Climatic zoning for building construction in a temperate climate of Chile

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Abstract

In Chile, the official document that defines energy efficiency for building construction is the General Ordinance of Urban Planning and Construction which defines seven thermal zones based on the annual average values of heating degree-days (base temperature of 15 °C) calculated in 1999. In the context of climate change, the obsolete meteorological data must be updated. In the present study, we assessed three regions in the south of Chile (La Araucanía, Los Ríos, and Los Lagos); updated annual average values of the heating degree-days using data from the meteorological observations for the past decade and updated the thermal zones. The results obtained shows that the 20% of the municipalities were different from the thermal zones of the General Ordinance of Urban Planning and Construction.

In addition, we considered the possibility of the climate severity index method application for climatic zoning in this study area. Due to this method, we identified the relative differences of energy demand for heating and cooling for the same building in different climatic conditions in the study area. The climatic zones were identifying based on the Technical Building Code of Spain. As a result, we detect three climatic zones for this regions in Chile and it was found that they were similar to the regions of northwest Spain. And finally, there was an analysis of the spatial distribution of the thermal and climatic zones and a comparison of the construction recommendations for each one of them.

Keywords: Building climatology; climatic zones; buildings; construction; Chile; Spain.

1. Introduction

Climatic zoning data is used in many areas of economic activity. The correct definition of climatic zones helps to increase agricultural productivity, use appropriate building materials, and design houses with the maximum energy efficiency, among other uses (de Rosa, Bianco, Scarpa, & Tagliafico, 2015; Falasca, Ulberich, & Ulberich, 2012; Moradchelleh, 2011; Rakoto-Joseph, Garde, David, Adelard, & Randriamanantany, 2009).

The classification of energy efficiency in housing is defined as the costs of energy needed to maintain comfortable housing conditions in different seasons of the year. In addition, energy efficiency in housing depends on architectonic, building characteristics and thermal systems (Carpio, Garcia-Maraver, Ruiz, & Martin-Morales, 2014; Carpio, Zamorano, & Costa, 2013), climatic parameters of the regions where the buildings are located (Carpio, Jódar, Rodríguez, & Zamorano, 2015) and building recommendations that are regulated by the standards of each country (Carpio, Garcia-Maraver, Ruiz, Martinez, & Zamorano, 2014).

The *Ordenanza General de Urbanismo y Construcciones* (OGUC) (General Ordinance of Urban Planning and Construction) of the Ministry of Housing and Urban Planning of Chile provided the building standards for the country. One of these standards is the Thermal Regulation of the OGUC that is directly related to energy efficiency of buildings. This standard defines seven thermal zones with different conditions for housing construction (Bustamante, 2009; Chile, 2009). The average annual values of heating degree-days (HDD) were used to determine these zones. This zoning is not considered alongside the other climatological parameters.

On the other hand, in Chile there is a standard NCh 1079-2008 *"Architectonic and construction – Climatic zoning for dwellings for Chile and recommendations for architectural design"* (Chile, 2008; Palme & Vásquez, 2015). The standard NCh 1079-2008 divides the country into 9 climatic zones and is based on various meteorological parameters (extreme and average temperatures, solar radiation, thermal oscillation, cloudiness, humidity, precipitation, vegetation, etc.) (Bustamante, Cepeda, Martínez, & Santa María, 2009). The main idea of this standard is to promote proper architectural design (Chile, 2008). However, this standard is only recommendatory and is not the main document that regulates energy-efficient construction in Chile (Bustamante, 2009; Bustamante et al., 2009; Ossio, Veas, & Herde, 2012): the main document is the Thermal Regulation of OGUC.

The main disadvantage of the zoning of OGUC is accounting specifically for winter conditions for buildings, the other disadvantage is the low standards of thermal transmission for the structural elements of buildings in some regions (Bustamante, 2009). Bustamante considers two cities in the same thermal zone of OGUC (the cities of Calama and Valparaiso) and defines that energy demand for heating in Calama is 65% more than in Valparaiso for the same building. Significant differences of the energy demand for heating in these cities is related to the inaccuracy in the determination of the thermal zones of OGUC (Bustamante et al., 2009). Simulation of thermal conditions inside these buildings, that were built based on standards of the OGUC for all thermal zones, showed a discrepancy between simulated temperatures and the comfortable thermal conditions in various regions of Chile (Vasco, Muñoz-Mejías, Pino-Sepúlveda, Ortega-Aguilera, & García-Herrera, 2017).

The method of the degree-days is used for thermal zoning in Chile and for climatic zoning in others countries of the world (ECBC, 2006; Owen, 2013; Walsh, Cóstola, & Labaki, 2017). This method has proven to be effective for analysing the influence of climatic conditions on the energy consumption of buildings (CIBSE, 2006). Currently, there are many methods and models for the calculation of degree-days (Borah, Singh, & Mahapatra, 2015); however, the most accurate method always uses hourly data of temperature measurements collected at weather stations (Carpio et al., 2015), therefore we will use this type of data in this work.

Another method for climate zoning to be consider in this work, is the climate severity index method (Markus, 1982). This method additionally, helps to take into account effects of solar radiation on buildings in climatic zoning. The climate severity index method reflects the relationship between the energy requirement of a building and climatic features based on ´severity´ of the climate. The climate severity index for some regions, is calculated on the basis of the simulation of energy consumption of building types, common in this region in the whole range of constructive and architectural scenarios in average climatic conditions (Makhmalbaf, Srivastava, & Wang, 2013). The division of climate severity index for the winter severity index (WSC) and summer severity index (SCS) allows for the analysis of energy consumptions of buildings for heating and cooling. Good correlation between the WSC and SCS indexes and climatic parameters (degrees-days and total solar radiation) makes it possible to calculate the values of these indexes in other regions where simulation of energy consumption of buildings was not carried out (de la Flor, Lissén, & Domínguez, 2006; Makhmalbaf et al., 2013).

The main advantage of this method is the possibility of comparing the energy consumption of certain buildings in different climatic zones relative to the reference point (Markus, 1982; Salmerón, Álvarez, Molina, Ruiz, & Sánchez, 2013). In this study, the method described in *Código Técnico de la Edificación* (CTE) (Technical Building Code) has been used for the calculation of the WSC and SCS indexes (de la Flor et al., 2006; Spain, 2006). This document, defines the norms for the proper characterization of energy efficiency in buildings in Spain (Spain, 2006). In CTE, combinations of WCS and SCS indexes define climatic zones of Spain.

The main goals of the present study were to update the HDD climatic values from hourly measured data of temperature for the studied area, and on the basis of this update, improve thermal zones of OGUC; determinate the climatic zones for buildings in the south of Chile with the climate severity index method; compare the spatial distribution of climatic zones of CTE and thermal zones of OGUC in the study area; and to determinate areas of equal energy consumption of buildings in Chile and Spain. The following steps to achieve the main goals of the study were performed: (a) defining the methods for identifying climatic and thermal zones;

(b) using actual data to determine the climatic and thermal zones in all the meteorological stations of the study area; (c) approximation and interpolation of parameters to obtain maps of climatic and thermal zones; (d) determining climatic and thermal zones for the capital cities of the municipalities; and (e) comparison of the recommendations and construction standards provided by the CTE and by the OGUC for study area.

2. Material and methods

2.1 Methods for determining climatic zones

2.1.1 Calculation of heating and cooling degree-days

Two parameters were used, to identify the climatic zones, namely: (a) cooling degree-days (CDD); and (b) heating degree-days (HDD). Degree-days is a universal climatic indicator used to calculate energy consumption of housing and emission of greenhouse gases resulting from the heating and cooling of dwellings (Carpio et al., 2015).

There are different methods to reconstruct and calculate CDD and HDD values. Some methods are based on daily average temperature values and their statistical characteristics (Walsh & Miller, 1983). Other methods use minimum and maximum daytime temperatures to calculate these parameters (CIBSE, 2006; Matzarakis & Balafoutis, 2004). In addition, to restore HDD values, used monthly (Erbs, Klien, & Beckman, 1983) and annual (Mourshed, 2012) average temperature values.

Indeed, these two parameters (CDD and HDD) are dependent on environmental temperature and have their own climatic trends (Castañeda & Claus, 2013; Lam, Tsang, & Li, 2004). That is why it is important to update and renew information about these parameters.

In order to reconstruct the CDD and HDD parameters in the present study, we used data of the hourly temperature measurements. Daily HDD and CDD are obtained by Eqs. (1) and (2), respectively (Mourshed, 2012):

$$HDD_d = \left[\sum_{i=1}^{24}(T_b - T_i)^+\right]\frac{1}{24} \quad (1)$$

$$CDD_d = \left[\sum_{i=1}^{24}(T_i - T_b)^+\right]\frac{1}{24} \quad (2)$$

where T_i – hourly temperature measured at the *i-th* hour of the day; index (+) means that it is only necessary to calculate positive differences between the base temperature (T_b) and T_i. Daily CDD and HDD values are used to calculate monthly, quarterly, and annual values.

To correctly calculate energy efficiency in housing, it is very important to use adequate base temperature for different weather conditions (Lindelöf, 2016), but in our situation in conditions of insignificant variation of climates in this study area we will use fixed values of base temperature. The American Society of Heating determined HDD with a base temperature of approximately 18 °C (Owen, 2013). On the other hand, the European Standard EN ISO 15927-6 recommends using a base temperature of 12 °C.

Spain and Portugal use the same base temperature of 20 °C to calculate HDD and CDD (Portugal, 2006; Spain, 2006). In Chile, the base temperature of 15 °C is used to calculate HDD (Chile, 2009).

2.1.2 Method of Technical Building Code of Spain

We used the CTE of Spain to determine the climatic zones. In this document, the climatic zones depend on two indexes: winter climatic severity (WCS) and summer climatic severity (SCS). Data of global solar radiation, HDD, and CDD is necessary to calculate those two indexes.

$$CS = a \times Rad + b \times DG + c \times Rad \times DG + d \times (Rad)^2 + e \times DG^2 + f \ (3);$$

CS here refers to WCS or SCS. For the case of WCS: DG is the monthly average HDD with base temperature of 20 °C for winter months (June, July, and August), and Rad [kWh/m2] is the monthly average accumulated global radiation incident upon a horizontal surface for the same months. For the case of SCS: DG is the monthly average CDD with base temperature of 20 °C for summer months (December, January, February, and March), and Rad [kWh/m2] is the monthly average accumulated global radiation incident upon a horizontal surface for the same months. Two types of DG are calculated from hourly temperature measurements (Eqs. 1 and 2). Coefficients a, b, c, d, e, and f are shown in Table 1.

Depending on WCS and SCS values, it is possible to determine five climatic zones (A, B, C, D, and E) for winter and four zones (1, 2, 3, and 4) for summer, as shown in Table 2, according to the corresponding intervals.

Combinations of values of the two indexes can characterise up to 20 climatic zones (Table 2). The concept of this climatology is that two similar houses located in two places with the same WCS consume a similar amount of energy for heating, and SCS provides the values of energy consumption to cooling the houses.

Climatic severity is defined as the ratio between the energy demands of a dwelling in any given location and the same dwelling in a reference point location. In the case of Spain, the reference point is Madrid. This way, the climatic severity in Madrid is 1.0 unit for SCS and WSC (Carpio et al., 2015).

The new descriptive document of the Reference Climates of the Ministry of Public Works and Transport of Spain, July 2015 (Spain, 2015), presents the following new formula for calculating SCS:

$$SCS = a \cdot GD + b \cdot GD^2 + c \quad (4)$$

where GD is the sum of the summer degree-days with a base temperature of 20 °C for the summer months (December, January, February and March in southern hemisphere); a = 2.990E-3; b = 1.1597E-07; and c = 1.713E-1. In this work, we calculate the SCS index with two methods: from solar radiation and CDD (Eq. 3); and only from CDD (Eq. 4). The possibility of using Eq. 4 is based on the fact that in summer the temperature is a function directly dependent on solar radiation.

2.1.3 Method of General Ordinance of Urban Planning and Construction of Chile

Decree No. 192 of 11th November 2005, which amended Decree No. 47 of the OGUC (Chile, 2009), incorporated provisions for thermal insulation requirements in dwellings, in accordance with zoning exclusively based on the required heating temperature for habitable comfort in Chile. The OGUC *Application Manual of Thermal Regulation* (Chile, 2009) determines seven thermal zones in Chile (Table 3). This table shows the values of heating degree-days, which is the sum of degree-days throughout the year.

In the zoning established by Decree No. 192, the required HDD to achieve thermal comfort with a base temperature of 15 °C, should increase in colder zones. This fact explains that zoning considers less HDD in zone 1 of the north of Chile (≤500) and greater HDD in zone 7 of the southern tip (>2000) (Bustamante, 2009). These values have only been calculated for 1999, which, from the climatology point of view, is not enough to obtain adequate thermal zoning.

2.2 Database

In the present study, direct-access data of hourly temperature and global solar radiation from different sources of various agencies were used.

Hourly temperature and global radiation measured by:

(a) Ministry of Agriculture - National Agroclimatic Network (35 stations) (Agromet, 2017);

(b) Ministry of the Environment - National Air Quality Information System (4 stations) (SINCA, 2017);

(c) Directorate General of Civil Aviation, Meteorological Directorate of Chile (5 stations) (DMC, 2017).

Modelled global radiation data:

(a) Solar Energy Explorer. Programme of the School of Physical Sciences and Mathematics of the University of Chile (ExSol, 2017).

2.3 Study area

The present study focused on three regions in southern Chile, namely: La Araucanía; Los Ríos; and Los Lagos. The three regions together have a total area of 98,855 km^2 and a total population of approximately 2 million inhabitants (INE, 2016). This area of study was chosen to carry out a direct comparison with areas of Spain where the same climate condition occurs, and compare two methods of climate zoning and the standards of housing construction in the two countries.

According to the Köppen-Geiger climate classification, the study area is located in a temperate climatic zone (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006), based on the new climatic zoning of the continental part of Chile (Sarricolea, Herrera-Ossandon, & Meseguer-Ruiz, 2016). The three regions of study were:

- **La Araucanía:** Parts of the central and northern areas of the region have a Mediterranean climate. The Pacific coast has a Mediterranean climate (warm summer) influenced by the ocean [Csb´] (Puerto Saavedra). Temuco, the capital city of the region, has a Mediterranean climate (warm summer) [Csb]. The lower ranges of the Andes Mountains have a Mediterranean climate (warm summer) influenced by the mountains [Csb(h)], and a Mediterranean climate (mild summer) [Csc] (Sarricolea et al., 2016).
- **Los Ríos:** This region is characterised by a marine west coast climate. Valdivia, the capital city of the region, is located in an area of marine west coast climate (warm and dry summer) influenced by the ocean [Cfb´(s)]. The central part of the region is characterised by a marine west coast climate (warm and dry summer) [Cfb(s)]. The lower ranges of the Andes Mountains have a Mediterranean climate (warm summer) influenced by the mountains [Csb(h)], and a Mediterranean climate (mild summer) [Csc] (Sarricolea et al., 2016).

- Los Lagos: This region is entirely located in a marine west coast climate, with the exception of the mountain areas. Osorno has a marine west coast climate (warm and dry summer) [Cfb(s)]. On the other hand, the capital city Puerto Montt, has a marine west coast climate (warm summer) influenced by the ocean [Cfb´]. The south of Puerto Montt has a marine west coast climate (warm summer) [Cfb] (Sarricolea et al., 2016).

In general terms, the three regions have temperate (97.5%) and tundra (2.5%) climates in the mountainous areas (Sarricolea et al., 2016). Temperate marine west coast climates prevail from 39°32' S to 43° S. The reduction in the height of the Andes Mountains in this part of Chile, the impact of western transfer of air masses, high rainfall, and the influence of the ocean, determine the climatic conditions in this region. In Valdivia, the average temperatures of the coldest and warmest months are +6.7 °C and +16.2 °C, respectively, and annual rainfall is 1734 mm. In Puerto Montt, the average temperatures of the coldest and warmest months are +6.2 °C and +14.3 °C, respectively, and annual rainfall is 1569 mm (DMC, 2017).

In La Araucanía, due to increased solar radiation and reduced rainfall, the climatic zones change to a Mediterranean climate. For this reason, it can be affirmed that this region has the coldest Mediterranean climate of Chile. In Temuco, the average temperatures of the coldest and warmest months are +6.9 °C and +16.1 °C, respectively, with an annual rainfall of 1103 mm (data of the Chilean Meteorological Department for 1986-2015) (ExClim, 2017).

3. Results

3.1 Winter and summer climatic severity

3.1.1 Winter and summer climatic severity per meteorological stations

The climatic severity index method was developed based on climatic values of air temperature and solar radiation in 50 cities of Spain. We analysed climatic values of solar radiation in 50 cities of Spain and in 44 meteorological stations of the study area for summer and winter periods (ExSol, 2017; Sancho, Riesco, & Jiménez, 2012). The Fig.1 shows the results of this analysis where it can be seen the intervals of climatic values of solar radiation in

Spain for which the Eq. 3 was developed. Global solar radiation has latitudinal dependence, and also depends on cloud cover, elevation above the sea level, and the composition of gases and aerosols in the atmosphere (IPCC, 2013). Three regions of Chile are located between 37°35′ S and 44°04′ S, and mainland Spain is located between 36°01′ N and 43°48′ N. As a result, we have almost the same climatic values of solar radiation in two parts of the world.

For the analysis of the thermal conditions in Spain and Chile climatological data of average maximum temperatures for summer period and average minimum temperatures for winter period were used (AEmet, 2011; Castillo, 2001). The Fig.1 shows that the amplitude of temperatures observed in La Araucanía, Los Ríos, and Los Lagos regions is included within the range of temperatures observed in Spain for winter period. In summer period 60% of the amplitude of climatological values of maximum temperatures in Chile is included within the interval of Spain. Therefore, we can confidently use this method to calculate WCS index in study area. In the case of calculation SCS index, errors can occur in the cold climates of study area.

Data of the temperatures measurements and global solar radiation in each station to calculate WCS and SCS (Eq.3) were used; even though the meteorological stations did not always have information about global radiation. For this reason, firstly the instrumental data of global radiation measurements on a horizontal surface were replaced with data from the atmospheric radiation model (Solar Energy Explorer) (ExSol, 2017). The calculation of WCS and SCS was made for all periods that present parallel measurements of temperature and global radiation. In addition, WCS and SCS indexes were calculated in relation to temperature measurements and modelled global radiation. The graph of Fig. 2 illustrates the dependence between WCS and SCS calculated from measurements and modelling of global radiation in 44 meteorological stations. Nearly all stations had WCS indexes calculated by two types of solar radiation data with less than 10% of errors (blue lines). In the case of the SCS index, there were augmentation errors together with decreased values of this index. In general terms, it is possible to affirm that the use of modelled global radiation was appropriate for our situation. The scheme of calculation WCS and SCS indexes is shown in Fig. 3.

Table 5 presents the information of meteorological stations and the results obtained for WCS and SCS, with information from years of measurements and capacity data of measurements in percentages for WCS between June and August, and for SCS between December and March. Eq. 3 (correlation between WCS and SCS indexes and meteorological parameters) was determined based on the simulation of the energy demand for heating and cooling in 50 cities of Spain. This correlation was obtained for an interval of the WCS index [0.2;1.75] and for an interval of the SCS index [0.05;1.70] (de la Flor et al., 2006). In our study, for meteorological stations, the values of the WCS and SCS indexes were recalculated for the intervals [0.72;1.44] and [-0.05;0.54], respectively (Table 5). Based on the similarity of climatic conditions in the study area and in Spain, is possible to confirm the adequacy of the use of the CTE method for the calculation of WCS and SCS indexes.

In addition, this table presents values of the SCS index calculated using Eq. 4. It can be observed that, to our study area, SCS from two equations only determined one type of climate, i.e., colder climate number 1 for summer. The map of Fig. 4 illustrates the meteorological stations indicated in Table 5 to demonstrate the spatial coverage of meteorological observations.

The graphs of Fig. 5 illustrate the dependence between SCS and WCS in meteorological stations of La Araucanía, Los Ríos, and Los Lagos. In La Araucanía was observed more continental type of climate, because Lonquimay (WCS = 1.35; SCS = 0.54) and Marimenuco (WCS = 1.44; SCS = 0.44) stations are located far away from the ocean and have maximum WCS and SCS values for study area. Therefore, these places had colder winters and hotter summers. On the other hand, Quiripo (WCS = 0.94±0.06; SCS = 0.10±0.01), Tranapuente (WCS = 0.86±0.10; SCS = 0.06±0.01) and Domínguez (WCS = 0.87±0.10; SCS =

0.04±0.007) stations are located near the coast of the Pacific Ocean and, therefore, have warmer climatic conditions in the winter and cooler in the summer in La Araucanía.

La Providencia (WCS = 0.97±0.11), Sta. Adela (WCS = 0.95±0.06), and Quiripo (WCS = 0.94±0.06) stations are located in La Araucanía. According to Table 2, there may be a problem of correct identification of the climatic zone, because the values of index WCS of these stations were located on the border between climate types C and D.

In Los Lagos, the stations are located in the south of the region, i.e., Butalcura (WCS = 1.20±0.04; SCS = 0.04±0.03) and Huyar Alto (WCS = 1.20±0.10; SCS = 0.005±0.017) observe colder climates in the whole region, which is reflected in the extreme values of WCS and SCS. It is possible to observe that the change in amplitude of WCS was greater than the change in amplitude of SCS (95% confidence interval of WCS, greater than that of SCS for annual averages obtained with more than 5-years of measurements). Narrow confidence intervals of SCS are linked to not very high absolute values of SCS and the sensitivity of Eq. 3 from the input parameters.

Finally, WCS and SCS were calculated for all meteorological stations, but for create maps of spatial distribution of these two indexes, approximation and interpolation methods will be use (Carpio et al., 2015).

3.1.2 Reconstruction of winter and summer climatic severity indexes

The analysis of the results for WCS in the meteorological stations indicated that this index was a function that depended on latitude and elevation above sea level. In addition, it was found that SCS was a factor that depended on latitude, altitude, and distance between the meteorological stations and the ocean.

In these regions, the most important climatic factor of the summer was the distance to the ocean. This distance defined the continentality of the climate at each location. Obviously, greater distances defined warmer places with higher SCS values. However, this spatial dependence only occurred up to some altitudes. In our situation, we could calculate SCS in places that were located up to 1,000 metres above sea level.

The dependence of WCS and SCS values on geographical parameters was obtained and a geographical relief model of 305 sites for the three regions using geographical coordinates, altitude of the sites, and the shortest distance to the ocean was built.

Subsequently, the approximation equations used to calculate WCS and SCS values in 305 sites of the relief model. Finally, through the use of ArcGIS (ArcGIS, 2017) and the Kriging method (Oliver & Webster, 1990), maps with the spatial distribution of WCS and SCS in the study area were created.

3.1.3 Final results of winter and summer climatic severity

Maps with the spatial distribution of WCS and SCS in the three assessed regions are presented in Fig. 6. The minimum WCS values are observed in the northwest part of La Araucanía close to the Pacific coast (WCS = 0.85-0.95) and in the city of Puerto Montt (WCS<0.75). The minimum value of this index characterised milder climatic conditions for winter in the three regions. The change in axis of the index WCS went from the northwest to the southeast of the study area. The maximum value of this index is observed in the southeast of Los Lagos, which is characterised by colder and more extreme climatic conditions of the three regions (WCS > 1.60).

In the case of the spatial distribution of SCS, it was observed the opposite situation. The maximum values were observed in the northeast part of La Araucanía (SCS > 0.50), and the minimum values in the southwest part of Los Lagos. Maximum values of SCS determined climate with the warmest summers in the three regions and maximum of dwelling energy consumption for cooling.

This spatial distribution of the indexes was defined in winter due to the climatic effect of ocean warming, and in summer due to the climatic effect of the underlying surface heating.

In general terms, the distribution of the indexes did not challenge the climatic logic of this region.

3.2 Updated map of the General Ordinance of Urban Planning and Construction of the Ministry of Housing and Urban Planning of Chile

Firstly, the differences between HDD calculations for 2011-2015 with data from meteorological stations (DMC, 2017) and HDD calculated by OGUC in 1999 for different cities of Chile (Table 4) were showed. It can be observed that data from the period 2011-2015 showed that Calama had a range of 1,242 HDD, which corresponds to the thermal zone 4; however, OGUC determined that this city belonged to zone 2. This discrepancy of thermal zones in the Calama city, was also reflected in the study of Bustamante (Bustamante et al., 2009). Another significant discrepancy is that La Serena had 697 HDD, and OGUC considered this city as belonging to zone 1, with annual HDD below 500. This mismatch of data indicates the need of continual updating of thermal zoning and the use of data collected over long periods of time.

Therefore, a recalculation for HDD for La Araucanía, Los Ríos, and Los Lagos was done, because the total energy consumption in the southern regions of Chile is more dependent on the energy demands of buildings for heating in winter period. In order to update the limits of thermal zones were used:

1. Maps of thermal zones of OGUC (1999 year of data) (Chile, 2009).
2. Bioclimatic zoning map of Chile (Sarricolea et al., 2016).
3. Interpolation of data from the National Agroclimatic Network using the Kriging method (Kumar, Maroju, & Bhat, 2007; Oliver & Webster, 1990).

In the first stage, the HDD values were calculated with data of the National Agroclimatic Network stations using Eq. 1. Table 6 shows the results of the calculation including the 35 stations of which 27 has more than two years of temperature measurements, while 7 stations has HDD values which not correspond to thermal zones of the OGUC. For example, the Santa Carla station has a calculated value of 1,622 HDD; however, according to OGUC zoning, this station was located in the area with HDD between 1,250 and 1,500.

In the second stage, the spatial distribution of HDD was calculated, after bioclimatic zoning as additional information to obtain updated limits of thermal zones was used. As a result, we obtained a new composite map of thermal zones for the three regions (Fig. 7 right).

The comparison between maps of the OGUC and new composite maps (Fig. 7) indicated that the climatic zone 4 moved to the south in the central part of La Araucanía, and there was insulation near Valdivia in Los Ríos. This fact changed zone 5 to zone 4 in 11 cities of these two regions. In this area, there were also changes of bioclimatic zones, i.e., the Mediterranean climate moved to the south, approximately to San José de la Mariquina in the northern area of Los Ríos (Sarricolea et al., 2016). In older climatic publications, this region was characterized by another type of climate – temperate marine (Fuenzalida-Ponce, 1971).

In the northeast of La Araucanía, the climatic zone 6 moved to the west, and in Curacautín was observed the change from zone 5 to zone 6, which was in line with data from measurements collected at the San Luis station, where there were 1,773 annual HDD (minimum of 1615 and maximum of 2074) from 2009 to 2016. In Los Lagos, was observed that zone 6 changed to zone 5 in Puerto Octay city.

For this reason, the updating of degree-days data indicated a large number of inconsistencies in La Araucanía, which can be linked to global climate change and effect of urban heat islands. This result is explained by the fact that some stations were located in urban areas.

3.3 Complex results of municipalities

By the end of the study, three climatic zones with climate types C1, D1, and E1 were obtained (Table 7, Fig. 8). Climatic zones for 74 municipalities of the three regions were calculate and, finally, it was observing that the climatic zone C1 occurred in 19% of the municipalities, climatic zone D1 in 74%, and E1 in 7% of them. On the other hand, with the calculation of the amount of population in these three regions, it was found that 47% of the population lived in zone C1, 50% in D1, and 3% in E1. That difference occurred because all large cities (Valdivia, Temuco, and Puerto Montt) with urban heat island effects belonged to the climatic zone C1. Fig. 8 shows a map of climatic zones of the CTE for study area. Climatic zone E1 also covers mountainous areas where there is no data on the SCS index (Fig. 6 right), because the mountainous areas are not characterized by the energy consumption of buildings for cooling in the summer period.

According to the CTE (Spain, 2006), in Spain, climate type C1 are observed in the north and northwest part of the country, and this type of climate is typical for the following cities: Pontevedra in the Autonomous Community of Galicia; Oviedo in the Autonomous Community of Asturias; and Bilbao and San Sebastian in the Autonomous Community of the Basque Country.

Climate type D1 is typical for the following cities: Lugo (Galicia); Palencia (Castilla and León); and Pamplona (Navarra). On the other hand, climate type E1 is typical for the following cities: León (Castile-León); Burgos (Castile-Leon); and Soria (Castile-León). In the north and northwest regions of the country there is a clear dependence, given for coastal cities with climate C1, as distant cities from the sea with climate D1, and those far from the sea and above sea level has climate E1, such as Burgos (861 meters above sea level) and Soria (984 meters above sea level).

Important factors for determining the climate in the north and northwest of Spain are: the relative position of the ocean and the coast; effect of the Gulf Stream; terrain; and continentality. For this reason, the cities located near the coast have milder winters (climate type C1)

In Spain, due to the heating effect of the Gulf Stream, there is climate type C1 on the coast of the ocean (43° N). However, in Chile, there was cooling effect caused by the Humboldt ocean current and, therefore, in the same longitude in Chile (between 42° S and 44°

S) there was climatic zone E1 on the ocean coast of Los Lagos region, which changed to D1 and then to C1 in the northern part of La Araucanía. The changes of climatic zones in the regions of Chile were linked to the latitudinal location of these regions (change of global solar radiation). On the other hand, in Spain, the regions with C1, D1, and E1 climate types have longitudinal location and the change of climatic zones was linked to the altitude changes.

Table 7 shows that climatic zone C1 corresponded to thermal zone 4 in 64% of the municipalities, and climatic zone C1 corresponded to thermal zones 5 and 6 in 44% and 45% of the municipalities, respectively. Table 8 presents the recommendations of thermal transmittance for roofs, walls, and floors for four thermal zones of the OGUC and three climatic zones of the CTE. It is possible to observe that the thermal transmittance interval for floors in the CTE [0.48-0.50 W/m^2K] was within the interval of the MINVU [0.32-0.60 W/m^2K]. For roofs, the CTE determines thermal transmittance for three climatic zones in the interval [0.35-0.41 W/m^2K] and the OGUC for four thermal zones in the interval [0.25-0.38 W/m^2K]. However, the maximum difference was observed in the recommendations of thermal transmittance for walls.

In Spain, the CTE is defined within the interval [0.57-0.73 W/m^2K], which is in line with MINVU recommendations for the thermal zone 7 [0.60 W/m^2K]. There were great differences in other thermal zones, such as zone D1, with a thermal transmittance of 0.66 W/m^2K for walls which corresponds to thermal zones 5 and 6, with thermal transmittance of 1.60 and 1.10 W/m^2K for walls, respectively. Thermal transmittance for windows and doors was nearly the same in the two countries. Therefore, rules for construction of walls in Spain were approximately two times stricter than in Chile for climatic zones C1 and D1 (corresponding in Chile to the thermal zones 4, 5, and 6). These differences in the recommendations for the thermal transmission of building structural elements can be associated with different base temperatures that determine indoor comfort in these two countries.

However, three regions in Chile are consider the leaders in the use of wood for heating of buildings, which, in turn, generates high concentrations of particulate materials in the atmosphere (Hernández & Arroyo, 2014). High concentrations of particulate materials, in turn, causes serious effects on individuals' health and mortality (Díaz-Robles et al., 2014). Along with atmospheric decontamination programmes in urban areas (Chile, 2014), southern regions of Chile need to develop building methods and rules that help minimize energy demand for heating and the reduction of air pollution emission.

4. Conclusions

The main conclusions were made after the assessment of the different methods to calculate and identify thermal and climatic zones for building construction in southern regions of Chile.

Thermal zoning map of the OGUC from meteorological measurement data over the past decade was updated.

The climatic severity index method was applied to find correspondence between climatic zones in the south of Chile and climatic zones in the north of Spain, plus the thermal zones of the OGUC and climatic zones of the CTE, and values of WCS and SCS indexes. For capital cities of the municipalities, thermal zone 4 corresponds to the average value (and standard deviation) of the WCS = 0.95 (0.07) and SCS = 0.35 (0.09), for thermal zone 5 WCS = 1.03 (0.05) and SCS = 0.29 (0.11), for thermal zone 6 WCS = 1.15 (0.12) and SCS = 0.09 (0.14), and for thermal zone 7 WCS = 1.60.

We can see that similar buildings will have an energy consumption for heating of on average 60% more when it is located in thermal zone 7, compared to its location in the reference point. The location of the house in thermal zone 4 is characterized by an energy consumption for cooling of equal to 35% of the energy consumption of the same house at the reference point.

Modelling of energy consumption of houses (with different building scenarios, standards, and recommendations) in the study area will help with the analysis of WCS and SCS indexes to determine the optimal constructive and architectonic recommendations for south regions of Chile.

At the urban meteorological stations, we found urban heat island effects in thermal and climatic zonings for dwellings. These effects were greater during the winters in large cities. Thus, WCS value is 0.72 (climatic zone of winter C) in the urban station Pto. Montt MMA of Puerto Montt city. On the other hand, in the nearest rural station (Colegual), the WSC value was 1.16 (climatic zone of winter D). In the urban station Las Encias Temuco MMA of Temuco city, the WCS value was 0.83 (climatic zone of winter C), and in the nearest rural station (Carrillanca), the WCS value was 1.01 (climatic zone of winter D). Finally, in the urban station Osorno MMA of Osorno city, the WCS value was 0.99, and in the nearest rural station (Remehue), the WCS value was 1.11. In addition, a difference was found in thermal zones of Valdivia, where the urban station has a thermal zone 4 (OGUC) and the rural station in Pichoy Airport has a thermal zone 5.

Therefore, to calculate thermal or climatic zones and modelling of the energy consumption of buildings for construction, it is necessary to take into account the microclimatic effects of urban heat islands. In addition, it is also necessary to upgrade the climatological data frequently.

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