analysis extending over the entire territory and divided into 15 regions.

The strokes were analyzed separately for every geopolitical region of Chile and classified in 24 hourly-segments, to examine the lightning activity per hour during the day.

Reg.	J	F	M	A	M	J	J	A	S	O	N	D
XV	10	10	8	4	$*$	$*$	$*$	$*$	1	2	2	7
I	6	6	4	1	$*$	$*$	$*$	$*$	$*$	1	1	3
II	4	4	2	1	$*$	$*$	$*$	$*$	$*$	$*$	1	2
III	3	2	1	$*$	$*$	$*$	$*$	$*$	$*$	$*$	$*$	1
IV	2	1	$*$	$*$	$*$	$*$	$*$	$*$	$*$	$*$	$*$	1
V	2	1	1	$*$	$*$	$*$	$*$	$*$	$*$	$*$	1	1
XIII	2	1	1	1	$*$	$*$	$*$	$*$	$*$	$*$	$*$	1
VI	1	1	$*$	$*$	$*$	$*$	$*$	$*$	$*$	$*$	1	1
VII	1	1	$*$	$*$	$*$	$*$	$*$	$*$	$*$	$*$	1	1
VIII	1	1	$*$	$*$	1	1	$*$	1	$*$	$*$	1	1
IX	2	1	1	1	$*$	$*$	$*$	1	$*$	$*$	1	1
XIV	1	1	$*$	1	1	$*$	1	1	$*$	$*$	1	1
X	$*$	$*$	$*$	1	1	$*$	1	1	$*$	$*$	$*$	1
XI	$*$	$*$	$*$	1	1	$*$	$*$	1	$*$	$*$	$*$	$*$
XII	$*$	$*$	1	$*$	1	$*$	1	$*$	$*$	$*$	$*$	$*$

Table 3: Monthly mean Td values for regions of Chile ordered by latitude. All values were approximated to their nearest integer. The symbol $*$ means a value less than half a day. Maximum values in red and minimum values in blue for every region.

Figure 3: The percentage of daily total strokes per hour. Regions XV, I and II. The number of strokes for the maximum value during the day is presented.

The results were presented in local time ($UTC-4$) showing that the highest lightning activity during the day is between 14:00 and 20:00 hours (almost 60% of strokes) and the lowest activity is between 6:00 and 11:00 hours (almost 6%), with a similar behavior for the four seasons. From the results presented in Figures 3 to 7, it is possible to note differences in lightning activity between two areas. First, regions XV, I, II, (17°- 26°S) present a mono-modal behavior with high lightning activity between 13:00 and 20:00 reaching the maximum activity at 16:00 local time (Figure 3), which is a characteristic of diurnal heating convection (Williams et al., 2000; Virts et al., 2013; Avila et al., 2015). On the other hand, between regions III and XIV (26°- 40°S) a midnight, early morning and afternoon maximum in lightning activity is observed, which combines diurnal heating and mountain-valley/water body circulations (Virts et al., 2013). According to (Virts et al., 2013), the nighttime lightning in the Andes is observed in the eastern side of the mountain top (Argentina), but not on the west side of the Andes (Chile). However, regions between III to XIV (26°- 40°S) presented in Figures 4, 5 and 6 show a different behavior in the period 2012 to 2018, i.e., the nighttime lightning is observed also in the west side (Chilean territory). On the other hand, in regions X, XI and XII (southern regions of Chile 40°- 56°S), there is no clear diurnal cycle, and the lightning activity is slightly higher in the afternoon hours.

Figure 4: The percentage of daily total strokes per hour. Regions III and IV. The number of strokes for the maximum value during the day is presented.

Figure 5: The percentage of daily total strokes per hour. Regions V, VI, VII and XIII. The number of strokes for the maximum value during the day is presented.

Figure 6: The percentage of daily total strokes per hour. Regions VIII, IX and XIV. The number of strokes for the maximum value during the day is presented.

Figure 7: The percentage of daily total strokes per hour. Regions X, XI and XII: Chilean Patagonia. The number of strokes for the maximum value during the day is presented.

Taking into consideration the differences in the behavior of lightning activity between the northern zone and the central and southern zones of the Chilean territory, a detailed analysis of this area is presented in Figure 8. This figure shows the hourly zonal (every 0.1°) thunderstorm activity observed between 76°W to 66°W for every 2°of latitude from 17°S to 55°S. In addition to the differences between the areas of Chile, the differences between Chile and Argentina (eastern side of the Andes) are analyzed. Fundamentally, it shows how often thunderstorms are observed on an hourly basis for every 0.1°of longitude and 2°of latitude. The detailed analysis allows to determine what is controlling the lightning activity in every region, mainly due circulation and cyclogenesis (cut-off), orography (mountain/valley) and to a lesser extent due to the diurnal heating, (Virts et al., 2013; R. D. Garreaud et al., 2014; Avila et al., 2015; Albrecht et al., 2016). To help the interpretation of the diurnal variation, the mean number of thunderstorm days every 0.1°of longitude and the longitude position of the maximum altitude over that latitude belt is presented. A very well pronounced diurnal cycle modulated by diurnal heating and topography effect is specially observed in the eastern side of the Andes (Argentina), from 17°S to 29°S, which triggers a nighttime convection that lasts for several hours, especially in the plateau. As the afternoon convection kicks off, the thunderstorms are boosted as crossing the Andes mountain range. In the western side (Chile), the diurnal cycle is less marked from 17°S to 41°S, which is governed by the arrival of synoptic systems. In the western side of the Andes, the maximum lightning activity occurs in the evening hours and is located in the mountain and valleys.

Further south, from 41°S to 55°S along the west coast of South America, there is a complex geography, full of small islands and fjords limited to the east by the Andes, which has heights up to 2000 m. Lightning activity tends to occur when the Chilean Patagonia is immersed in a pool of cold air behind a front that reaches the coast at 40°S. Forced uplift of the strong westerlies impinging on the coastal mountains can trigger convection and produces significant lightning activity in this zone (R. D. Garreaud et al., 2014). This important lightning activity is marked between 45°S and 53°S with maximum values in the Taitao Peninsula (46.5°S), islands of Madre de Dios (50°S) and the coast of Golfo de Penas (47.5°S) in agreement with the annual thunderstorm days values presented in Figures 1 and 2.

Figure 8: Hourly zonal thunderstorm activity for every 2 degrees of latitude. The color scale shows the thunderstorm frequency of occurrence (as a %) every hour (local time) and 0.1 degrees of longitude. The mean number of thunderstorm days every 0.1 degrees of longitude in black line. The dashed horizontal lines indicate 6:00 h and 18:00 h in local time. The vertical red line indicates the position of the maximum altitude over that latitude belt.

5 Conclusions

The analysis presented in this study used the information obtained from a global lightning location system during seven years (2012-2018) in order to obtain the thunderstorm days and seasonal variations for 15 geopolitical regions of Chile . The results obtained from the WWLLN showed a marked lightning activity in the north of Chilean territory, the area of the country located in the tropical zone, mainly concentrated in the afternoon (14:00 - 20:00) for the summer season. The highest value of thunderstorm day in that zone is 85 (17°S) located in the Andes mountain. In the central zone of the country, from (28°S to 42°S), the Td varies from 5 to 12 days in the year, regardless of the time of day. The lightning activity is concentrated in summertime with maximum values located in the Andes mountain. In the same latitudes of the Argentine territory a pronounced diurnal cycle modulated by diurnal heating and topography is specially observed on the eastern side of the Andes, with more than 24 thunderstorm days per year. From 42°S to 48°S, despite the absence of a diurnal cycle to the west of the Andes, the presence of bays and land masses over the coast help to increase the number of thunderstorms days, from 6-9 to 12 a year. Further south, in the Chilean Patagonia (48°S to 58°S) the maximum number of Tds west of the Andes indicates that topography is the main triggering mechanism for thunderstorms development as cyclogenesis propagates eastward. In this area, the daily activity exhibits a nearly constant behavior during all day, slightly higher in the afternoon, with up to 20 thunderstorm days per year. Additionally, the analysis of this seasonal variation showed that the lightning activity in Patagonia is fairly evenly distributed during the year with low values on September. This behavior cannot be generalized due to the low number of thunderstorm days in that zone. Further exploration requires additional years of analysis to confirm.

The methodology to obtain the values of thunderstorms days for all Chilean territory had an additional consideration, every cell has the same area in km^2 based on a UTM coordinate system. The size of every cell considering the human threshold was 30 x 30 km^2. The results are more consistent, because this consideration allows Td values to be calculated uniformly for low and high latitudes, which was relevant for this study because subtropical zones were being analyzed. Using the conventional methodology, cells of equal size in earth degrees, would cause to underestimate the results mainly for the southern regions of the country. Despite the low values of stroke detection efficiency reported for the WWLLN, the seasonal and spatial variation and the thunderstorms days are less affected by the lightning location system performance, consequently the results presented here are reliable. The detection efficiency values for the Chilean territory have not been previously calculated, therefore they should be obtained in future studies.

The only information available for the entire Chilean territory regarding thunderstorm days dates from 1953 from the World Meteorological Organization. The values reported there often represented values of zero or close to zero for the Chilean territory. When comparing such values with the results of this study, it was observed that the WWLLN values are higher, thus concluding that the WMO values were highly dependent on the veracity of the information provided by each country regarding the meteorological station operation. Therefore, the results presented in this study update that information, the analysis contributes to the knowledge of lightning activity in the region and can serve as a basis for future research to determine the way this natural phenomenon behaves, which is important for both climatological analysis and engineering purposes. It is necessary to continue analyzing the information from available networks (WWLLN, STARNET and GLM), to update the lightning activity values for the Chilean territory and determine the detection efficiency of the networks, either by comparing data among them or by local measurement (video-cameras, lightning strike counters or instrumented towers).

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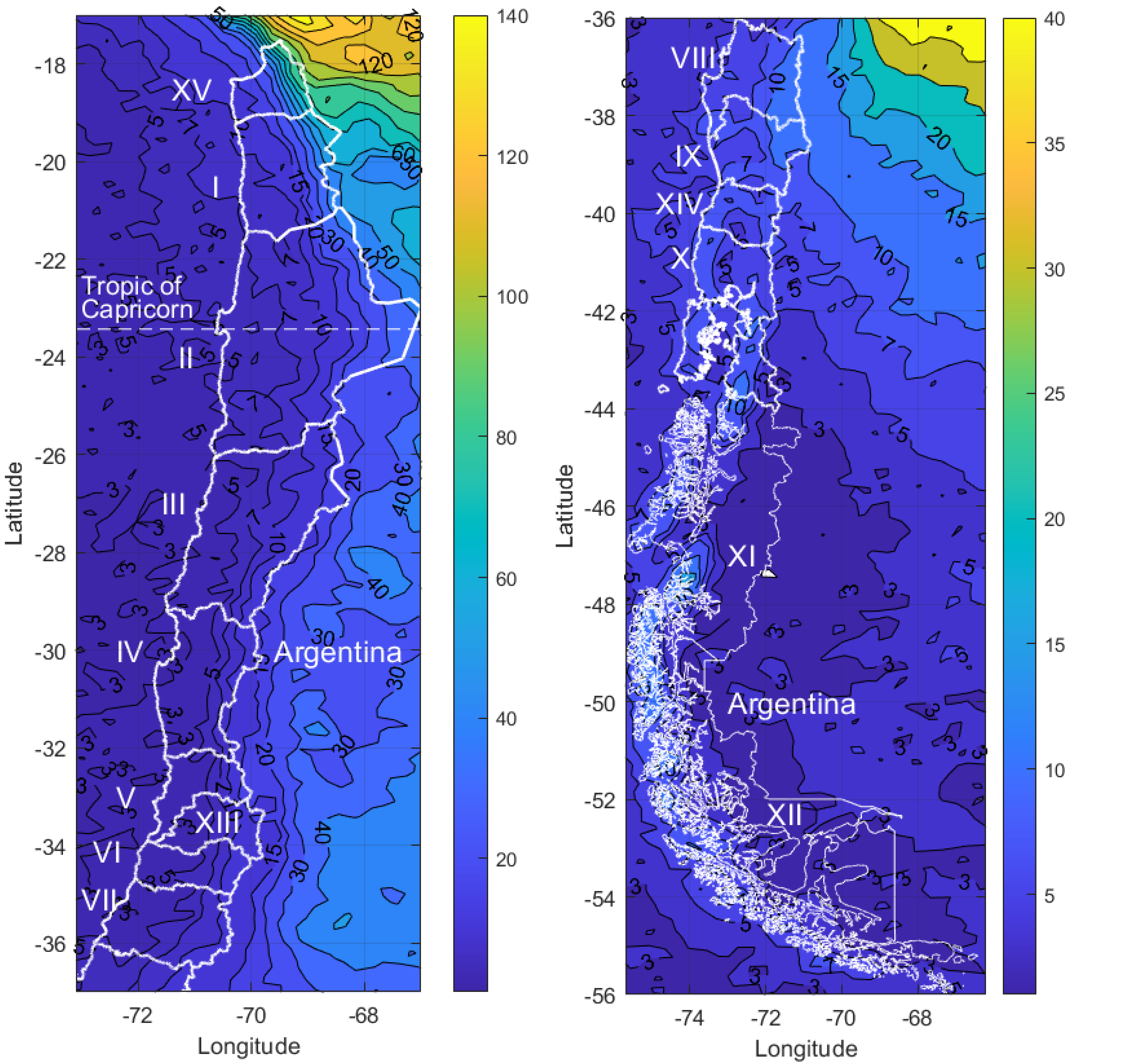

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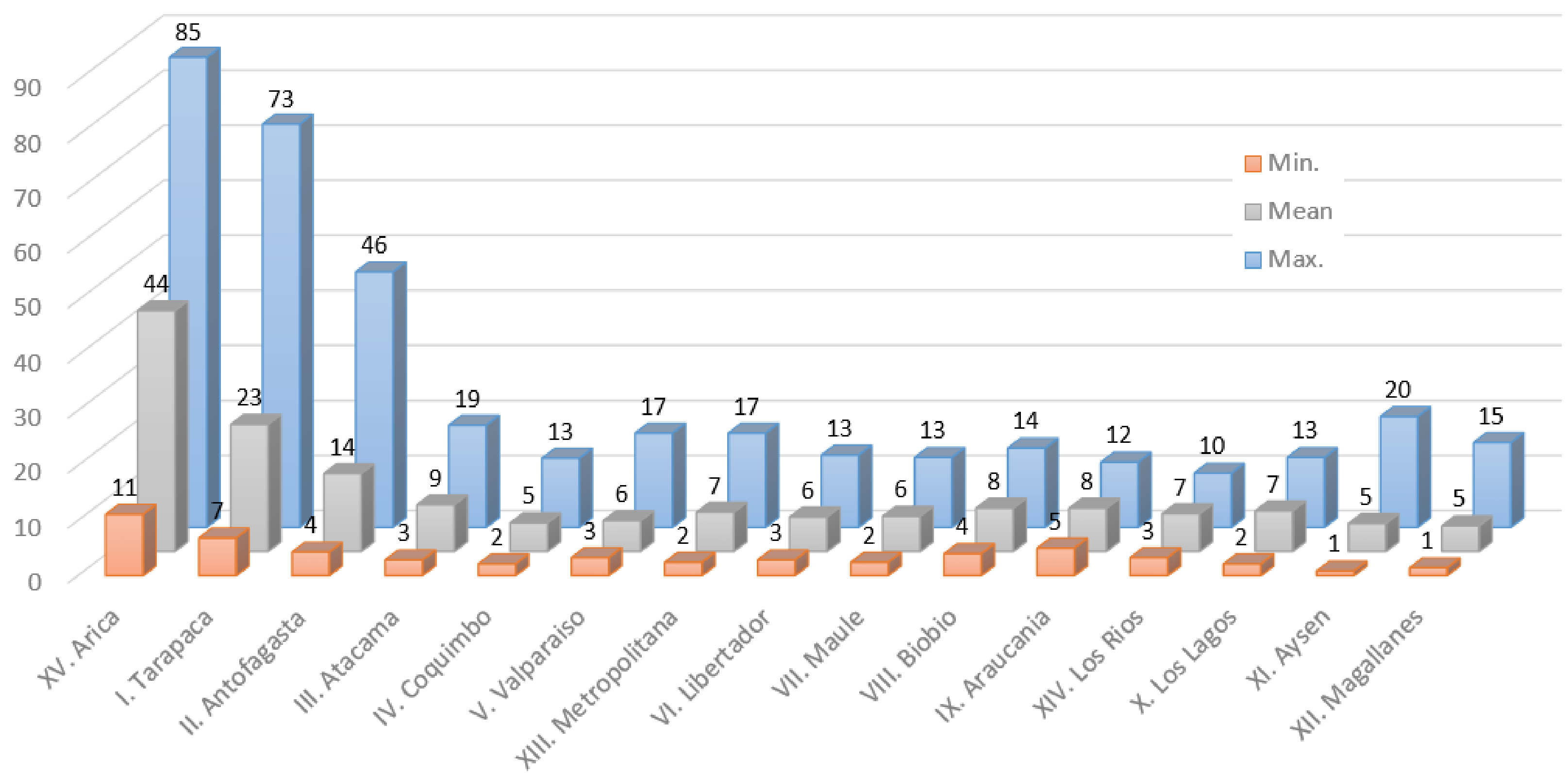

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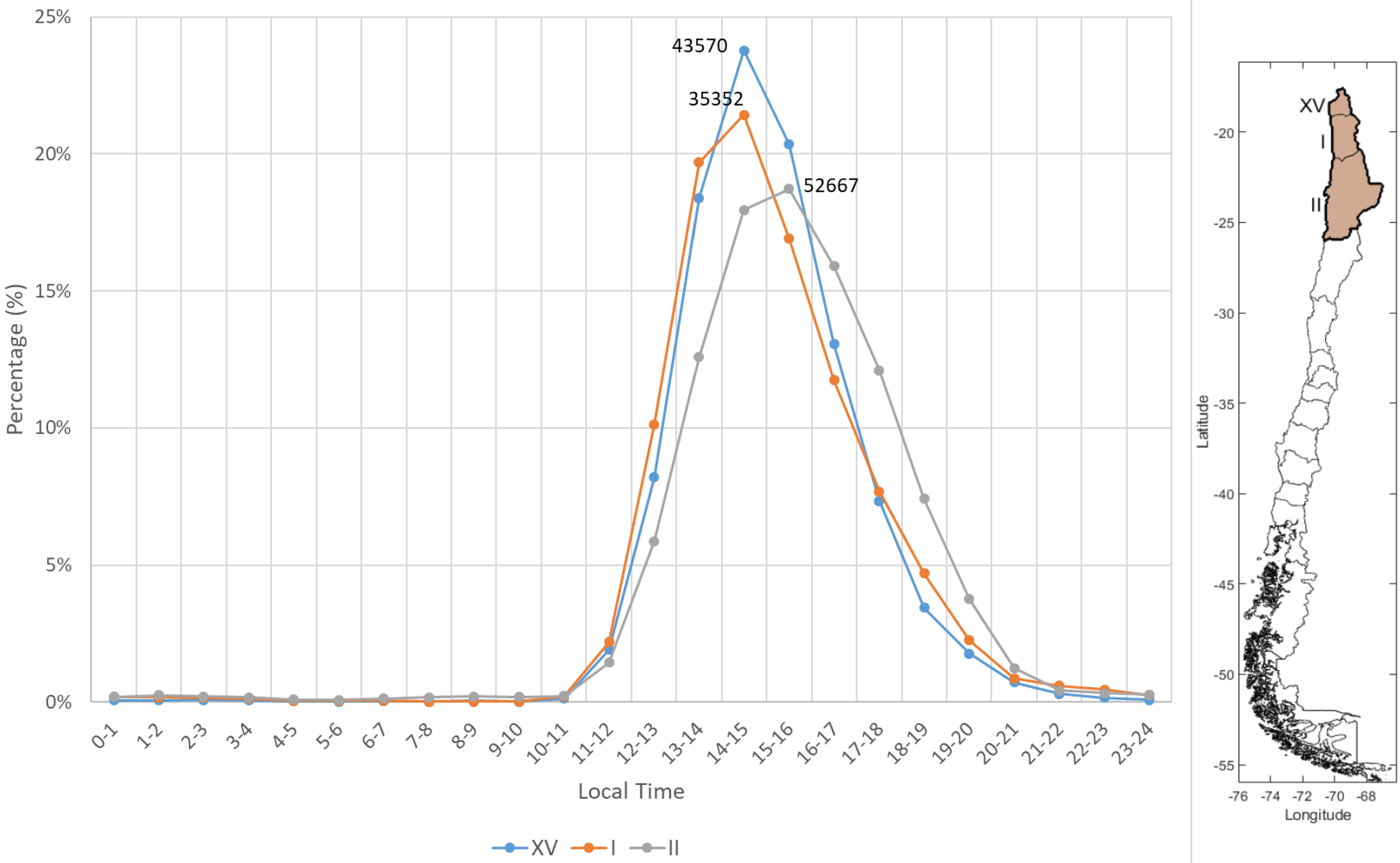

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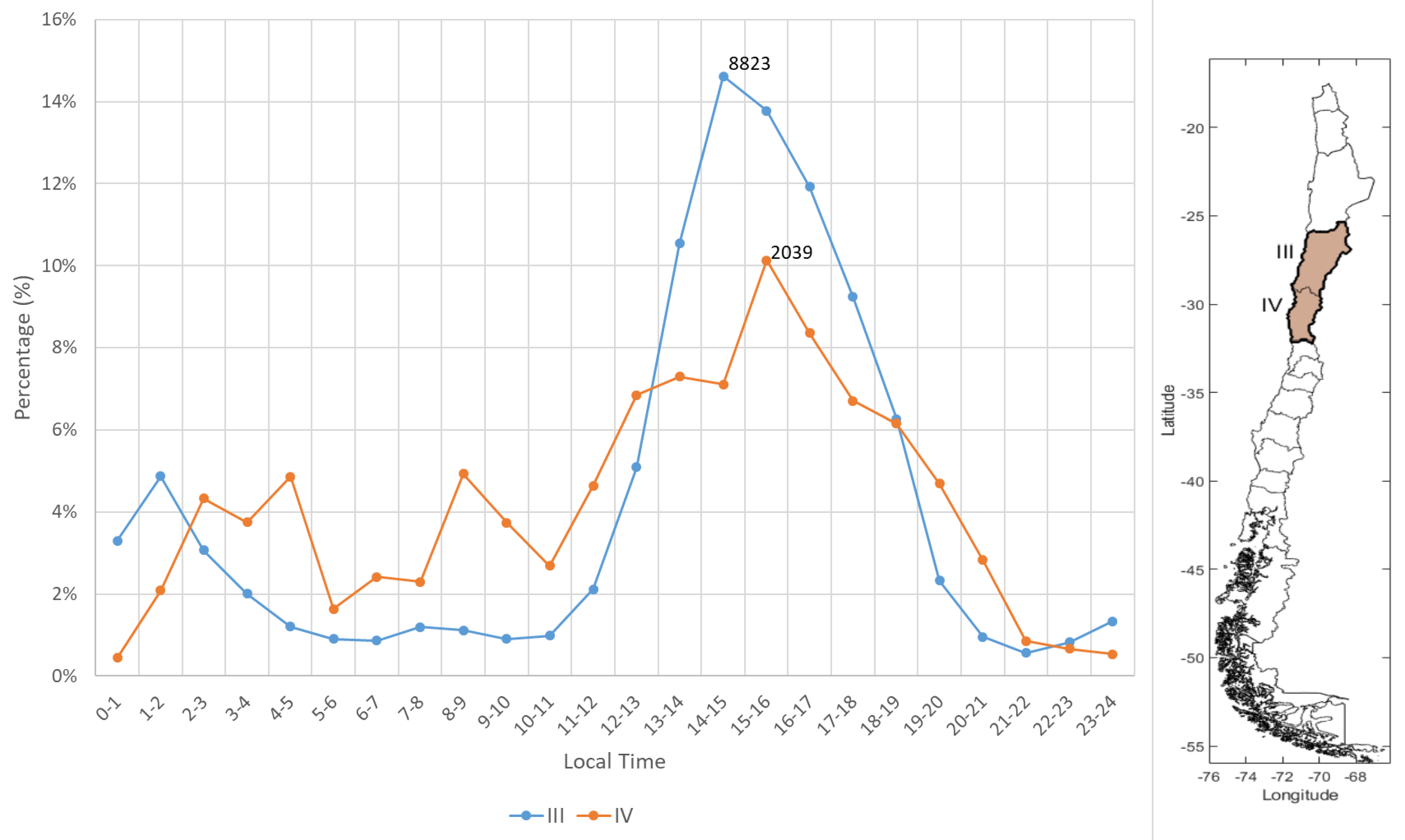

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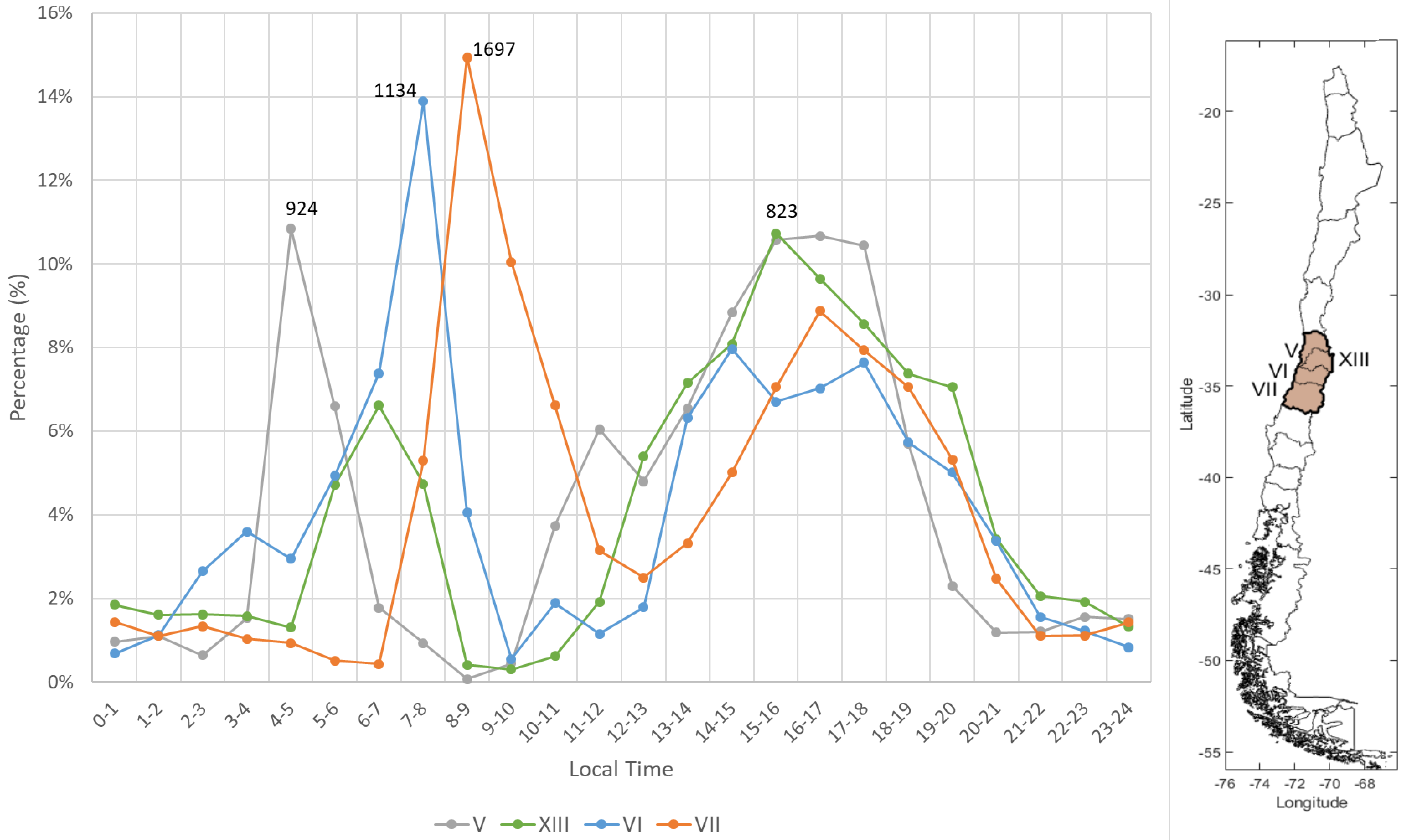
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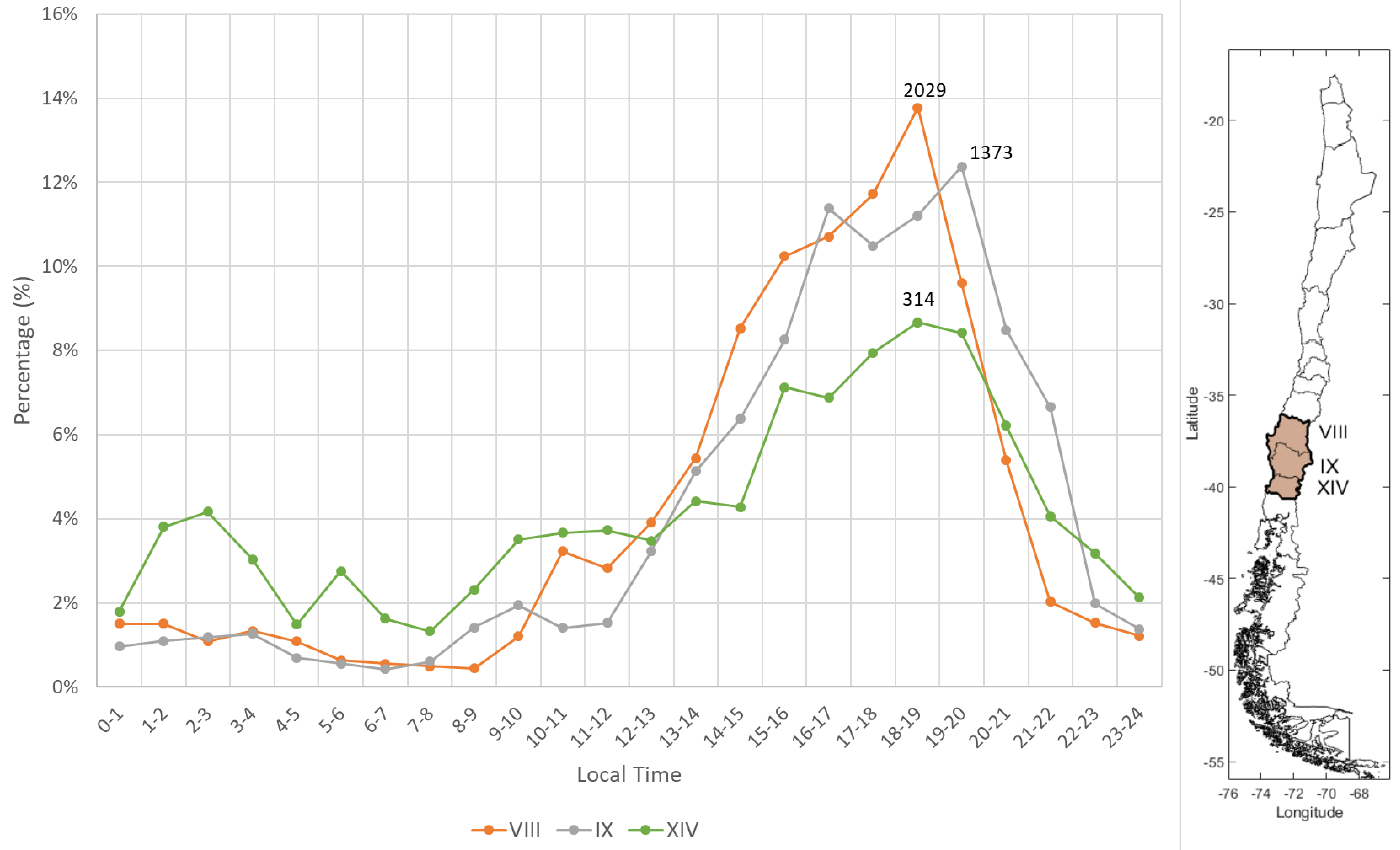

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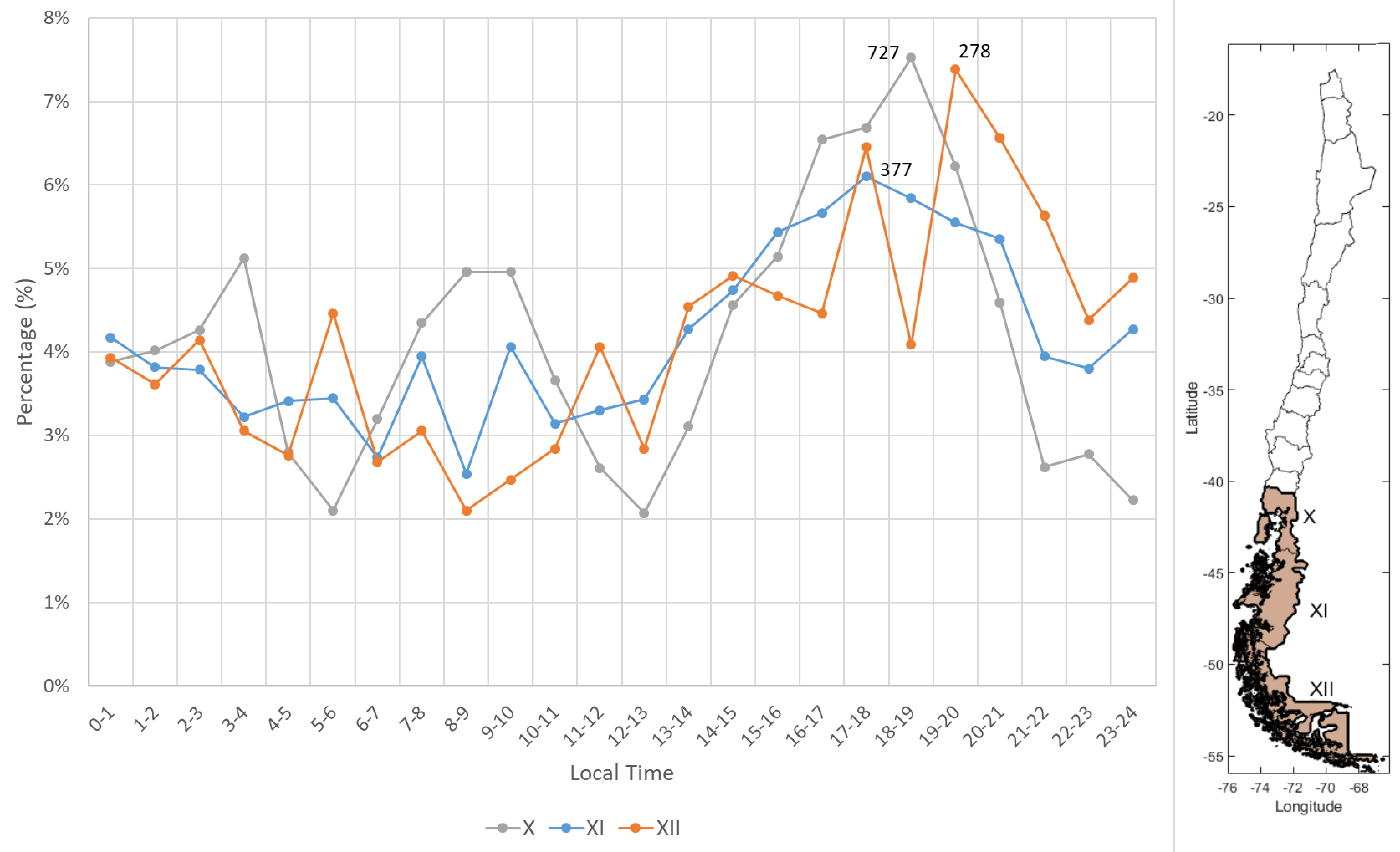

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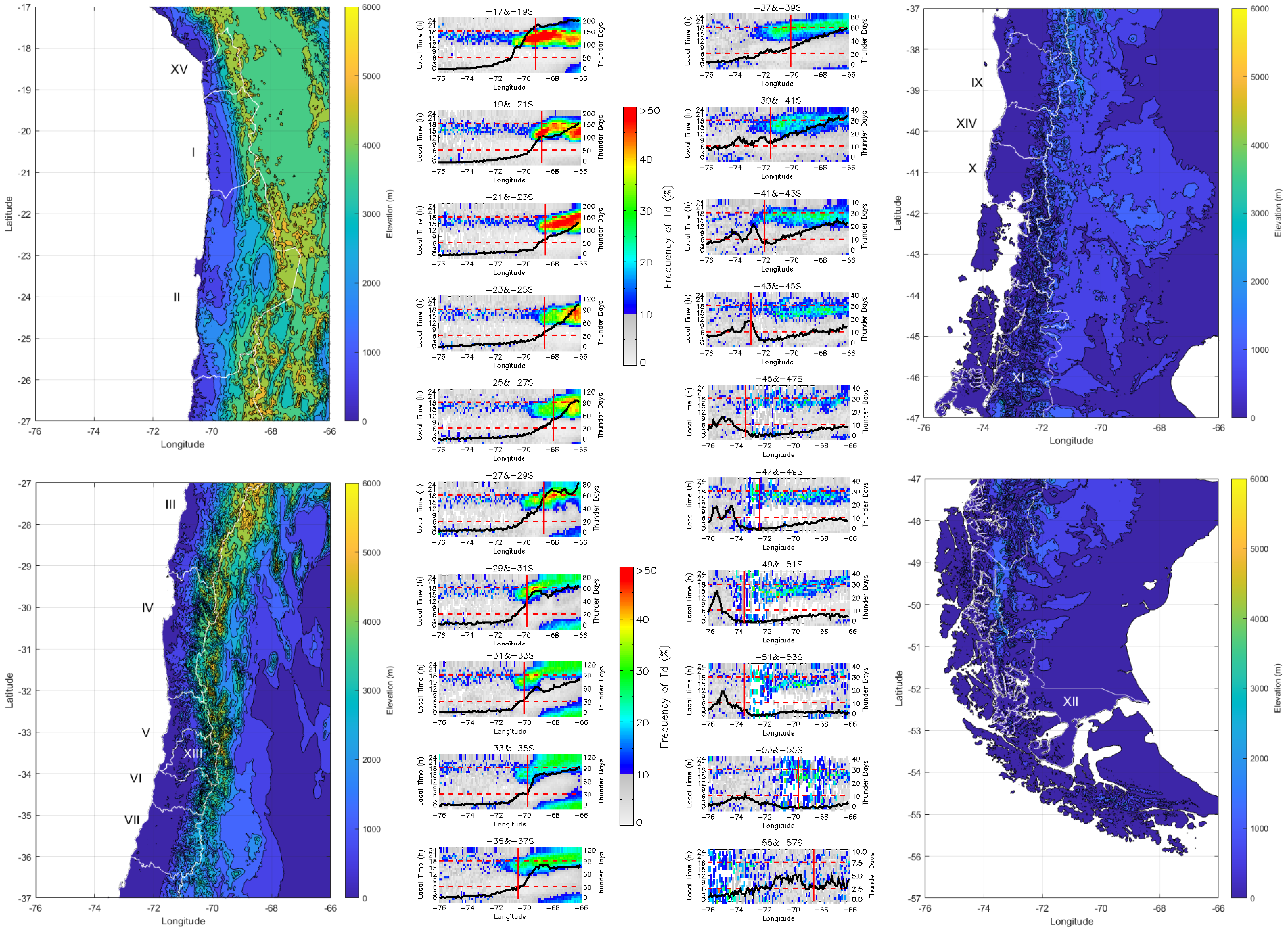

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