Article

Climates of Jalisco according to the Köppen-García system with adjustment for potential vegetation

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Abstract

The objective of the present research was to update the climate map of the state of Jalisco according to the Köppen-García climate classification, based on high-resolution (90 m) raster climate images and a climate-potential vegetation correspondence adjustment. We worked with daily, monthly and annual climatic data from 154 meteorological stations in the state of Jalisco and 151 stations in neighboring states. The data correspond to the 1961-2014 series in the case of the Jalisco stations and the 1961-2010 series for neighboring states. With this information, raster images were obtained for the classification of the climate with the Köppen-García method, through interpolation processes implemented with the Anusplin method. In the Idrisi system and using map algebra routines, the climate map of Jalisco was obtained at the climatic type and subtype level. Said map was corrected taking into account the correspondence of the climates obtained with the potential vegetation according to COTECOCA. The results showed an 84% correspondence between climates and vegetation types and only 16% of the climatic polygons were corrected. Twenty-nine climatic variants were obtained, of which dry or semi-arid climates represent 13.78% of the state territory, warm humid Aw 21.77%, semi-warm humid A(C)w 4.45%, semi-warm humid (A)C(w) 41.67%, temperate humid Cw 18.33% and cold E, 0.001%. In descending order, the number of climates by region was: South Region 21, Western Sierra Coast 19, Amula Sierra 18, North 14, Southeast 13, South Coast 12, Altos Sur 11, Valles 10, Lagunas 9, Centro 8, Altos Norte 7 and Ciénega 7. It is concluded that the state of Jalisco has a thermal gradient from warm to cold, including semi-warm and temperate, and a semi-arid to sub-humid monsoon through a humidity gradient. The authors consider that the climatic maps obtained can be useful in applications for various areas, such as agriculture, soil science, ecology and environmental sciences.

Keywords: climate classification, climate-vegetation relationship, GIS.

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Introduction

Climate is one of the environmental components of greatest variation in both space and time, because it is the result of the interaction of various factors such as latitude, altitude, terrain relief and exposure, distribution of land and water bodies, vegetation, and global distribution systems of sea currents and winds (Critchfield, 1983; García, 1989). All of these factors interact to form multiple combinations of environmental conditions that are reflected in a wide range of climatic variants. To understand the nature and differentiation of such variants, we use climate classification systems (Griffiths, 1994).

The classification of the climates of a geographical entity is fundamental to characterize the prevailing environmental conditions in a synthetic way, but at the same time sufficiently descriptive. There are several climate classification systems, however, none of them covers all possible climate classification needs (Medina *et al*., 1998). Within the macroclimate classification systems, the Köppen system is the most used worldwide (Sánchez-Santillán and Garduño, 2008) since it was conceived to define the large climatic areas of the Earth (García, 2004), basically based on a climatic variation of latitudinal origin.

The extent of the use of the Köppen system on a global scale has been achieved not without prior adaptations to the environmental conditions of different regions of the world, in order to satisfactorily characterize regional climate diversity (Stern and de Hoedt, 2000). This is the case of Mexico, where the spatial variation of the climate is mainly due to orographic factors, so there was a need to adapt the Köppen system to properly represent the climatic diversity of the country. This was achieved through the serial and continuous improvement works of García (2004). The result of this decades-long work by García (2004) is a climate classification system that differs significantly from Köppen's original version.

While the original system is designed to define the planetary distribution of climates at macroscale and basically based on a latitudinal variation of climate, the system modified by García allows representing in detail the distribution of climates in Mexico at mesoscale, product of considering a spatial variation of the climate as a product of the interaction of multiple climate modifying factors such as altitude, relief, terrain exposure, distance to the sea and vegetation. Therefore, the authors of this paper consider that it is amply justified to refer to the Köppen system modified by García as the Köppen-García system (2004). Based on the Köppen-García system (2004), the climate cartography of the country was periodically drawn up and updated at scales 1:500 000 (CETENAP, 1970), 1:1 000 000 (SPP, 1981) and 1:4 000 000 (UNAM, 1991) and 1:1 000 000 again (CONABIO, 1998).

The use of the Köppen-García system in Mexico goes beyond the climate-vegetation relationship, since it has been used in agricultural applications (Álvarez and Salazar, 2017) and that considers orography as a determining climatic factor in the national territory (Hernández-Cerda *et al*., 2018), its application in urban planning has also been raised (Velázquez-Ruiz *et al*., 2012); likewise, it is known that the Köppen-García system today continues to be applied in the fields of geography, geomorphology, ecology, biology, veterinary medicine and architecture (García, 2004).

The objective of this research was to update the climate map of the state of Jalisco according to the Köppen-García climate classification system. For this, it was proposed to consider an extensive climate database updated to 2014, a high-resolution information system in the environment of Geographic Information Systems (GIS) and the due adjustment of the climates obtained, due to their correspondence with the potential vegetation, according to the collections of the technical advisory commission on rangeland coefficients (COTECOCA).

For the state of Jalisco, several studies have been developed related to the generation of climate and agroclimatic cartography (Villalpando and García, 1993; Ramírez-Sánchez *et al*., 2013); however, none of them has focused specifically on updating the entity's climate charted based on the Köppen-García system.

Materials and methods

Climate database

The data used were daily and monthly precipitation, maximum temperature, minimum temperature and evaporation from 305 meteorological stations distributed in the interior and surroundings of the state of Jalisco (Figure 1). The information corresponded to the period 1961-2014 for the stations of Jalisco (154) and the period 1961-2010 for the stations of the neighboring states (151). All stations belong to the weather monitoring network of the national weather service. For the case of the point of maximum altitude in the state, which is the southern peak of the Nevado de Colima, there was no data from a meteorological station, so it was decided to use information from the station located in the Nevado de Toluca, which is located at an altitude of 4 283 m, very similar to that of the Nevado de Colima, which is located at 4 330 masl.

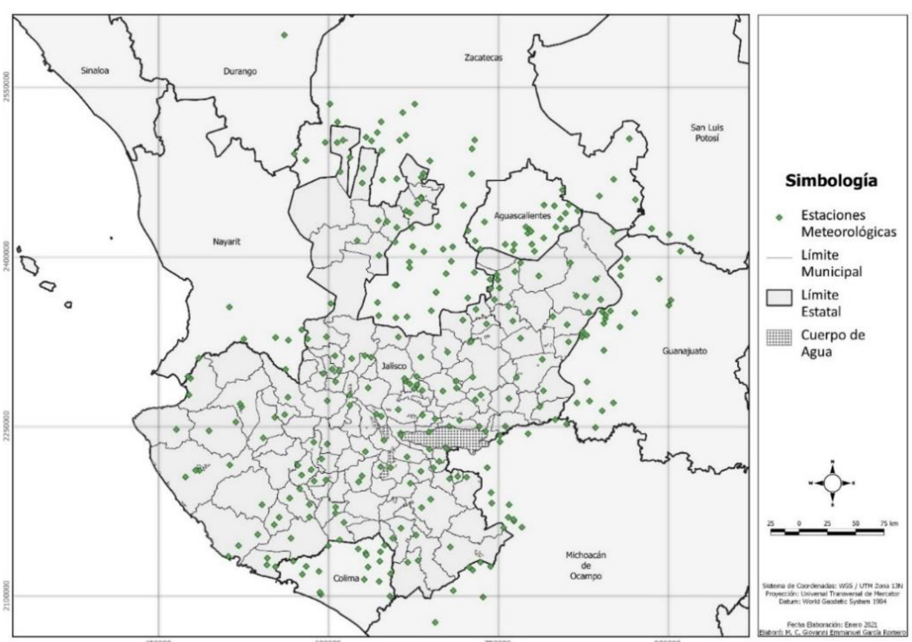


Figure 1. Spatial distribution of 305 meteorological stations used in the study.

Climate information system

From the daily data, pivot tables were constructed for the calculation of normal monthly and annual parameters in Microsoft Excel. With the normal monthly tables of the 305 stations, georeferenced data matrices were constructed and then proceeded to implement interpolation processes based on the Anusplin method using the Anusplin v. 4.4 software (Hutchinson and Xu, 2020). The interpolations were configured to generate images with a resolution of 90 m. Both for the case of precipitation and temperature, altitude was used as a covariate.

Anusplin was created by Moradi Daleh and is a method widely used by various prestigious institutions such as the Canadian Forest Service (Price *et al*., 2000), Oregon State University (Daly, 2006) and the National Meteorological Information Centre of China (Xu *et al*., 2020). Anusplin can model the topographic effect effectively involving both the horizontal and vertical coordinate system while performing precipitation interpolation, it also represents comparative advantages over other interpolation methods, due to its simplicity since it does not require calibration of its parameters as in the case of the Kriging method. Using the Anusplin method, several of the most used precipitation and temperature grids in the world have been generated, this is the case of WorldClim 1.0 (Hijmans *et al*., 2005) and WorldClim 2.0 (Fick and Hijmans, 2017).

The outputs of the interpolation processes were recovered and documented as raster images in the Idrisi Selva system (Eastman, 2012) to integrate a climate information system that was originally constituted with 12 monthly images of average maximum temperature, 12 of average minimum temperature, 12 of monthly average accumulated precipitation and 12 of monthly average accumulated evaporation. From the monthly climatic images derived from the interpolations, other additional variables were calculated in the IDRISI Selva system, such as average temperature for each month and annually.

Generation of the climate map of Jalisco

From the monthly and annual raster images of precipitation and average temperature, a raster of climates of Jalisco was generated using the application of the Köppen-García climate classification method (García, 2004). For practicality purposes, it was decided to represent in the results of the climate classification procedure, only the elements of the climate formula corresponding to the levels of climatic type and subtype.

To implement the Köppen-García climate classification procedure, it was necessary to generate in addition to the monthly and annual images of average temperature and precipitation, the images of percentage of winter rain, 'r' factor, average temperature of the warmest month, average temperature of the coldest month, precipitation of the driest month, annual precipitation/average annual temperature (CPT) ratio and number of months with average temperature >10 °C. This was done with the Idrisi Selva system using map algebra routines using the overlay, scalar and reclass modules. In order to automate the spatial process of climate classification and to facilitate the detection of errors in the process and their rapid correction, a macro file (extension.iml) was developed through the Idrisi file editor.

Analysis of correspondence between climates and potential vegetation

Once the Jalisco climate raster was obtained, the correspondence between the climates obtained and the potential vegetation was analyzed according to the COTECOCA vegetation type map scale 1: 500 000. To do this, the climate raster and the potential vegetation raster were overlaid by means of map algebra, creating a new raster, from which the climates and their corresponding type of vegetation were extracted in Excel format. Climates that did not correspond to the vegetation type proposed by COTECOCA were corrected. In the report of rangeland coefficients of the state of Jalisco (COTECOCA, 1979), the description of the geological units, soil units and climates that are present in each type of vegetation is included.

In addition, grassland sites with their corresponding rangeland coefficients are included. It should be noted that it was necessary to analyze how many climatic variants could correspond to some types of vegetation of wide territorial coverage, such the case of the low deciduous forest, for which it was found that it could be present in various climatic types (Trejo-Vázquez, 1999).

Results and discussion

Of a total of 205 polygons resulting from the overlaying of the climate image and the image of potential vegetation types, correspondence was obtained in 84% of the cases (172 polygons), that is, in 33 polygons (10.7%) there was a need to reclassify or adjust the climate that had been obtained only with the analysis of climatic variables. Of these 33 polygons, six refer to a misclassified BS_1 climate, six to Aw, 14 to A(C)w climate and seven cases to (A)C(w) climate.

Of the 33 polygons that were corrected, eight corresponded to a change from semi-warm climate of group C to semi-warm climate of group A; six polygons went from a warm climate A classification to a semi-warm group A climate; six more corresponded to only one change of subtype of semi-arid group BS_1; four cases involved a change from warm climate A to semi-warm climate of group C; four more changes were from semi-arid climate BS_1 to warm climate A; three polygons of semi-warm climate of group C only underwent a change at the subtype level. There was also a change at the level of climate subtype A and finally, there was only one case of change from temperate climate C to semi-warm climate of group A.

Figure 2 shows the map obtained of climates of Jalisco; according to this, there is a great climatic diversity in the State, represented by a total of 29 climatic variants (Figure 2 and Table 1), at the level of climatic type and subtype, according to the Köppen-García system (García, 2004). In this way, it can be seen that the climate (A)Ca(w_0) is the one with the highest surface coverage, since it is present in almost a fifth (18.35%) of Jalisco's territory. Other climates of importance are (A)Ca(w_1), Cb(w_1) Aw_1 and Aw_0 with a territorial coverage of 12.57, 9.62, 9.41 and 8.87%, respectively. These five climates add up to about 60% of the state's territory.

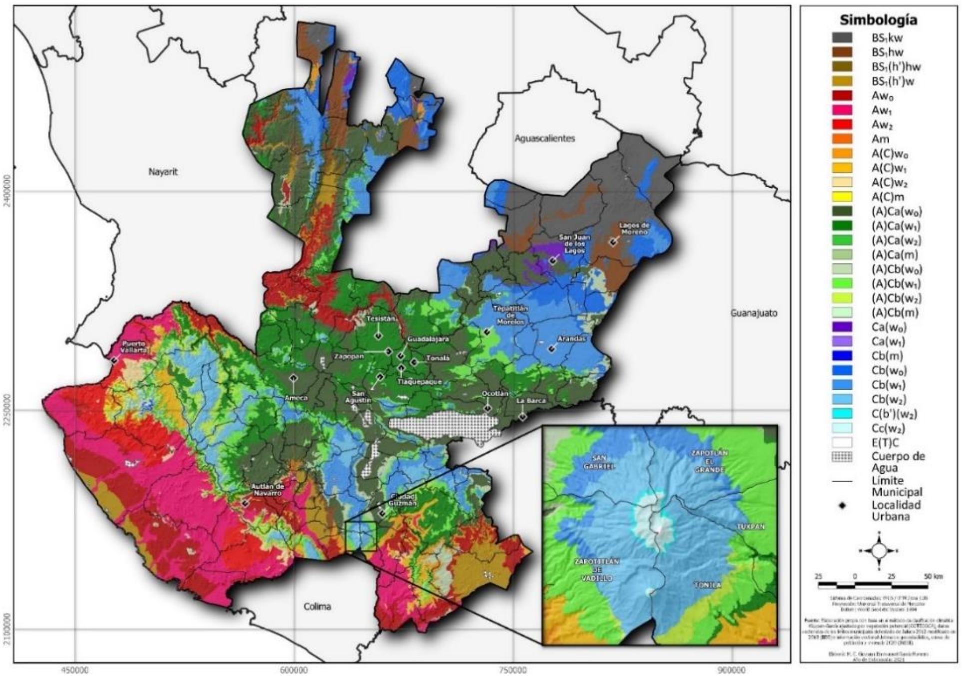


Figure 2. Climates of Jalisco according to the Köppen-García system (2004).

Table 1. Representativeness of the climates of Jalisco in terms of territorial coverage.

Climate	State territory		Climate	State territory	
	(ha)	(%)		(ha)	(%)
BS_1kw	543 797.82	6.86	(A)Ca(m)	15 835.33	0.2
BS_1hw	260 948.56	3.29	(A)Cb(w_0)	193 105.16	2.44
BS_1(h')hw	1 6497.15	0.21	(A)Cb(w_1)	415 174.2	5.24
BS_1(h')w	270 938.33	3.42	(A)Cb(w_2)	156 145.99	1.97
Aw_0	702 697.74	8.87	(A)Cb(m)	12 214.29	0.15
Aw_1	745 402.32	9.41	Ca(w_0)	52 912.85	0.67
Aw_2	258 621.69	3.26	Ca(w_1)	4.78	0.0001
Am	18 379.05	0.23	Cb(w_0)	337 244.46	4.26
A(C)w_0	117 981.09	1.49	Cb(w_1)	762 630.64	9.62
A(C)w_1	139 754.4	1.76	Cb(w_2)	295 057.66	3.72
A(C)w_2	72 729.63	0.92	Cb(m)	2 220.39	0.03
A(C)m	22 000.78	0.28	C(b')(w_2)	472.7	0.01
(A)Ca(w_0)	1 453 999.33	18.35	Cc(w_2)	1 361.76	0.02
(A)Ca(w_1)	995 844.42	12.57	E(T)C	59.59	0.001
(A)Ca(w_2)	59 656.04	0.75			

When analyzing the representativeness of the climates in Jalisco, but now by groups of climates, it is found that the dry or semi-arid climates represent 13.78% of the state territory, the warm humid climates A 21.77%, the semi-warm humid climates A(C) 4.45%, the semi-warm humid climates (A)C 41.67%, the temperate humid climates C, 18.33% and the cold climates E, 0.001%.

This provides a clear idea about the climatology of the state and shows the predominance of semi-warm climates in Jalisco, since adding the semi-warms of group C and the semi-warms of group A, it turns out that approximately half (45.76%) of the state territory has a semi-warm climate.

This highlights the importance of the modifications that García (2004) made to the original Köppen climate classification system, without which it would be difficult today to adequately represent the climatic diversity of the state. The predominance of semi-warm humid climates provides Jalisco with a transitional climatic condition between warm and temperate climates that are ideal for a great diversity of plant species.

Semi-warm climates, especially those derived from group C, present warm days and cool nights, which results in optimal conditions for thermoperiodic species (Wendell *et al*., 2017) such as corn (Benacchio, 1982), hence the state of Jalisco is considered one of the regions of the country with the highest yield potential for this crop (Castañeda-Zavala *et al*., 2014).

Table 2 and Figures 3 to 8 show a vision of climate diversity on a regional scale, also highlight the regions South, Coast Western Mountain Range and Amula Mountain Range as the most diverse, because they host 21, 19 and 18 climatic variants respectively, this is 72.4, 65.5 and 62.1% of the total climatic variation of the state. According to Table 2, the North Highlands Region (R01) is predominantly semi-arid temperate, since 56.36% of its territory is occupied by the BS_1kw climate, while the South Highlands Region (R02) is mostly temperate with a long cool summer and a moderately humid rainy season, since 51.22% of its surface is represented by the $Cb(w_1)$ climate.

For the Central Region (R03) as well as for the Valleys Region (R12), the climate (A)Ca(w1) is the most representative (58.39% of the regional surface), so they can be referred to as semi-warm temperate regions with a tendency to be warm and a moderately humid rainy season. The regions Cienega (R04), Lagoons (R07) and North (R08) can also be classified as semi-dry regions, but with a moderately dry rainy season, given the predominance of the climate $(A)Ca(w_0)$.

The Coast Western Mountain Range (R05) and South (R10) regions do not present a clear predominance of a climate, partly due to their high environmental diversity (19 and 21 climates, respectively), but, on the other hand, this characteristic makes them regions that can host an important floristic diversity (Suárez-Mota *et al*., 2017). More than 72% of the area of the South Coast Region (R06) has a warm climate Aw (Aw_1 47.61% and Aw_0 25.05% of the territory). Finally, in the Amula Mountain Range (R09), three variants of the climate (A)C predominate, while in the Southeast Region (R11), four climates predominate covering a range that goes from Aw to temperate Cb(w).

Table 2. Territorial percentage of various climates in the 12 ecological regions of Jalisco.

Climate	Regions											
	R01	R02	R03	R04	R05	R06	R07	R08	R09	R10	R11	R12
BS_1kw	56.36	0.01						5.97	0.02	0.04		
BS_1hw	13.51	0.06					0.12	12.46	0.74	1.28		
$BS_1(h')hw$							0.02	1.59				
$BS_1(h')w$						6.44		4.41	4.08	13.41	8.12	
Aw_0			3.71		4.56	25.05		6.84	9.69	13.17	12.23	22.8
Aw_1					14.39	47.61			6.66	13.7	0.002	
Aw_2					15.24	12.38			0.04	0.01		
Am					2.03							
$A(C)w_0$					1.93			0.11	2.41	5.49	3.67	1.26
$A(C)w_1$					5.35	0.92			1.71	8.53	0.11	0.01
$A(C)w_2$					4.52	2.48			0.42	0.62		
A(C)m					2.42							
$(A)Ca(w_0)$	4.1	22.25	23.30	62.24	0.48		48.96	34.22	28.07	5.63	19.52	24.9
$(A)Ca(w_1)$		2.87	58.39	19.20	11.01	0.48	7.71	3.86	13.77	11.97	4.99	44.3
$(A)Ca(w_2)$					4.81	1.21			0.65	0.06		
(A)Ca(m)					1.75							
$(A)Cb(w_0)$	3.12	2.65	1.3	1.2	0.002	0.6	6.46	1.35	2.57	7.13	4.83	0.78
$(A)Cb(w_1)$		7.69	8.26	10.49	4.08	0.005	8.45	2.62	11.83	7.77	12	3.71
$(A)Cb(w_2)$			0.0003		11.13	1.75			3.63	1.56	0.68	0.33
(A)Cb(m)					1.35							
$Ca(w_0)$	2.93	2.18						3.32				
$Ca(w_1)$		0.0007										
$Cb(w_0)$	16.78	10.69		0.24			0.17	11.5	0.004	0.05	0.58	
$Cb(w_1)$	3.2	51.22	4.76	6.63	0.28		21.41	11.75	3.75	5.59	24.05	0.65
$Cb(w_2)$		0.37	0.28	0.003	14.42	1.08	6.7	0.001	9.95	3.76	9.22	1.25
Cb(m)					0.24							
$C(b')(w_2)$										0.06		
$Cc(w_2)$										0.16		
E(T)C										0.01		
Total	7	11	8	7	19	12	9	14	18	21	13	10

R01= North Highlands Region; R02= South Highlands Region; R03= Central Region; R04= Cienega Region; R05= Coast Western Mountain Range Region; R06= South Coast Region; R07= Lagoons Region; R08= North Region; R09= Amula Mountain Range Region; R10= South Region; R11= Southeast Region; R12= Valleys Region.

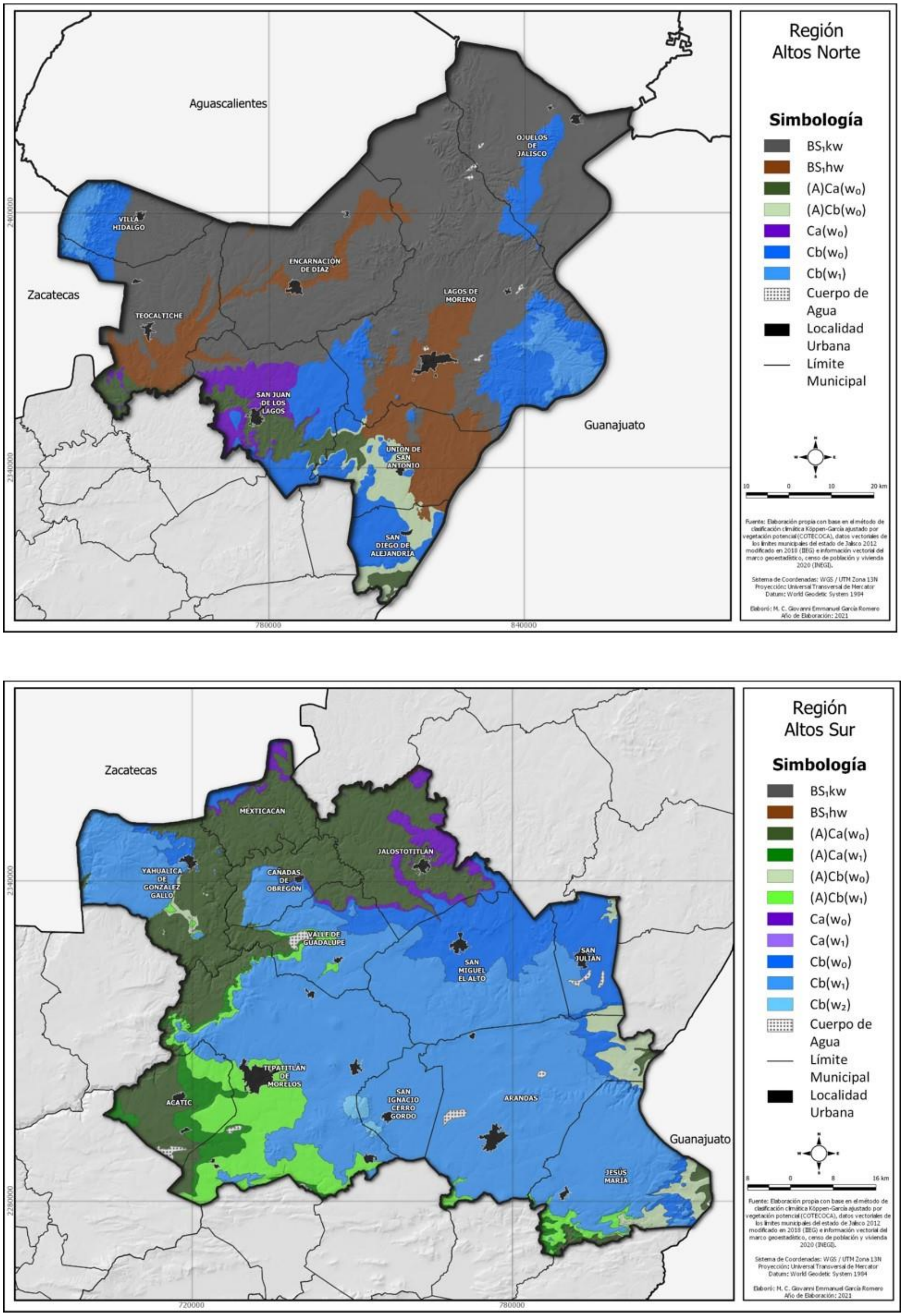


Figure 3. Climatic diversity of the North Highlands and South Highlands Regions.

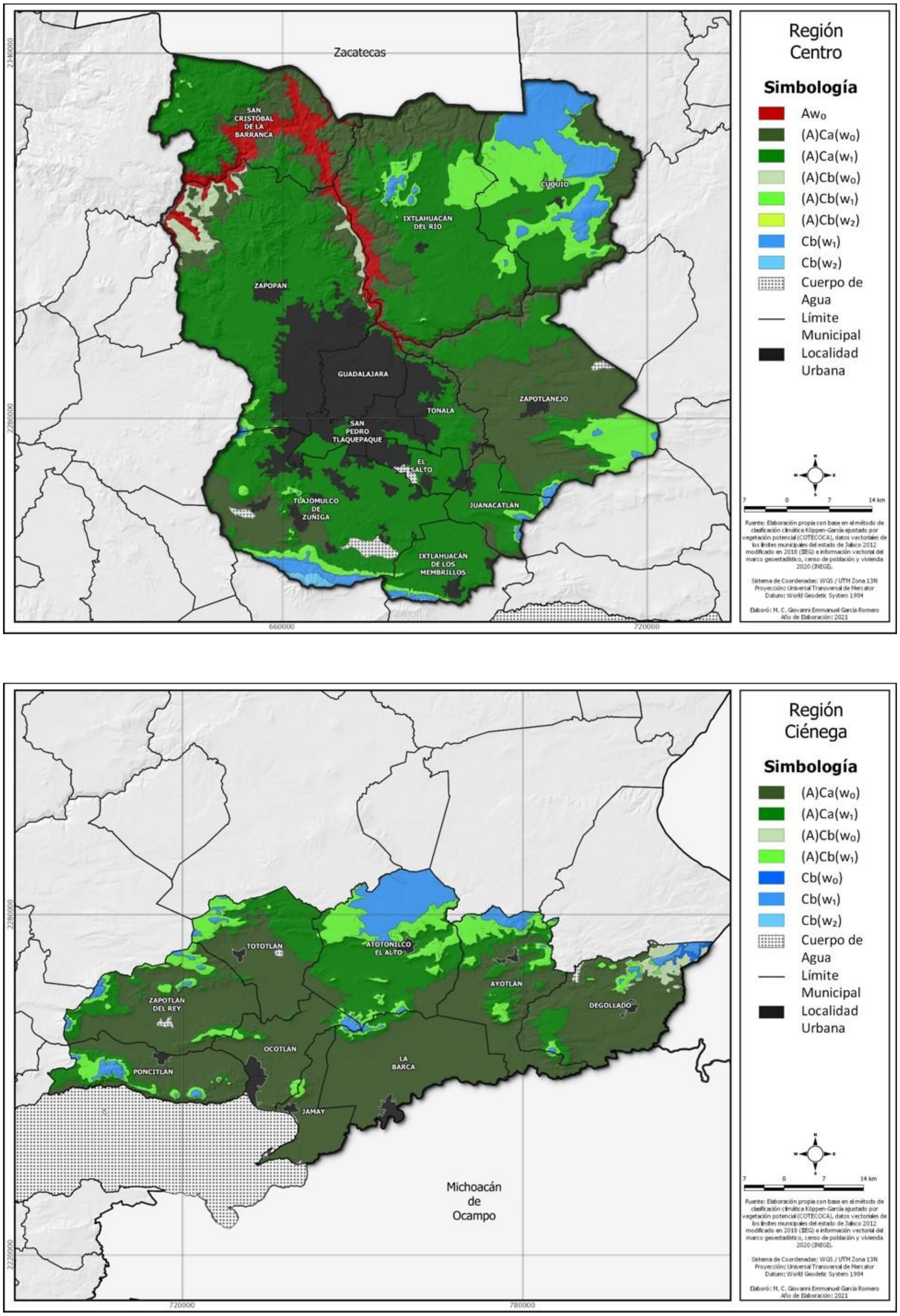
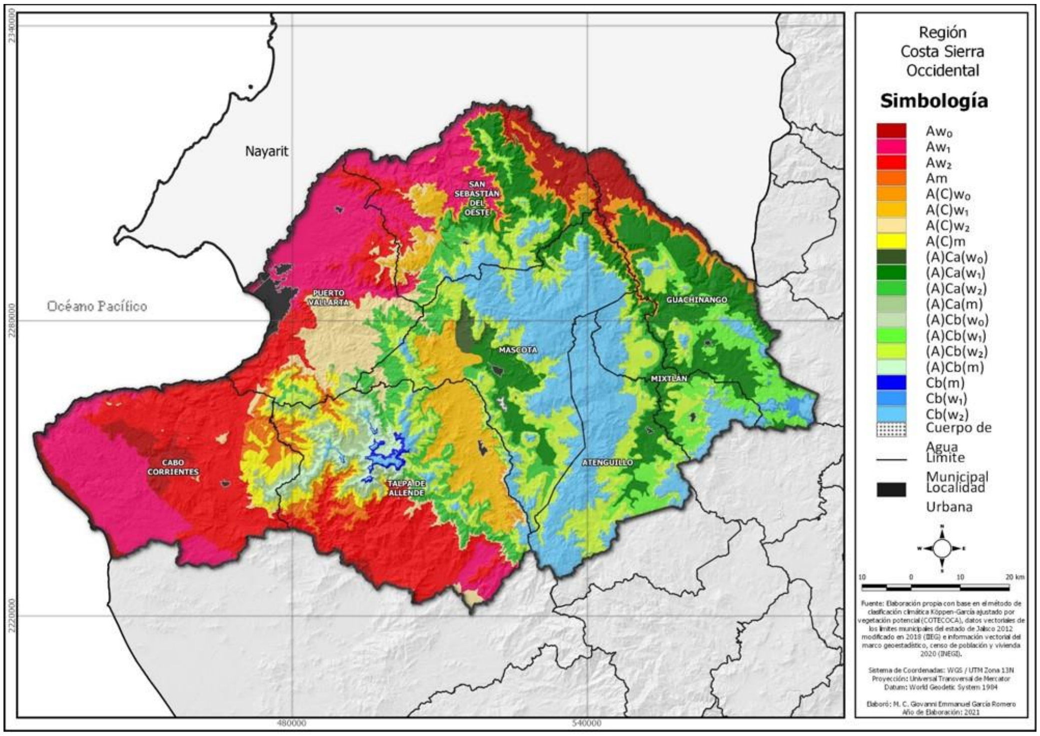


Figure 4. Climatic diversity of the Central and Cienega Regions.



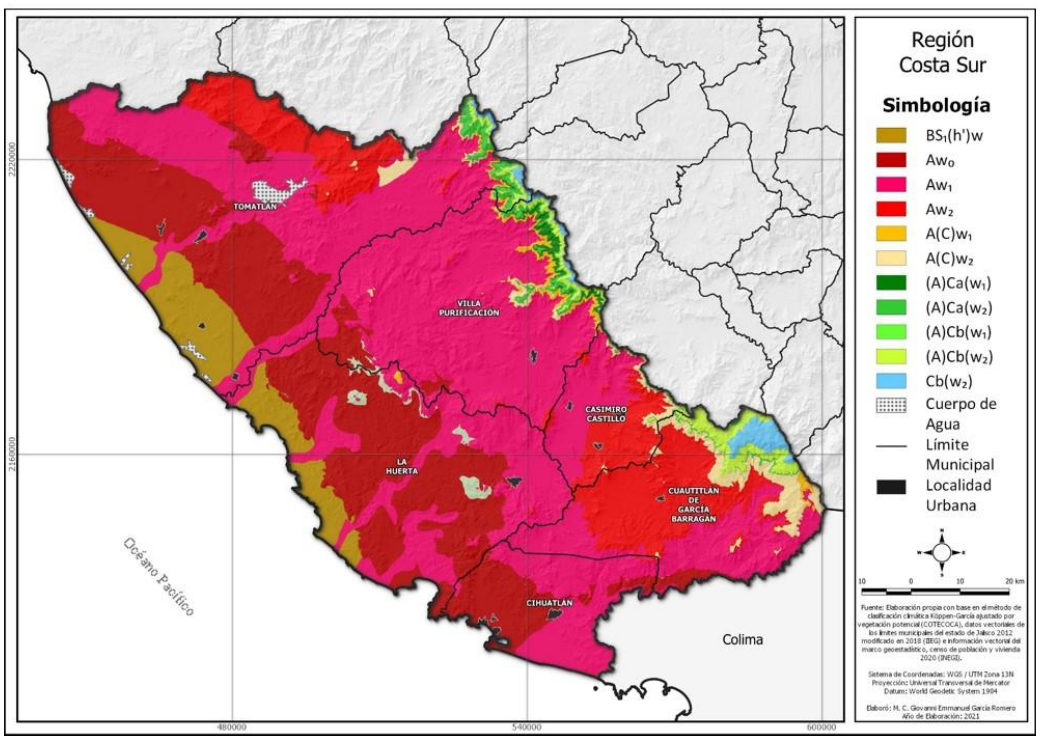


Figure 5. Climatic diversity of the Coast Western Mountain Range and South Coast Regions.

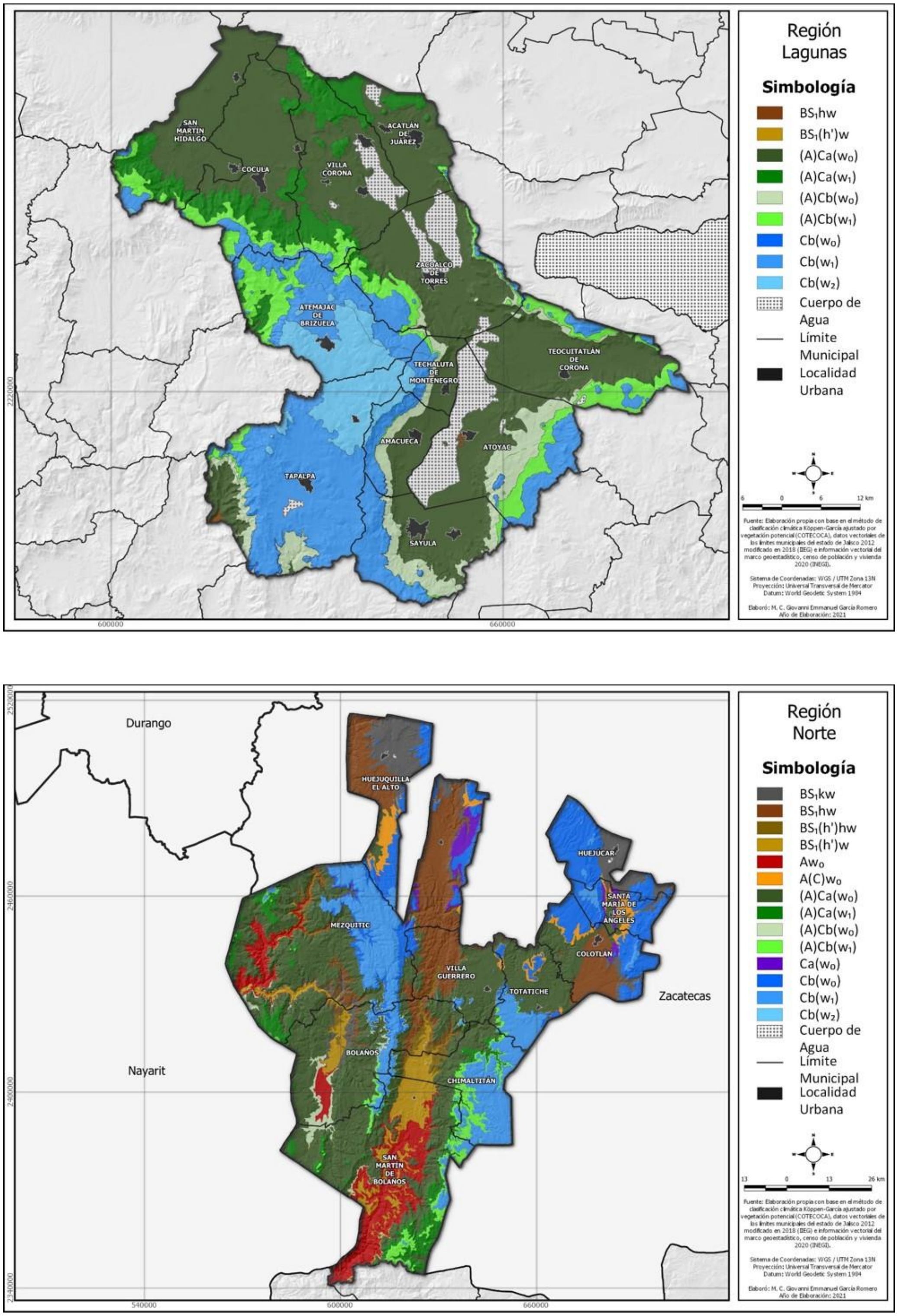


Figure 6. Climatic diversity of the Lagoons and North Regions.

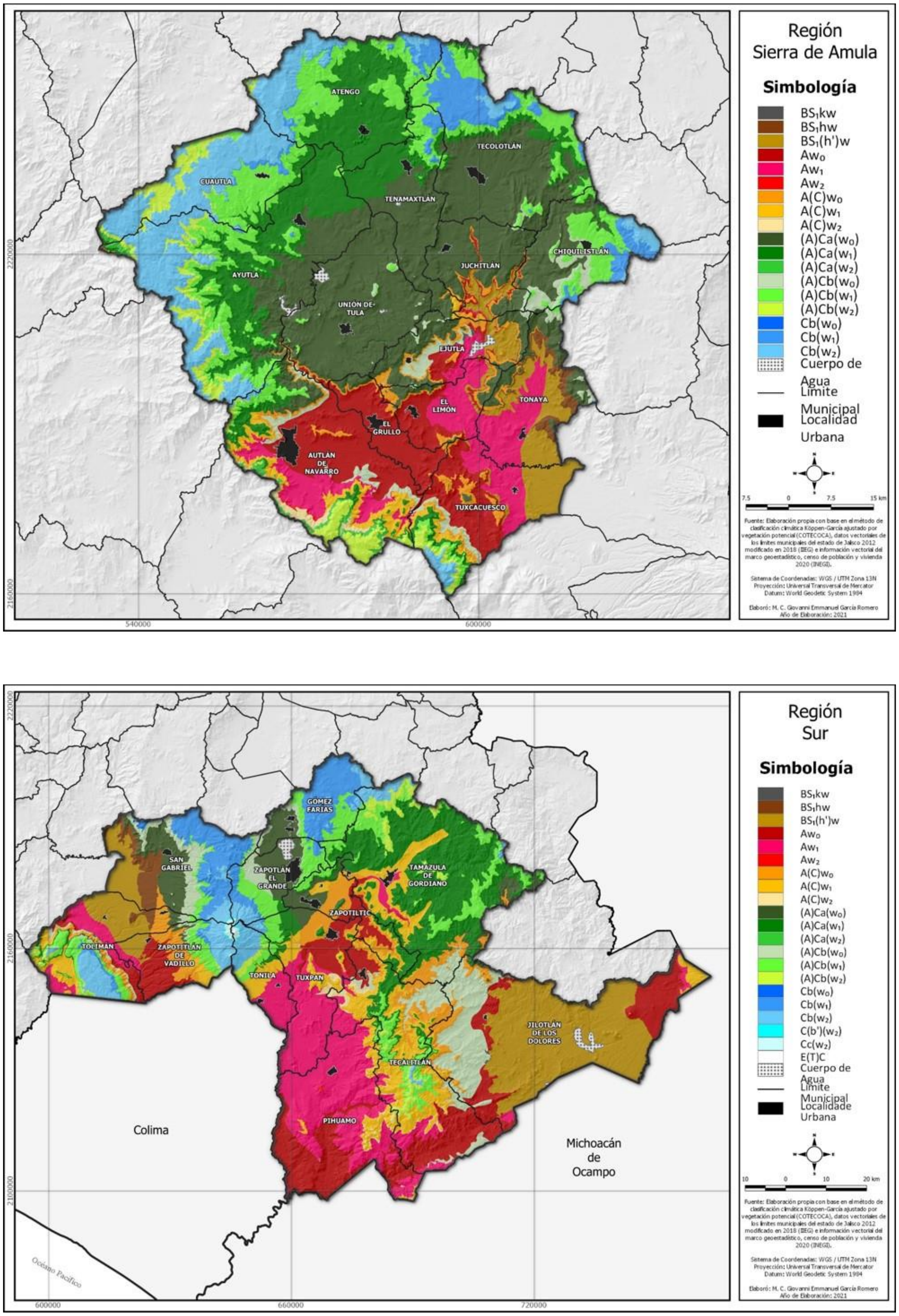


Figure 7. Climatic diversity of the Amula Mountain Range and South Regions.

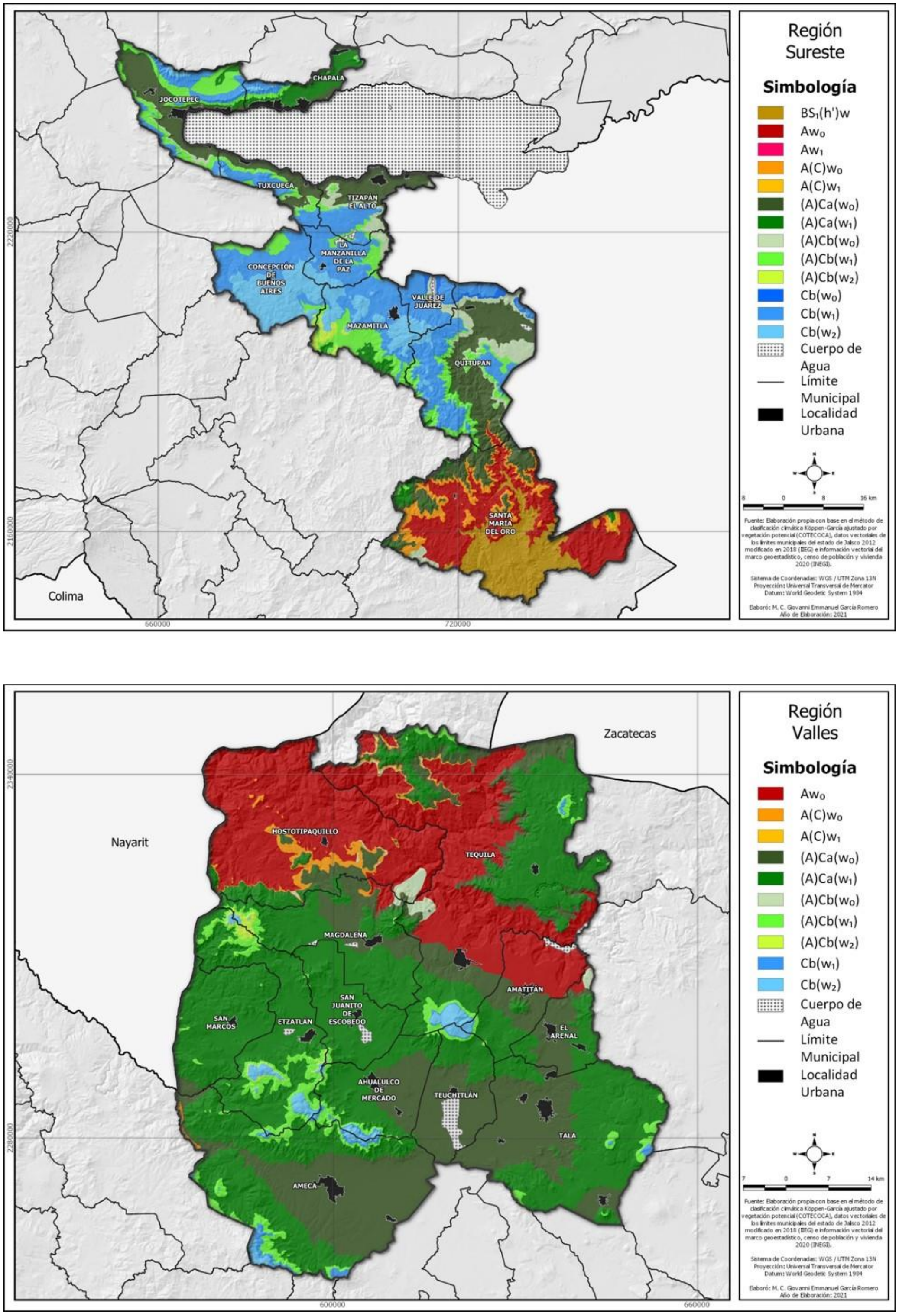


Figure 8. Climatic diversity of the Southeast and Valleys Regions.

The description of the 29 climates obtained in this study is shown in Table 3. Note: Generated maps can be requested to: ariel.ruiz@academicos.udg.mx and sergio.contreras@academicos.udg.mx.

Table 3. Description of 29 climates of the state of Jalisco.

Climate	Description
BS_1kw	Semi-arid temperate with warm summer (TMA 12-18 °C; TMMC≥18 °C); summer rains
BS_1hw	Semi-arid semi-warm (TMA 18-22 °C; TMMF<18 °C), summer rains
BS_1(h')hw	Semi-arid warm (TMA≥22 °C; TMMF<18 °C), summer rains
BS_1(h')w	Semi-arid warm (TMA≥22 °C; TMMF≥18 °C), summer rains
Aw_0	Warm with summer rains; CPT<43.2
Aw_1	Warm with summer rains; CPT between 43.2 and 55.3
Aw_2	Warm with summer rains; CPT > 55.3
Am	Warm with summer monsoon rains
A(C)w_0	Semi-warm of group A with summer rains; CPT <43.2
A(C)w_1	Semi-warm of group A with summer rains; CPT between 43.2 and 55.3
A(C)w_2	Semi-warm of group A with summer rains; CPT > 55.3
A(C)m	Semi-warm of group A with summer monsoon rains
(A)Ca(w_0)	Semi-warm with warm summer; summer rains; CPT <43.2, TMMC >22 °C.
(A)Ca(w_1)	Semi-warm with warm summer; summer rains; CPT from 43.2 to 55, TMMC >22 °C
(A)Ca(w_2)	Semi-warm with warm summer; summer rains; CPT >55, TMMC >22 °C
(A)Ca(m)	Semi-warm with warm summer; summer monsoon rains and TMMC >22 °C
(A)Cb(w_0)	Semi-warm with long cool summer; summer rains; CPT <43.2, TMMC <22 °C.
(A)Cb(w_1)	Semi-warm with long cool summer; summer rains; CPT from 43.2 to 55, TMMC <22°C
(A)Cb(w_2)	Semi-warm with long cool summer; summer rains; CPT >55, TMMC <22 °C
(A)Cb(m)	Semi-warm with long cool summer; summer monsoon rains; TMMC <22 °C
Ca(w_0)	Temperate with warm summer; summer rains; TMMC >22 °C, CPT <43.2
Ca(w_1)	Temperate with warm summer; summer rains; TMMC >22 °C, CPT from 43.2 to 55
Cb(w_0)	Temperate with long cool summer; summer rains; TMMC <22 °C, CPT <43.2
Cb(w_1)	Temperate with long cool summer; summer rains; TMMC <22 °C, CPT from 43.2 to 55
Cb(w_2)	Temperate with long cool summer; summer rains; TMMC <22°C, CPT >55
Cb(m)	Temperate with long cool summer; summer monsoon rains; TMMC <22 °C
C(b')(w_2)	Semi-cold with long cool summer. TMA from 5 to 12 °C, >4 months >10 °C
Cc(w_2)	Semi-cold with short cool summer. TMA from 5 to 12 °C, <4 months >10 °C
E(T)C	Cold climate, with TMA from -2 to 5 °C and MMF >0 °C

TMA= average annual temperature; TMMF= average temperature of the coldest month; TMMC= average temperature of the warmest month; CPT= annual precipitation/annual average temperature ratio.

Conclusions

The climate map of Jalisco was updated adjusted to the potential vegetation. The map of climate types obtained shows the climatic diversity of the state, represented by 29 variants, which include a thermal range that goes from warm climates to cold climates, including semi-warm and temperate climates.

Regarding humidity, climates range from semi-arid to monsoon-type climates, covering sub-humids with a humidity gradient available <43.2 to >55 CPT. About 14% of the state's territory are semi-arid areas and the rest of the territory has humid climate. Semi-warm sub-humid climates are the most representative, covering almost half of the state’s territory.

The regions with the greatest climatic diversity are the South Region, the Coast Western Mountain Range Region and the Amula Mountain Range Region with 21, 19 and 18 climatic variants of the 29 present in the state. While the regions with less climatic diversity are the North Highlands Region, Central Region and Cienega Region with 7, 8 and 7 climatic variants, respectively.

The climatic maps obtained, both state and regional, have potential applications in various areas, such as agriculture, for the possible definition of potential areas of crops or soil, for the generation of a map of agroecological zones.

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