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PONTIFICIA UNIVERSIDAD CATÓLICA DE CHILE

PROPOSAL ON A NEW CLIMATIC ZONING FOR BUILDING IN THE SOUTH OF CHILE

PROPUESTA DE UNA NUEVA ZONIFICACIÓN CLIMÁTICA PARA EDIFICACIÓN EN EL SUR DE CHILE

TESIS DOCTORAL

KONSTANTIN VERICHEV

Directores:

MONTSERRAT ZAMORANO TORO, MANUEL CARPIO MARTÍNEZ

PROGRAMA DE DOCTORADO EN INGENIERÍA CIVIL (B23.56.1) DE LA UNIVERSIDAD DE GRANADA, ESPAÑA Y PROGRAMA DE DOCTORADO EN CIENCIAS DE LA INGENIERÍA DE LA PONTIFICIA UNIVERSIDAD CATÓLICA DE CHILE, CHILE

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LA TESIS EN RÉGIMEN DE COTUTELA

Esta tesis dostoral se realizó de acuerdo con Convenio para un Doctorado Colaborativo entre la Pontifica Universidad Católica de Chile y la Universidad de Granada conducente a Doble Título en el marco de los programas de Doctorado en Ciencias de la Ingeniería, Área Ingeniería Civil de la Pontifica Universidad Católica de Chile y el programa de Doctorado de Ingeniería Civil de la Universidad de Granada. Teniendo en cuenta la normativa aplicable a los estudios de doctorado en ambas universidades:

En la Pontificia Universidad Católica de Chile:

(i) Reglamento General de Estudios de Doctorado UC (DR N°135/2013).

(ii) Reglamento del Alumno de Doctorado UC (DR N°136/2013).

(iii) Reglamento del Doctorado en Ciencias de la Ingeniería (DR N°384/2014).

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(i) Real Decreto 99/2011 del 28 de mayo de 2011 por el que se regulan las enseñanzas oficiales de doctorado.

(ii) (Normas Reguladoras de las Enseñanzas Oficiales de Doctorado y del Título de Doctor por la Universidad de Granada (aprobadas en la sesión ordinaria del Consejo de Gobierno de 30 de octubre de 2013).

(iii) Normativa de cotutela internacional de tesis doctorales de la Universidad de Granada, aprobada en la sesión ordinaria del Consejo de Gobierno de 27 de septiembre de 2018.

TÍTULO DE DOCTOR CON MENCIÓN INTERNACIONAL POR LA UNIVERSIDAD DE GRANADA

Con el fin de obtener el Título de Doctor por la Universidad de Granada con Mención Internacional, que el Real Decreto 99/2011 establece en su artículo 15, se han cumplido los siguientes requisitos:

(i) Durante el periodo de formación necesario para la obtención del Título de Doctor, el doctorando realizó una estancia mínima de tres meses fuera de España en una institución de enseñanza superior o centro de investigación de prestigio, cursando estudios o realizando trabajos de investigación.

(ii) Parte de la tesis doctoral se ha redactado y presentado en una de las lenguas habituales para la comunicación científica en su campo de conocimiento, distinta a cualquiera de las lenguas oficiales en España.

(iii) La tesis ha sido informada por un mínimo de dos expertos doctores pertenecientes a alguna institución de educación superior o instituto de investigación no española.

(iv) Un experto perteneciente a alguna institución de educación superior o centro de investigación no española, con el título de doctor, y distinto del responsable de la estancia mencionada en el apartado (i), forma parte del tribunal evaluador de la tesis.

TESIS COMO AGRUPACIÓN DE PUBLICACIONES

La presente tesis doctoral se presenta como reagrupamiento de los trabajos de investigación publicados por el doctorando en medios científicos relevantes en su ámbito de conocimiento. Se han cumplido los siguientes requisitos:

(i) Los coautores de los trabajos han aceptado por escrito la presentación de los mismos como parte de la tesis doctoral.

(ii) Los artículos que configuran la tesis doctoral están publicados o aceptados con fecha posterior a la obtención del título de grado y del máster universitario, no habiendo sido utilizados en ninguna tesis anterior y haciéndose mención a la Universidad de Granada y a la Pontifica Universidad Católica de Chile a través de la afiliación del doctorando.

DIFUSIÓN DE RESULTADOS

Los trabajos descritos en la presente memoria se encuentran recogidos en las siguientes publicaciones:

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Verichev, K., Zamorano, M. and Carpio, M. 2019 Assessing the applicability of various climatic zoning methods for building construction: Case study from the extreme southern part of Chile. *Building and Environment*, 106165. Journal Citation Reports (JCR)-2019 IF 4.971. Civil Engineering, Q1, 4/134; Construction and Building Technology, Q1, 6/63; Environmental Engineering, Q1, 12/53. https://doi.org/10.1016/j.buildenv.2019.106165

Verichev, K., Zamorano, M. and Carpio, M. 2020 Effects of climate change on variations in climatic zones and heating energy consumption of residential buildings in the southern Chile. *Energy and Buildings*, 109874. Journal Citation Reports (JCR)-2019 IF 4.867. Civil Engineering, Q1, 5/134; Construction and Building Technology, Q1, 7/63; Energy & Fuels, Q2, 31/112. https://doi.org/10.1016/j.enbuild.2020.109874

Verichev, K., Zamorano, M., Fuentes-Sepúlveda, A., Cárdenas, N. and Carpio, M. 2021 Adaptation and mitigation to climate change of envelope wall thermal insulation of residential buildings in a temperate oceanic climate. *Energy and Buildings*, 110719. Journal Citation Reports (JCR)-2019 IF 4.867. Civil Engineering, Q1, 5/134; Construction and Building Technology, Q1, 7/63; Energy & Fuels, Q2, 31/112. https://doi.org/10.1016/j.enbuild.2021.110719

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INDEX

Index of figures

Index of tables

Index of equations

Index of acronyms

Agromet – Ministry of Agriculture of Chile

AMY – Actual Meteorological Year

AR5 – The 5-th Assessment Report of the IPCC

AR6 – The 6-th Assessment Report of the IPCC

ASHRAE – The American Society of Heating, Refrigerating and Air-Conditioning Engineers

ATC – Adaptive Thermal Comfort

BIM – The Building Information Modeling

Bsk – Cold semi-arid climate of the Köppen-Geiger classification

CCRR – Center for Climate and Resilience Research

CDD – Cooling Degree-Days

Cfb – Marine west coast climate with warm summer

Cfc – Marine west coast climate with mild summer

CHCP, CCHP – Combined Heating, Cooling and Power system

CHP – Combined Heating and Power system

CHP–ORC – CHP systems with Organic Rankine Cycle

CMIP5 – Coupled Model Intercomparison Project (v.5)

CMIP6 – Coupled Model Intercomparison Project (v. 6)

COP – Coefficient of performance

CORMA – Chilean Wood Corporation

Csb – Mediterranean climate with warm summer

Csc – Mediterranean climate with mild summer

CTE – Technical Building Code of Spain

DGAC – Meteorological Directorate of Chile

DHW – Domestic Hot Water

EC – Energy Consumption

ECS – The Sustainable Construction Standards for building in Chile of the MINVU

EIM – Environmental Impact Minimization

ET – Tundra climate

FEL – Following the Electricity Load operation strategy

FTL – Following the Thermal Load operation strategy

GBS – Green Building Studio

GHG – Greenhouse gas

HDD – Heating Degree-Days

HDD15°C – Heating Degree-Days with a base temperature of 15

HDD18°C – Heating Degree-Days with a base temperature of 18°C

HDD18.3°C – Heating Degree-Days with a base temperature of 18.3°C

HRV – Heat Recovery Ventilator

HVAC – Heating, Ventilation, and Air Conditioning systems

IEQ – Indoor Environmental Quality

IPCC – Intergovernmental Panel on Climate Change

ISO – International Organization for Standardization

LCA – Life Cycle Assessment

MINVU – Ministry of Housing and Urban Development of Chile

MM5 – Mesoscale Meteorological Model version 5

MMA – Ministry of the Environment of Chile

N.Ch – Official Chilean Standard

OCR – Operation Cost Reduction

OSB – Oriented Strand Board

PDA – Air Pollution Control Plans of the MMA

PCM – Phase Change Material

PMV – Predicted Mean Vote thermal comfort model

PM2.5 – Atmospheric particles with a diameter of 2.5 µm or less

PV – Photovoltaics systems

RCP – Representative Concentration Pathways of IPCC

R_t – Thermal resistance, [m^2K/W]

RT OGUC – Thermal Regulation Application Manual of the General Ordinance of Urban Planning and Housing of the MINVU of Chile

SCS – Summer Climate Severity index

SRES –The Special Report on Emissions Scenarios of IPCC

SSP – Shared Socio-Economic Pathway of IPCC

TMY – Typical Meteorological Year

TPCY – Typical Principal Component Year

U-value, U – Thermal transmittance, [$W/m^2 \cdot K$]

UHI – Urban Heat Island

WOS – Web of Science

WCS – Winter Climate Severity index

WWR – Windows/Wall Ratio

λ – Conductivity,[W/mK]

ρ – Density, [kg/m^3]

σ – Standard deviation

RESUMEN

Las zonas climáticas para la edificación, correctamente definidas y teniendo en cuenta las características meso- y microclimaticas, así como los altos estándares de construcción, permiten la implementación de edificios energéticamente eficientes con un impacto ambiental mínimo. Sin embargo, el cambio climático está provocando que la clasificación actual de zonas climáticas no se ajuste a la realidad climática existente, por lo que se hace necesario revisar y actualizar las clasificaciones existentes. Este es el caso de Chile, y de manera particular en sus regiones situadas más al sur, donde la zonificación climática actual para la edificación, así como los códigos de edificación, no pueden garantizar la implementación de edificaciones energéticamente eficientes. Esto se refleja en un elevado nivel de consumo energético para calefacción de los edificios, en los que predomina el uso de la biomasa, lo que se traduce en problemas de contaminación atmosférica excesiva en las áreas más pobladas.

En consecuencia, esta tesis ha tenido como objetivo desarrollar una propuesta de zonificación climática para edificación residencial en regiones meridionales de Chile, con una metodología reproducible que permita una actualización constante, mitigue y se adapte al cambio climático, reduciendo así los efectos en el medio ambiente en su proceso de climatización. Para ello, en las cinco regiones más australes del país, se ha analizado la adecuación de la aplicación de diferentes métodos de zonificación climática para la edificación, tales como la basada en grados-día para calefacción, la bioclimática, la basada en el método de clusterización de los parámetros climatológicos, las dos metodologías del Código Técnico de la Edificación de España, la de la *American Society of Heating, Refrigerating and Air-Conditioning Engineers*, así como la metodología aplicada para determinar la transmitancia térmica energéticamente óptima para la envolvente del edificio en el contexto del cambio climático.

Como resultado, se concluye con una propuesta metodológica que ha permitido determinar nuevas zonas climáticas para la edificación, así como proporcionar recomendaciones para el diseño de la envolvente de los edificios, y que se ha basado en la metodología del Código Técnico de la Edificación de España y de la *American Society of Heating, Refrigerating and Air-Conditioning Engineers*.

La proyección realizada de las zonas climáticas de España y Estados Unidos al área de estudio permitirá implementar proyectos de las viviendas de acuerdo con altos

estándares energéticos, así como una constante actualización que facilitará el desarrollo de códigos de construcción dinámicos que permitirán mitigar los efectos del cambio climático, pero también la adaptación de la edificación a los mismos.

ABSTRACT

Correctly defined climate zones for buildings, considering meso- and microclimatic characteristics and high construction standards, allow the implementation of energy-efficient buildings with minimal environmental impact. However, climate change is causing that the current classification of climate zones does not fit the existing climatic reality, so it is necessary to review and update the existing classifications.This is the case in Chile, and particularly in its southern regions, where the current climate zoning for building and building codes cannot guarantee implementation of energy-efficient dwellings. This is reflected in a high level of energy consumption for heating buildings, where the use of biomass predominates, resulting in problems of excessive air pollution in the most populated areas.

Consequently, the aim of this thesis has been to develop a climate zoning proposal for residential buildings in southern regions of Chile, with a reproducible methodology that allows constant updating, mitigating, and adapting to climate change, thus reducing the effects on the environment in its heating, ventilation and air conditioning processes. For this purpose, in the five southern regions of the country, the suitability of the application of different climate zoning methods for buildings has been analysed, such as zoning based on heating-degree days, bioclimatic zoning, cluster zoning, two methodologies of the Spanish Technical Building Code, the American Society of Heating, Refrigerating and Air-Conditioning Engineers methodology, as well as the methodology applied to determine the optimal thermal transmittance for a building envelope in the context of climate change.

As a result, a methodological proposal has been obtained that has made it possible to determine new climatic zones for buildings, as well as to provide recommendations for the design of the building envelope, based on two methodologies: the Spanish Technical Building Code and the American Society of Heating, Refrigerating and Air-Conditioning Engineers.

The projection made of the climatic zones of Spain and the United States on the study area will enable the implementation of housing projects in accordance with high energy standards, as well as a constant updating that will facilitate the development of dynamic building codes that will mitigate the effects of climate change, and the adaptation of buildings to them.

INTRODUCCIÓN, MOTIVACIÓN Y OBJETIVOS

La industria de la construcción, en general, y de la edificación, de forma particular, se caracterizan por un alto nivel de consumo de recursos y emisiones, lo que genera un gran impacto sobre el medio ambiente (de Klijn-Chevalerias & Javed, 2017; Hossain & Ng, 2020); de hecho, el 40% del consumo total de energía, así como un tercio de las emisiones totales de gases de efecto invernadero (GHG) están asociadas con la construcción y la operación de los edificios (Marique & Rossi, 2018; Pal, Takano, Alanne, & Siren, 2017; UNEP's (SBCI), 2009). Estos GHG, mayoritariamente CO_2, se emiten durante todo el ciclo de vida de los edificios, aunque normalmente la fase de operación proporciona la mayor parte del consumo de energía y las emisiones en comparación con la fase de construcción y la de demolición (G. Liu et al., 2020; C. Peng, 2016; Pérez-Lombard, Ortiz, & Pout, 2008). Se puede decir que actualmente, la industria de la construcción es, al menos, un tercio responsable del efecto antropogénico en el cambio climático planetario. Además, se espera que las emisiones mundiales de GHG asociadas con la construcción de edificios se dupliquen para el 2050 (Pomponi & Moncaster, 2016).

El consumo energético de un edificio durante su fase de uso depende de factores intrínsecos al edificio como su forma, los materiales de construcción utilizados, instalaciones y equipamiento (climatización, agua caliente sanitaria, iluminación), o tipo del uso, pero también depende de las condiciones climáticas en las que está ubicado. De hecho, aunque la influencia del clima en el rendimiento térmico de los edificios se conoce desde hace muchos siglos (Bodach, Lang, & Hamhaber, 2014; Z. Zhai & Previtali, 2010), es a partir de la segunda mitad del siglo XX cuando los investigadores han abordado la definición de zonas climáticas como herramientas en los programas de eficiencia energética de edificios (Walsh, Cóstola, & Labaki, 2017b). Una zona climática para edificación se define como un área geográfica en la que las variables climáticas tienen una variación pequeña; esto permite el uso de recomendaciones uniformes para construcción o valores obligatorios para determinadas características o parámetros de la edificación en toda el área dentro de la zona climática (Australian Greenhouse Office, 2000; Lebanon, 2005; Walsh et al., 2017b).

Las zonificaciones climáticas para edificación en países del mundo generalmente se basan en un conjunto de variables/técnicas/parámetros que incluyen (Walsh et al., 2017b):

(i) Método de grados-días, el cual no tiene en cuenta el efecto de otros parámetros meteorológicos, como por ejemplo la humedad atmosférica (Yilmaz, 2007), además, este método necesita una actualización constante (Verichev & Carpio, 2018).

(ii) Método de zonificación climática para edificación basado en simulación energética, el cual no puede tener en cuenta todo el espectro de resoluciones arquitectónicas y constructivas que puede existir en alguna región geográfica (de la Flor, Lissén, & Domínguez, 2006).

(iii) Método de zonificación basado en análisis de clusters, el cual depende de la cantidad y calidad de los parámetros utilizados para la zonificación (Walsh, Cóstola, & Labaki, 2017a).

(iv) Método de diagrama bioclimático de Givoni basado en la temperatura y humedad atmosférica, el cual tiene límites para su aplicación en climas severos (Etxebarria Mallea, Etxepare Igiñiz, & de Luxán García de Diego, 2018; Givoni, 1992).

Sin embargo, alrededor del 80% de los países utilizan sólo hasta tres variables/técnicas/parámetros para definir su zonificación climática para la edificación (Walsh et al., 2017b). Basándose en ello existen dos principales tipos de zonificaciones climáticas para la edificación (Walsh et al., 2017b):

(i) Normas que prescriben el consumo de energía total máximo permitido para viviendas. Este es el caso de las zonificaciones de normas como las de Francia y Finlandia (Finland, 2020; France, 2020).

(ii) Normas que prescriben valores mínimos (o máximos) aceptables para ciertas propiedades térmicas de los componentes de la envolvente del edificio, como valores-U, ganancias térmicas solares, relación ventana-pared, COP de HVAC sistemas, etc. Aquí se engloban las zonificaciones en diversas normas, entre ellas la vigente en Chile, la cual regula los estándares de edificación y es la Reglamentación Térmica de la Ordenanza General de Urbanismo y Construcciones (RT OGUC) del Ministerio de Vivienda y Urbanismo de Chile (MINVU) (Chile, 2006b) y la de la *American Society of Heating, Refrigerating and Air-Conditioning Engineers* (ASHRAE) (ASHARE, 2018; ASHRAE, 2013).

Cabe señalar que recientemente ha habido una tendencia a mezclar los dos tipos de normas presentadas anteriormente. Es el caso del Documento Básico HE Ahorro de energía del Código Técnico de la Edificación de España (CTE) (Spain, 2019) y de los Estándares de Construcción Sustentable (ECS) para viviendas de Chile del MINVU (Chile, 2018a).

Cada técnica de definición de zonas climáticas tiene sus fortalezas y debilidades, así como los límites de aplicación en diferentes áreas geográficas. Por todo esto, no existe una técnica que pueda ser aplicada para todas zonas geográficas del mundo (Walsh et al., 2017b). En cualquier caso, es común a todas ellas la necesidad de una definición correcta de las mismas ya que en caso contrario, esto provoca el uso de estándares de construcción inadecuados en una ubicación geográfica particular, lo que a su vez afecta el nivel de consumo de energía de las viviendas y confort térmico interior. Por este motivo, recientemente, ha habido un creciente interés científico en mejorar y optimizar las normas y aclarar las fronteras de las zonas climáticas para edificación. Así, en China los equipos de varias instituciones presentaron diferentes técnicas para actualizar las fronteras de zonas climáticas para edificación en aspectos meso- y microclimáticos; para ello propusieron la aplicación de las zonas climáticas de ASHRAE, a las que añadieron subzonas adicionales para aquellas regiones en las que las zonas de ASHRAE no reflejaron condiciones climáticas reales (R. Wang & Lu, 2020; Xiong, Yao, Grimmond, Zhang, & Li, 2019; L. Yang, Lyu, Li, & Liu, 2020). Por otro lado, en España el trabajo de López-Ochoa *et al.* demostró que el desarrollo y el cambio de la metodología de zonificación climática recogida en el CTE, así como la mejora de las recomendaciones para la transmitancia térmica de elementos constructivos de viviendas presentados en el CTE, ayudó a disminuir la demanda y el consumo energético de las viviendas hasta el 70% en el norte de España en las últimas dos décadas (Lopez-Ochoa, Las-Heras-Casas, Lopez-Gonzalez, & Olasolo-Alonso, 2018). Por otro lado, recientemente se ha desarrollado una dirección científica de evaluación de zonas climáticas con un método de simulación energética de viviendas en múltiples puntos geográficos, como en las investigaciones de Walsh e*t al.* (Walsh et al., 2017a; Walsh, Cóstola, & Labaki, 2018, 2019).

En cualquier caso, la definición de las zonas climáticas se ha hecho basándose en las condiciones climáticas actuales en el momento de su formulación. Sin embargo, en las últimas décadas se ha observado un cambio climático que está afectado a las citadas clasificaciones. Así, el Grupo Intergubernamental de Expertos sobre el Cambio Climático (IPCC) en su Quinto informe de evaluación del año 2014 (AR5) (IPCC, 2013) nota que:

"cada uno de los tres últimos decenios ha sido sucesivamente más cálido en la superficie de la Tierra que cualquier decenio anterior desde 1850" y *"el incremento total de la temperatura entre el promedio del período 1850-1900 y del período 2003-2012 es de 0.78 [con un intervalo de incertidumbre del 90% de 0.72 a 0.85]°C"*. Al mismo tiempo, se prevé un aumento de la temperatura media mundial para 2100 en el rango de 1.4 a 5.8°C, lo que revela una creciente disparidad entre los patrones climáticos históricos y las condiciones climáticas actuales y futuras como resultado de la actividad antropogénica (IPCC, 2013). Este amplio rango de aumento de temperatura en el año 2100 se caracteriza por diferentes proyecciones de cambio climático. En 2000, se publicó el documento del IPCC *"The Special Report on Emissions Scenarios"* (SRES) (IPCC, 2000). Este documento describe una serie de escenarios de emisión de GHG, basados en diferentes situaciones de desarrollo socioeconómico global, que fueron incorporados en el Tercer Informe de Evaluación del IPCC en 2001 (IPCC, 2001) y en el Cuarto Informe de Evaluación del IPCC en 2007 (IPCC, 2007). Los escenarios establecidos y sus características son los siguientes:

(i) **A1**:del mundo con un desarrollo económico muy acelerado. Incluye tres especificaciones:

a. **A1FI**:donde prevalecerá el uso de combustibles fósiles.

b. **A1B**: con equilibrio de fuentes de energía.

c. **A1T**: donde prevalecerá el uso de combustibles no fósiles.

(ii) **A2**: del mundo heterogéneo con menor preocupación por el rápido desarrollo económico, con diferencias regionales en el desarrollo económico.

(iii) **B1**: del mundo convergente con rápidos cambios en la estructura de la economía (predominio del servicio y la información), reducción del consumo de materiales, introducción de procesos y tecnologías limpias.

(iv) **B2**: del mundo centrado en la sostenibilidad, soluciones locales para problemas ambientales y económicos, cambio tecnológico menos rápido y más diverso, desarrollo económico intermedio.

Con el fin de incorporar nuevos escenarios y desarrollar modelos climáticos que mejoren nuestro conocimiento de los procesos físicos y químicos del sistema climático del planeta, en 2013 se publicó el AR5 (IPCC, 2013). En este documento la comunidad científica ha definido un conjunto de cuatro escenarios, denominados Vías Representativas de Concentración (RCPs), que se caracterizan por el cálculo aproximado que hacen del Forzamiento Radiativo total de la atmósfera en el año 2100 en relación con el año 1750:

(i) **RCP2.6**: Este escenario de mitigación muestra emisiones negativas por uso de energía en la segunda mitad del siglo XXI, requiriendo cambios sustanciales en el uso de energía y emisiones de *non*-CO_2 gases. Todos los países deben aceptar las políticas de cambio climático (IPCC, 2013; Van Vuuren et al., 2007, 2011).

(ii) **RCP4.5**: El escenario de estabilización con cambios en el sistema energético, incluyendo cambios a la electricidad, a tecnologías energéticas de bajas emisiones y al despliegue de tecnología de captura de carbono y almacenamiento geológico. Las emisiones alcanzan su punto máximo alrededor de 2040, luego disminuyen (IPCC, 2013; Thomson et al., 2011).

(iii) **RCP6.0**: El escenario de estabilización con las tasas de mejora de la intensidad energética, que cambia de 0.9% por año a 1.5% por año alrededor de 2060. Se estima que las emisiones se reducirán de manera económico-eficiente en cualquier período a través de un mercado global de permisos de emisiones. Las emisiones alcanzan su punto máximo alrededor de 2080 y luego disminuyen (IPCC, 2013; Masui et al., 2011).

(iv) **RCP8.5**: El escenario sin cambios importantes en el consumo de energía y la tecnología, las emisiones continúan aumentando a lo largo del siglo XXI (IPCC, 2013; Riahi et al., 2011).

En el AR5, los autores señalan que: *"Los nuevos escenarios de RCP especifican concentraciones y las emisiones correspondientes, pero no se basan directamente en caracteristicas socioeconómicas como los escenarios de SRES. Los escenarios de RCP se basan en un enfoque diferente e incluyen cambios de uso de la tierra y gases con vida corta más consistentes. No son necesariamente más capaces de representar desarrollos futuros que los escenarios SRES"*. Por lo tanto, el uso equivalente de escenarios RCP o SRES en las investigaciones científicas es apropiado.

Usando estos escenarios de cambio climático, algunos de los trabajos se centran en evaluar los cambios en el consumo de energía de los edificios residenciales para calefacción y refrigeración, así como, el confort térmico interior en distintas partes del mundo (Gupta & Gregg, 2012; Hacker, De Saulles, Minson, & Holmes, 2008; Kendrick, Ogden, Wang, & Baiche, 2012).

Cabe señalar también que para la evaluación de cambios de consumo energético para calefacción y refrigeración de edificios residenciales, se utilizaron distintas técnicas de aproximación de condiciones climáticas futuras (Aguiar, Oliveira, & Gonccedilalves, 2002; Dolinar, Vidrih, Kajfež-Bogataj, & Medved, 2010; Frank, 2005; Gaterell & McEvoy, 2005; Z. Ren, Chen, & Wang, 2011). Así, en trabajo de Gaterell & McEvoy (Gaterell & McEvoy, 2005) fue implementada la suposición de que el archivo meteorológico de la ciudad de Milán puede ser utilizado para representar el clima del Reino Unido en 2050 en el escenario climático de bajas emisiones y de la ciudad de Roma para el clima del Reino Unido en 2050 en el escenario climático de altas emisiones. También se han realizado estudios en los que se han analizado los efectos del cambio climático sobre el consumo energético de calefacción y refrigeración (Gupta & Gregg, 2012; Hacker et al., 2008; Kendrick et al., 2012) sobre análisis de temperatura interior y confort térmico (Barclay, Sharples, Kang, & Watkins, 2012; Mavrogianni, Wilkinson, Davies, Biddulph, & Oikonomou, 2012; Shikder, Mourshed, & Price, 2012) o bien también sobre métodos de adaptación de edificación en condiciones de cambio climático (Barclay et al., 2012; Gupta & Gregg, 2012; Sajjadian, Lewis, & Sharples, 2015) basándose en escenarios desarrollados por institutos meteorológicos locales; como es el caso del Programa de Impactos Climáticos del Reino Unido (UKCIP), del Real Instituto Meteorológico de los Países Bajos (Hamdy, Carlucci, Hoes, & Hensen, 2017), de la Agencia de Medio Ambiente de Abu-Dhabi y el Ministerio de Energía en los Emiratos Árabes Unidos (Radhi, 2009), del Instituto Nacional de Estudios Ambientales y de la Agencia de Ciencia y Tecnología Marina-Terrestre de Japón (Arima, Ooka, Kikumoto, & Yamanaka, 2016; Kikumoto, Ooka, Arima, & Yamanaka, 2015).

En la ultima década, se empiezan a publicar artículos sobre la evaluación de cambios en consumo energético para calefacción y refrigeración y cambio de confort térmico de vivienda residencial bajo los escenarios SRES y RCP (Tabla 1), que muestran que el escenario A2 es más popular y reflejado en una gran cantidad de artículos científicos.

También se observa que los escenarios SRES se utilizan más, incluyendo una distribución geográfica bastante amplia de las publicaciones en países como Finlandia (Jylhä et al., 2015), Hong Kong (A. L. S. Chan, 2011), Bangladesh (Mourshed, 2011), Turquía (Yildiz, 2014), Taiwán (Huang & Hwang, 2016), Australia (X. Wang, Chen, & Ren, 2010), Brasil (Invidiata & Ghisi, 2016; Triana, Lamberts, & Sassi, 2018), EE.UU. (P. Shen, 2017; P. Shen & Lior, 2016; H. Wang & Chen, 2014), Canadá (Robert & Kummert, 2012), Argentina (Flores-Larsen, Filippín, & Barea, 2019), y escenarios de RCP en Suecia (Dodoo, Gustavsson, & Bonakdar, 2014), Francia (Roux, Schalbart, Assoumou, & Peuportier, 2016), Portugal (Andrić et al., 2016), Brasil (Alves, Duarte, & Gonçalves, 2016), EE.UU. (Sailor, 2014; Z. J. Zhai & Helman, 2019), Italia (Pierangioli, Cellai, Ferrise, Trombi, & Bindi, 2017) y Argentina (Filippín, Ricard, Flores Larsen, & Santamouris, 2017). Esto se puede justificar porque los escenarios SRES han estado operando desde 2001 y por su comprensión socioeconómica. Sin embargo, en los últimos años ha habido un aumento en el uso de escenarios RCP en artículos científicos.

Tabla 1 Publicaciones revisadas con escenarios SRES y RCP.

Scenario		Ref.
SRES scenarios		
A1	A1FI	(H. Wang & Chen, 2014; X. Wang et al., 2010)
	A1T	—
	A1B	(A. L. S. Chan, 2011; Huang & Hwang, 2016; Jylhä et al., 2015; Wan, Li, & Lam, 2011; X. Wang et al., 2010)
A2		(Flores-Larsen et al., 2019; Invidiata & Ghisi, 2016; Jylhä et al., 2015; Mourshed, 2011; Robert & Kummert, 2012; Roetzel & Tsangrassoulis, 2012; Roetzel, Tsangrassoulis, & Dietrich, 2014; Sánchez-García, Rubio-Bellido, Marrero Meléndez, Guevara-García, & Canivell, 2017; P. Shen, 2017; P. Shen & Lior, 2016; Triana et al., 2018; H. Wang & Chen, 2014; Yildiz, 2014)
B1		(A. L. S. Chan, 2011; Jylhä et al., 2015; Robert & Kummert, 2012; Wan, Li, & Lam, 2011; Wan, Li, Pan, & Lam, 2012; H. Wang & Chen, 2014)
B2		(P. Shen & Lior, 2016)
RCP scenarios		
RCP2.6		(Andrić et al., 2016; Z. J. Zhai & Helman, 2019)
RCP4.5		(Dodoo et al., 2014; Filippín et al., 2017; Roux et al., 2016; Sailor, 2014; Z. J. Zhai & Helman, 2019)
RCP6.0		(Andrić et al., 2016; Z. J. Zhai & Helman, 2019)
RCP8.5		(Alves et al., 2016; Andrić et al., 2016; Dodoo et al., 2014; Pierangioli et al., 2017; Roux et al., 2016; Z. J. Zhai & Helman, 2019)

Se puede resumir que la mayoría de los trabajos científicos están orientados en el análisis de los efectos de cambio climático sobre el consumo energético para refrigeración y calefacción en el futuro. De hecho estos estudios prevén, en las regiones con un clima cálido, un aumento del consumo total de energía de las edificaciones, (H. Wang & Chen, 2014; X. Wang et al., 2010), así como una disminución en el caso de las de clima frío, todo ello como consecuencia de la reducción del consumo de energía para calefacción y el incremento de la energía utilizada para enfriamiento (Dolinar et al., 2010; Jylhä et al., 2015).

En el caso de Chile, la RT OGUC (Chile, 2006b) es un documento que define los valores máximos de las transmitancias térmicas de los elementos constructivos de la vivienda de acuerdo con la zona térmica donde está ubicada la vivienda. Este documento es aplicable para todo el país, definiendo 7 zonas térmicas basadas solamente en los valores anuales de grados-días de calefacción con temperatura base de 15°C (HDD15°C). La zonificación normada por la RT OGUC ha sido objeto de diversas críticas en varios aspectos como (Bustamante, 2009; Bustamante, Cepeda, Martínez, & Santa María, 2009; F. Ossio, De Herde, & Veas, 2012; Felipe Ossio, Veas, & Herde, 2012; Rouault, Ossio, González-Levín, & Meza, 2019; Verichev & Carpio, 2018; Verichev, Zamorano, & Carpio, 2019a): estar desactualizada desde el punto de vista climatológico; no cumplir con los estándares de vivienda energéticamente eficiente; tener las fronteras de las zonas basadas en las fronteras administrativas; no tener en cuenta los efectos meso- y microclimatológicos; y estar basada en un solo parámetro meteorológico. En particular, muchos de los problemas indicados con las zonas y las normas de la RT OGUC se observan en regiones del sur de Chile.

Para intentar subsanar algunas de estas deficiencias, en el año 2018 fueron publicados los ECS para viviendas de Chile por el MINVU (Chile, 2018a). En estos estándares se incluyen zonas térmicas actualizadas basadas en zonas térmicas de Norma Chilena (N.Ch) 1079-2008 (Chile, 2008), los valores mejorados de transmitancias térmicas para elementos constructivos de edificios y los valores máximos permisibles de consumo energético de viviendas para enfriamiento y calefacción, tanto para periodo actual como para futuros periodos. Sin embargo, este documento es únicamente informativo, es decir, no obligatorio y no tiene una metodología clara que permita identificar las zonas térmicas. Esta situación, hace imposible reproducir esas zonas, analizar su evolución en el futuro y utilizar esta zonificación en investigaciones científicas relacionadas con el cambio climático.

Hay que tener en consideración que Chile continental comprende una franja en la costa suroeste de América del Sur, que se extiende entre los paralelos 17°29'57" S y 56°32'12" S, alcanzando una longitud de 4.270 km, mayormente desde la ribera sudoriental del océano Pacífico hasta las cumbres más altas de la cordillera de los Andes. En consecuencia, se caracteriza por una diversidad bioclimática que incluye desde el desierto de Atacama, en el norte, hasta los Campos Glaciares en la Patagonia chilena en el sur. Estas diferentes zonas geográficas del país se caracterizan por peculiaridades en el consumo de energía de los edificios residenciales; así, en el norte, prevalece el consumo de energía para enfriamiento de los edificios, mientras que en las regiones más meridionales (La Araucanía, Los Ríos, Los Lagos, Aysén y Magallanes), lo hace el consumo de energía para calefaccionar edificios.

Estas cinco regiones ubicadas al sur del país, con una extensión que supone el 45% de la superficie total del país, incluyen el 13.9% de la población total, así como el 15% de todas las viviendas (generalmente son casas unifamiliares aisladas) en el país (Chile, 2018b). Sin embargo, estas regiones se caracterizan por un importante consumo energético de los hogares para calefacción, en comparación con el resto del país, excluyendo la región altoandina. Así, el consumo de energía por parte del sector residencial se encuentra entre el 14.7 y el 38.4% en la matriz de consumo final de energía de las regiones (Fig. 1), siendo el 80% de esta energía utilizada para calefacción (Chile, 2016a). En comparación, con otro país del hemisferio sur, Nueva Zelanda con condiciones climáticas similares con el sur de Chile, en 2017, mostró un porcentaje de consumo de energía para el sector residencial de 10.8% (New Zealand, 2019). En el caso de un país con condiciones climáticas más severas, como por ejemplo Canadá, solo el 17% de toda la energía es consumida por el sector residencial, donde el 58% de la energía consumida por el sector residencial se utiliza para calefacción de viviendas (Cuddihy, Kennedy, & Byer, 2005).

La incorrección de las zonas climáticas para la edificación en regiones del sur de Chile, junto con los bajos estándares de construcción en términos de eficiencia energética de las viviendas, está provocando la construcción de viviendas térmicamente deficientemente aisladas, lo que genera elevados consumos de energía para la calefacción en el sector residencial. De hecho, Bustamante (Bustamante, 2009) estimó la demanda energética para calefacción en ciudad de Temuco, capital de la región La Araucanía, en 131 kWh/m^2/año para una vivienda unifamiliar de una planta, que cumplía con todas las exigencias de la RT OGUC y en 185 kWh/m^2/año en la ciudad Punta Arenas, capital de la región Magallanes. Estos valores son considerablemente más elevados que los establecidos en los ECS para la demanda de calefacción y enfriamiento, que no deberían superar los 90-110 kWh/m^2/año en regiones del sur de Chile para el año 2030 (Chile, 2018a).

Con el fin de cubrir la alta demanda energética para calefacción por parte de los edificios residenciales en las regiones de La Araucanía, Los Ríos, Los Lagos y Aysén, la biomasa es el combustible predominante (Fig. 1) (Chile, 2018d). Esto, unido a la prevalencia de viviendas térmicamente aisladas deficientemente, resultado del desajuste de eficiencia energética de los estándares de construcción con las zonas climáticas de edificación, provoca altas concentraciones de PM2.5 en la atmosfera de las ciudades, lo que genera problemas ambientales importantes en dichas regiones (Chile, 2015b, 2015a, 2016b, 2018d), así como un aumento en el número de las enfermedades y muertos relacionados con esta situación ambiental (Chile, 2016b). Así, por ejemplo, en la ciudad de Valdivia, un 94.1% de la concentración de PM2.5 en la atmósfera de la ciudad procede de la combustión de biomasa por el sector residencial (Chile, 2016b).

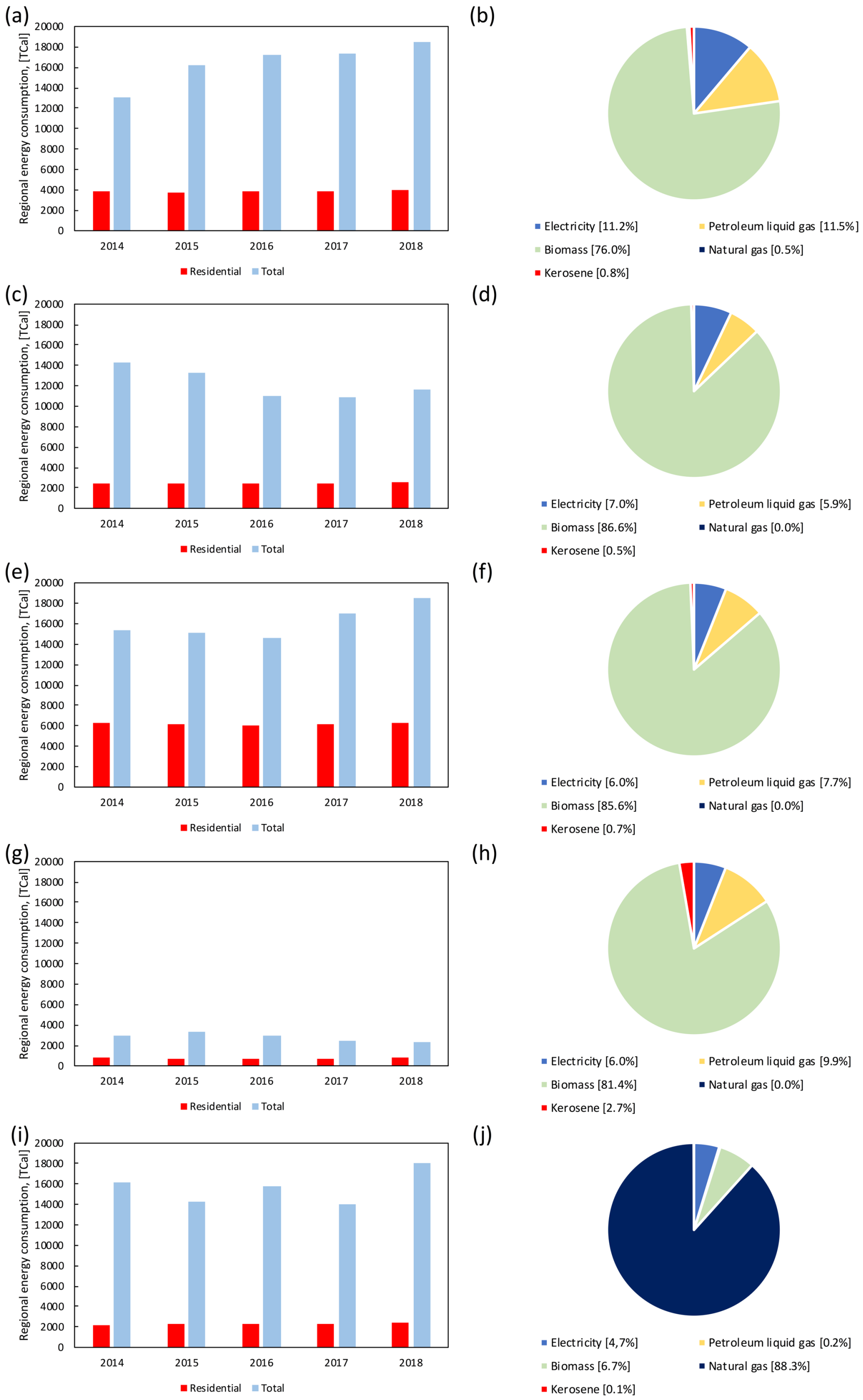


Fig. 1 El parte del sector residencial en el consumo energético final de las regiones y la matriz de las principales fuentes de energía en el sector residencial de las regiones – La Araucanía (a,b), Los Ríos (c,d), Los Lagos (e,f), Aysén (g,h) y Magallanes (i,j).

Por todo lo indicado, en la última década, el MINVU y el Ministerio del Medio Ambiente de Chile (MMA) ha desarrollado los Planes de Descontaminación Atmosférica (PDA) en estas regiones. Así, actualmente, existen cuatro PDA para las comunas de

Temuco y Padre las Casas (Chile, 2015b), Valdivia (Chile, 2016b), Osorno (Chile, 2015a) y Coyhaique (Chile, 2018d), todas ellas en el sur del país. Estos planes, concordantes con la Estrategia Nacional de Planes de Descontaminación Atmosférica del MMA la cual pretende disminuir las emisiones del sector residencial, se basan en:

(i) El mejoramiento térmico de las viviendas.

(ii) La mejora de la eficiencia de los artefactos de combustión a leña y otros derivados de la madera.

(iii) La sustitución de sistemas de calefacción contaminantes por sistemas eficientes y con menos emisiones, el cual tiene por objetivo reducir las emisiones a la atmósfera.

(iv) El mejoramiento de la calidad de la leña y disponibilidad de otros combustibles.

(v) La educación y sensibilización a la comunidad.

Estos planes presentan recomendaciones para mejorar la envolvente térmica de los edificios con requisitos de edificación mejores que en la RT OGUC, pero en cualquier situación solo abarcan cinco comunas, las cuales representan solo un tercio de la población del área de estudio. No obstante, los problemas ambientales y energéticos que pretenden solucionarse con ellos son similares a los observados en otras ciudades y comunas del área de estudio, para las que aún no se han desarrollado PDAs.

Por tanto, se puede concluir que hay evidencias claras de que las zonificaciones y normas actuales no pueden garantizar la realización de viviendas energéticamente eficientes en el sur de Chile en el periodo actual, pero tampoco permiten analizar la evolución de zonas climáticas para la edificación en condiciones de cambio climático futuro. Además, es necesario definir zonas climáticas más precisas para la edificación en la parte extrema del sur de Chile, lo que fue notado en la N.Ch 1079-2008, y que no fue tenido en cuenta en el proceso de desarrollo de los ECS del año 2018. Todo ello permitirá definir envolventes térmicas mejoradas para las viviendas construidas en estas regiones, que podrán ser utilizadas en la redacción de los PDAs.

En consecuencia, el objetivo principal que se establece para esta investigación ha sido la propuesta de una nueva zonificación climática para edificación residencial en las regiones meridionales de Chile, basada en una metodología clara y reproducible, que permita su adaptación al cambio climático y que reduzca los efectos provocados por la climatización de las viviendas en el medio ambiente. La propuesta podrá ser utilizada por constructores, diseñadores, arquitectos, ingenieros, así como instituciones gubernamentales, todos ellos responsables de tomas de decisiones en edificación sustentable en aspectos energéticos y medioambientales.

Para alcanzar este objetivo principal, se establecen los siguientes objetivos específicos:

- Definir los principales temas, tipos y la importancia de las investigaciones climáticamente orientadas y sobre las zonas climáticas en el área de la edificación.
- Evaluar los tipos de zonificaciones climáticas existentes para el área del estudio mediante la modelización del consumo de energía de los principales tipos de las viviendas en periodos actuales y futuras.
- Identificar los aspectos claves que pueden mejorar la zonificación climática para la edificación en el sur de Chile.
- Analizar la posibilidad de aplicar metodologías de zonificación climática para la edificación de otros países para el área de estudio.
- Proponer una nueva zonificación climática y presentar recomendaciones de transmitancia térmica de los elementos constructivos a través de la búsqueda y selección de métodos óptimos para zonificación.
- Evaluar efectos medioambientales y energéticos de cambio climático para el diseño de las viviendas y proponer la metodología que tenga en cuenta estos efectos.

INTRODUCTION, MOTIVATION AND OBJECTIVES

The construction industry, in general, and the building industry, in particular, are characterised by a high level of consumption of resources and emissions, which greatly impacts the environment (de Klijn-Chevalerias & Javed, 2017; Hossain & Ng, 2020); in consequence, 40% of the total energy consumption and one-third of the total greenhouse gas (GHG) emissions are associated with the construction and operation of buildings (Marique & Rossi, 2018; Pal et al., 2017; UNEP's (SBCI), 2009). Furthermore, global GHG emissions associated with building construction are expected to double by 2050 (Pomponi & Moncaster, 2016). These GHGs, mainly CO_2, are emitted throughout the entire life cycle of buildings, although typically, the operation phase accounts for the majority of energy consumption and emissions compared to the construction and demolition phases (G. Liu et al., 2020; C. Peng, 2016; Pérez-Lombard et al., 2008).

The energy consumption of a building during its use phase depends on factors intrinsic to it such as its shape, the construction materials used, installations and equipment (heating, ventilation, air conditioning, hot water, lighting), or type of use, but also depends on the climatic conditions of the area in which it is located. In fact, although the influence of climate on the thermal performance of buildings has been known for many centuries (Bodach et al., 2014; Z. Zhai & Previtali, 2010), it is from the second half of the 20th century that researchers have approached the definition of climate zones as tools in energy efficiency programs of buildings (Walsh et al., 2017b). A building climate zone is defined as a geographical area where climatic variables have a small variation; this allows the use of uniform building recommendations or mandatory values for certain building characteristics or parameters throughout the area within the climate zone (Australian Greenhouse Office, 2000; Lebanon, 2005; Walsh et al., 2017b).

Climate zoning for buildings in countries around the world is generally based on different variables/techniques/parameters. (Walsh et al., 2017b), the most frequent being:

(i) Degree-days methods, which only take into account this variable but not the effects of other meteorological parameters, such as atmospheric humidity (Yilmaz, 2007), should be under constant updating (Verichev & Carpio, 2018).

(ii) Methods of climatic zoning for building, which are based on energy simulation and cannot consider the entire spectrum of architectural and constructive resolutions that may exist in a given geographical region (de la Flor et al., 2006).

(iii) Zoning methods, which are based on cluster analysis and depends on the amount and quality of the parameters used for the zoning procedure (Walsh et al., 2017a).

(iv) Givoni's building bioclimatic chart, which is based on temperature and atmospheric humidity but is limited when is used under severe climatic conditions (Etxebarria Mallea et al., 2018; Givoni, 1992).

However, around 80% of the countries use only up to three variables/techniques/parameters to define their climate zoning for buildings (Walsh et al., 2017b). On this basis, there are two main types of climate zoning for building (Walsh et al., 2017b):

(i) Standards are prescribing the maximum allowable total energy consumption for dwellings. This is the case for zoning of standards in France and Finland. (Finland, 2020; France, 2020).

(ii) Standards are prescribing minimum (or maximum) acceptable values for certain thermal properties of building envelope components, such as U-values, solar heat gains, window-to-wall ratio, COP of HVAC systems, etc. Here are included the zoning of various standards, among them, includes official norm in Chile, which regulates building standards, the Thermal Regulation of the General Ordinance of Urbanism and Constructions (RT OGUC) of the Chilean Ministry of Housing and Urbanism (MINVU) (Chile, 2006b) and includes climatic zoning for the building of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (ASHARE, 2018; ASHRAE, 2013).

It should be noted that recently there has been a tendency to combine the two types of standards presented above, as, for example, in the case of climate zones in the Basic Document HE Energy Saving of the Spanish Technical Building Code (*Código Técnico de la Edificación de España* (CTE))(Spain, 2019) and the Sustainable Construction Standards (*Estándares de Construcción Sustentable* (ECS)) for Chilean dwellings of the MINVU (Chile, 2018a).

Each climate zone definition technique has its strengths and weaknesses, as well as the limits of application in different geographical areas. Therefore, there is no one technique that can be applied to all geographical areas of the world (Walsh et al., 2017b).

In any case, common to all of them is the need for their correct definition; otherwise, this leads to the use of inappropriate building standards in a particular geographical location, which affects the energy consumption level of dwellings and indoor thermal comfort. For this reason, there has recently been a growing scientific interest in improving and optimising standards and clarifying the boundaries of climate zones for buildings. For example, in China, teams from various institutions presented different techniques to update the boundaries of climate zones for building climate in meso- and microclimatic aspects, proposing the application of ASHRAE climate zones, to which they added additional sub-zones for those regions where the ASHRAE zones did not reflect actual climatic conditions (R. Wang & Lu, 2020; Xiong et al., 2019; L. Yang et al., 2020). In Spain, it has been demonstrated in the work of López-Ochoa *et al.* how the development and change of the climate zoning methodology contained in the CTE, and the improvement of the recommendations for thermal transmittance of building elements of dwellings presented in the CTE, helped to reduce the energy demand and consumption of houses up to 70% in the north of Spain in the last two decades (Lopez-Ochoa et al., 2018). Also recently, a scientific direction of climate zone assessment with a multi-geographic housing energy simulation method has been developed, such as in the research of Walsh A. *et al.* (Walsh et al., 2017a, 2018, 2019).

In any case, the definition of climate zones has been made based on the current climatic conditions at the time of their formulation. However, in recent decades it has been observed that climate change is affecting these classifications. Thus, the Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment Report 2014 (AR5), notes that: *"Each of the last three decades has been successively warmer at the Earth's surface than any previous decade since 1850"* and *"The total temperature increase between the average of the period 1850-1900 and the period 2003-2012 is 0.78 [with a 90% uncertainty interval of 0.72 to 0.85]°C"*. At the same time, the global average temperature is projected to increase by 2100 in the range of 1.4 to 5.8°C, revealing a growing disparity between historical climate patterns and current and future climate conditions as a result of anthropogenic activity. This wide range of temperature increase in the year 2100 is characterised by different projections of climate change. In 2000, "The Special Report on Emissions Scenarios" (SRES) (IPCC, 2000) IPCC document was published. This document describes a series of GHGs emission scenarios, based on different situations of global socio-economic development, which were incorporated into the Third Assessment Report of IPCC in 2001 (IPCC, 2001) and in the Fourth Assessment Report of IPCC in 2007 (IPCC, 2007). The established scenarios and their characteristics are as follows:

(i) **A1**: of very rapid economic development. It includes three specifications:

a. **A1FI**: where the use of fossil fuels will prevail.

b. **A1B**: with a balance of energy sources.

c. **A1T**: where the use of non-fossil fuels will prevail.

(ii) **A2**: of the heterogeneous world with less concern for rapid economic development, with regional differences in economic development.

(iii) **B1**: of the convergent world with rapid changes in structure of economy (prevalence of service and information), reduction in material consumption, the introduction of clean processes and technologies.

(iv) **B2**: focused on sustainability, local solutions for environmental and economic problems, less rapid and more diverse technological change, intermediate economic development.

To incorporate new scenarios and develop climatic models that improve our knowledge of the physical and chemical processes of the planet's climate system, the AR5 was published in 2013 (IPCC, 2013). In this document, the scientific community has defined a set of four scenarios, called Representative Concentration Pathways (RCPs), which are characterised by the approximate calculation they make of the total Radiative Forcing of the atmosphere in the year 2100 in relation to the year 1750:

(i) **RCP2.6**: this mitigation scenario shows negative emissions from energy use in the second half of the 21st century, requiring substantial changes in energy use and emissions of non-CO_2 gases. Every country must accept climate change policies (IPCC, 2013; Van Vuuren et al., 2007, 2011).

(ii) **RCP4.5**: stabilisation scenario with changes in the energy system, including shifts to electricity, to lower-emission energy technologies and the deployment of carbon capture and geologic storage technology. Emissions peak around 2040, then decline (IPCC, 2013; Thomson et al., 2011).

(iii) **RCP6.0**: stabilisation scenario with the energy intensity improvement rates change from 0.9% per year to 1.5% per year around 2060. Emissions are assumed to be reduced cost-effectively in any period through a global market for emissions permits. Emissions peak around 2080 and then decline (IPCC, 2013; Masui et al., 2011).

(iv) **RCP8.5**: Scenario without significant changes in energy consumption and technology, emissions continue to rise throughout the 21st century (IPCC, 2013; Riahi et al., 2011).

In AR5, the authors note that: *"RCP scenarios are new ones that specify concentrations and corresponding emissions but are not directly based on socio-economic storylines like the SRES scenarios. The RCP scenarios are based on a different approach and include more consistent short-lived gases and land-use changes. They are not necessarily more capable of representing future developments than the SRES scenarios"*. Therefore, the equivalent use of RCP or SRES scenarios in scientific research is appropriate.

Using these climate change scenarios, some studies have focused on evaluating changes in the EC of residential buildings for heating and cooling, as well as the interior thermal comfort in different parts of the world (Gupta & Gregg, 2012; Hacker et al., 2008; Kendrick et al., 2012).

It should be noted that also for evaluating changes in energy consumption for heating and cooling residential buildings, different techniques for approximating future climatic conditions were used (Aguiar et al., 2002; Dolinar et al., 2010; Frank, 2005; Gaterell & McEvoy, 2005; Z. Ren et al., 2011). Thus, in the work of Gaterell and McEvoy (2005) (Gaterell & McEvoy, 2005), it is assumed that the Milan weather file used to represent the UK climate in 2050 under the low emissions climate scenario and Rome for the UK climate by 2050 under the high emissions climate scenario. Studies have also been carried out that have analysed the effects of climate change on energy consumption for heating and cooling (Barclay et al., 2012; Mavrogianni et al., 2012; Shikder et al., 2012), on analysis of indoor temperature and thermal comfort (Barclay et al., 2012; Mavrogianni et al., 2012; Shikder et al., 2012) or on adaptation methods of building in conditions of climate change (Barclay et al., 2012; Gupta & Gregg, 2012; Sajjadian et al., 2015) based on scenarios developed by local meteorological institutes such as the United Kingdom Climate Impacts Program, the Royal Netherlands Meteorological Institute in the Netherlands (Hamdy et al., 2017), the Environment Agency of Abu-Dhabi and the Ministry of Energy in the United Arab Emirates (Radhi, 2009), the National Institute for Environmental Studies and Agency for Marine-Earth Science and Technology of Japan (Arima et al., 2016; Kikumoto et al., 2015).

In the last decade, studies on the evaluation of changes in heating and cooling EC and change of interior thermal comfort of residential dwellings, under the SRES and RCP scenarios, have been published (Table 1), showing that the scenario A2 is more popular and reflected in a large number of scientific papers.

It is also observed that SRES scenarios are used more, including a fairly wide geographical distribution of the works in countries such as Finland (Jylhä et al., 2015), Hong Kong (A. L. S. Chan, 2011), Bangladesh (Mourshed, 2011), Turkey (Yildiz, 2014), Taiwan (Huang & Hwang, 2016), Australia (X. Wang et al., 2010), Brazil (Invidiata & Ghisi, 2016; Triana et al., 2018), the USA (P. Shen, 2017; P. Shen & Lior, 2016; H. Wang & Chen, 2014), Canada (Robert & Kummert, 2012), Argentina (Flores-Larsen et al., 2019), and RCP scenarios in Sweden (Dodoo et al., 2014), France (Roux et al., 2016), Portugal (Andrić et al., 2016), Brazil (Alves et al., 2016), the USA (Sailor, 2014; Z. J. Zhai & Helman, 2019), Italy (Pierangioli et al., 2017) and Argentina (Filippín et al., 2017); this can be justified because SRES scenarios have been operating since 2001 and because of their socioeconomic understanding. However, in recent years there has been an increase in the use of RCP scenarios in scientific papers.

Table 1 Revised publications with SRES and RCP scenarios.

Scenario		Ref.
SRES scenarios		
A1	A1FI	(H. Wang & Chen, 2014; X. Wang et al., 2010)
	A1T	—
	A1B	(A. L. S. Chan, 2011; Huang & Hwang, 2016; Jylhä et al., 2015; Wan, Li, & Lam, 2011; X. Wang et al., 2010)
A2		(Flores-Larsen et al., 2019; Invidiata & Ghisi, 2016; Jylhä et al., 2015; Mourshed, 2011; Robert & Kummert, 2012; Roetzel & Tsangrassoulis, 2012; Roetzel et al., 2014; Sánchez-García et al., 2017; P. Shen, 2017; P. Shen & Lior, 2016; Triana et al., 2018; H. Wang & Chen, 2014; Yildiz, 2014)
B1		(A. L. S. Chan, 2011; Jylhä et al., 2015; Robert & Kummert, 2012; Wan, Li, & Lam, 2011; Wan et al., 2012; H. Wang & Chen, 2014)
B2		(P. Shen & Lior, 2016)
RCP scenarios		
RCP2.6		(Andrić et al., 2016; Z. J. Zhai & Helman, 2019)
RCP4.5		(Dodoo et al., 2014; Filippín et al., 2017; Roux et al., 2016; Sailor, 2014; Z. J. Zhai & Helman, 2019)
RCP6.0		(Andrić et al., 2016; Z. J. Zhai & Helman, 2019)
RCP8.5		(Alves et al., 2016; Andrić et al., 2016; Dodoo et al., 2014; Pierangioli et al., 2017; Roux et al., 2016; Z. J. Zhai & Helman, 2019)

It can be summarised that most of the cited scientific works are oriented to the analysis of the effects of climate change on cooling and heating EC in the future (Y. Shi & Wang, 2020; Z. J. Zhai & Helman, 2019).

In fact, these studies foresee, in regions with a warm climate, an increase in the total energy consumption of buildings(H. Wang & Chen, 2014; X. Wang et al., 2010), as well as a decrease in the case of those with a cold climate, all as a consequence of the reduction in energy consumption for heating and the increase of that used for cooling (Dolinar et al., 2010; Jylhä et al., 2015).

In the case of Chile, the RT OGUC (Chile, 2006b) is a document that defines the maximum values of the thermal transmittances of the construction elements of the dwellings, according to the thermal zone where the unit is located. This document is applicable for the whole country, defining 7 thermal zones based only on the annual values of heating degree-days with a base temperature of 15°C. (HDD15°C). The zoning regulated by the RT OGUC has been criticised in several aspects (Bustamante, 2009; Bustamante et al., 2009; F. Ossio et al., 2012; Felipe Ossio et al., 2012; Rouault et al., 2019; Verichev & Carpio, 2018; Verichev et al., 2019a), such as being climatologically outdated; not complying with energy efficient housing standards; having zone boundaries based on administrative boundaries; not taking into account meso- and microclimatological effects; and being based on a single meteorological parameter. Many of the problems with the RT OGUC zones and standards are observed in regions in southern Chile.

To correct some of these deficiencies, in 2018, the MINVU published the ECS for Chilean dwellings (Chile, 2018a). These standards include updated thermal zones based on thermal zones of Chilean Standard (N.Ch) 1079-2008 (Chile, 2008), improved thermal transmittance values for building construction elements and maximum permissible values of energy consumption of dwellings for cooling and heating, not only for the current period but also for future periods. However, this document is only informative, meaning, that it is not mandatory and has no clear methodology for identifying thermal zones. This situation makes it impossible to reproduce these zones, analyse their evolution in the future and use this zoning in scientific research related to climate change.

It should be taken into consideration that continental Chile comprises a strip on the southwest coast of South America extending between parallels 17°29'57"S and 56°32'12"S, reaching a length of 4,270 km, mostly from the southeastern shore of the Pacific Ocean to the highest peaks of the Andes Mountains. As a result, it is characterised by a bioclimatic diversity ranging from the Atacama Desert in the north to the Glacier Fields in Chilean Patagonia in the south. These different geographical areas of the country are characterised by peculiarities in the energy consumption of residential buildings; thus, in the north, energy consumption for cooling buildings prevails, while in the southern regions (La Araucanía, Los Ríos, Los Lagos, Aysén and Magallanes), energy consumption for heating buildings prevails during a year.

These five regions located in the south of the country, with an extension that corresponds to 45% of the total area, include 13.9% of the total population, as well as 15% of all dwellings (generally detached single-family houses) in the country (Chile, 2018b). However, it is characterised by significant household energy consumption for heating compared to the rest of the country, excluding the high Andean region. Thus, energy consumption by the residential sector is between 14.7 and 38.4% in the final energy consumption matrix of the regions (Fig. 1), with 80% of this energy being used for heating (Chile, 2016a). For comparison, in the southern hemisphere, New Zealand with similar climatic conditions to southern Chile, in 2017, showed a percentage of energy consumption for the residential sector of 10.8% (New Zealand, 2019). In the case of a country with more severe climatic conditions, for example, Canada, only 17% of all energy is consumed by the residential sector, where 58% of the energy consumed by the residential sector is used for house heating (Cuddihy et al., 2005).

The incorrectness of the climatic zones for building in these regions, together with the low construction standards in terms of energy efficiency of dwellings, leads to the construction of thermally poorly insulated houses, resulting in high energy consumption for heating in the residential sector. In fact, Bustamante (Bustamante, 2009) estimated the energy demand for heating in the city of Temuco, capital of the La Araucanía region, at 131kWh/m^2/year for a single-family, one-storey house, which complied with all RT OGUC requirements, and at 185 kWh/m^2/year in the city of Punta Arenas, capital of the Magallanes region. These values are considerably higher than those established in the ECS for the demand for heating and cooling, which should not exceed 90-110 kWh/m^2/year in southern regions of Chile by 2030 (Chile, 2018a).

In order to cover the high heating energy demands of residential buildings in the regions of La Araucanía, Los Ríos, Los Lagos and Aysén, biomass is the predominant fuel used (Fig. 1) (Chile, 2018d). This, together with the prevalence of poorly insulated houses, a result of the energy efficiency mismatch of building standards with building climatic zones, causes high concentrations of PM2.5 in the atmosphere of cities, which generates significant environmental problems in those regions (Chile, 2015b, 2015a, 2016b, 2018d), as well as an increase in the number of diseases and deaths related to this environmental situation (Chile, 2016b). Thus, for example, in the city of Valdivia, 94.1%

of the concentration of PM2.5 in the city's atmosphere comes from biomass combustion produced by the residential sector (Chile, 2016b).

For all the above, in the last decade, the MINVU and the Ministry of the Environment of Chile (MMA) have developed Air Pollution Control Plans (PDAs) in these regions. Thus, there are currently four PDAs for the communes of Temuco and Padre las Casas (Chile, 2015b), Valdivia (Chile, 2016b), Osorno (Chile, 2015a) and Coyhaique (Chile, 2018d), all in the south of the country. These plans, in line with the National Strategy for Atmospheric Decontamination Plans of the MMA, which aims to reduce emissions from the residential sector, rely on:

(i) Thermal upgrading of dwellings.

(ii) Improving the efficiency of wood-burning and other wood-based combustion appliances.

(iii) The replacement of polluting heating systems with efficient and less emitting systems, which aims to reduce emissions into the atmosphere.

(iv) Improving the quality of fuelwood and availability of other fuels.

(v) Education and community awareness on these issues.

These plans present recommendations to improve the thermal envelope of buildings with building requirements higher than those of RT OGUC, but in any case, only cover five communes, which represent just one-third of the population of the study area. However, the environmental and energy problems intended to be solved by PDAs are similar to those observed in other cities and communes in the study area, for which they have not yet been developed.

It can therefore be concluded that there is clear evidence of the current zoning and standards cannot guarantee the construction of energy-efficient housing in southern Chile in the current period, but neither do these standards allow for an analysis of the evolution of climate zones for building under conditions of future climate change. In addition, it is necessary to define more precise climatic zones for buildings in the extreme southern part of Chile, which was noted in N.Ch 1079-2008, and which was not considered in the process of developing the ECS in 2018. All of this will lead to the definition of improved thermal envelopes for the dwellings built in these regions, which can be used in the drafting of the PDAs.

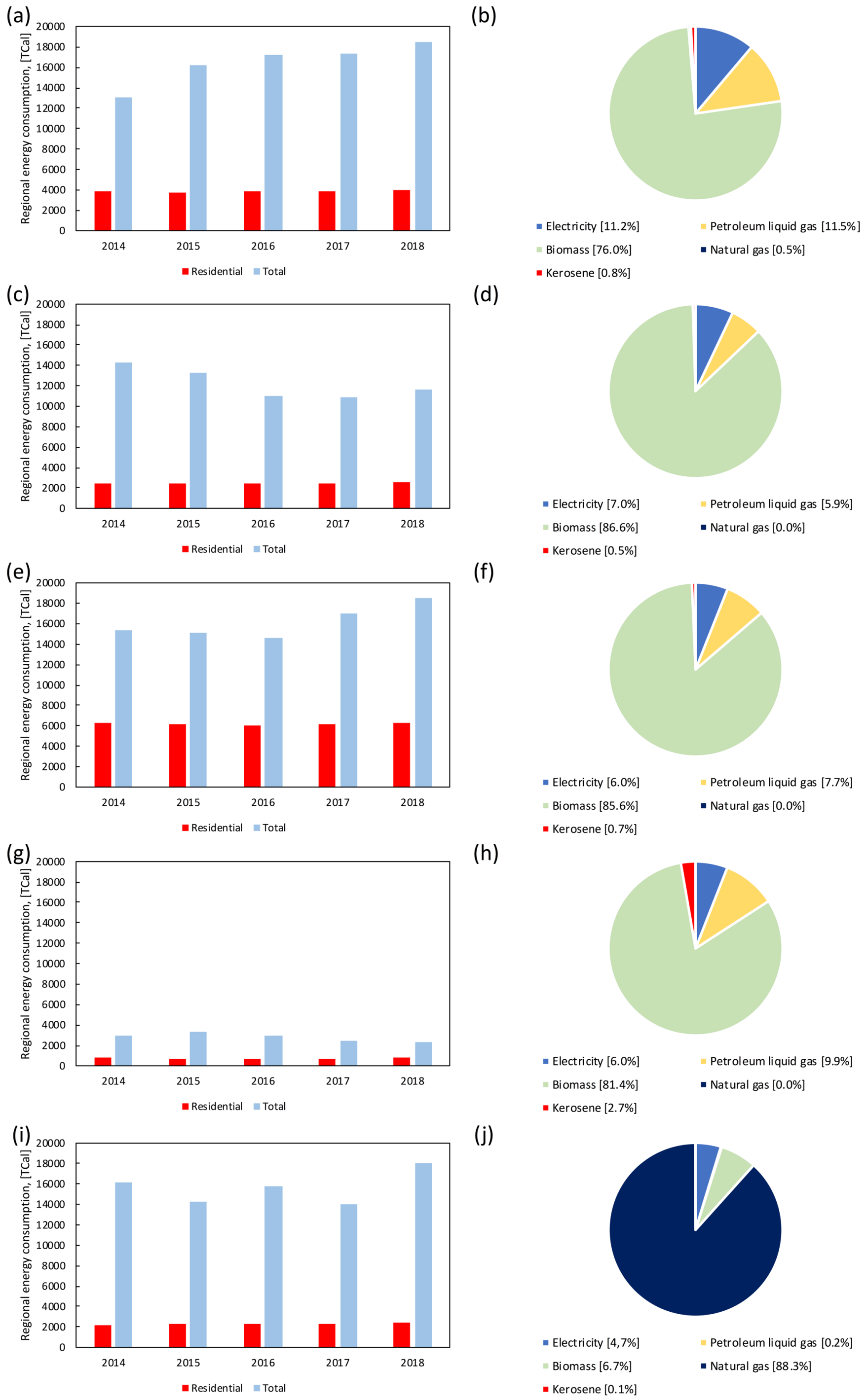


Fig. 1 The share of the residential sector in the final energy consumption of the regions and the matrix of the main energy sources of the residential sector in the regions - La Araucanía (a,b), Los Ríos (c,d), Los Lagos (e,f), Aysén (g,h) and Magallanes (i,j).

Consequently, the main objective of this research is the proposal of a new climate zoning for residential buildings in the southern regions of Chile, based on a clear and reproducible methodology that allows adaptation to climate change and reduces the effects on the environment caused by heating, ventilation and air conditioning of dwellings. The proposal can be used by builders, designers, architects, engineers, as well as governmental institutions, all of them responsible for decision making in sustainable building in energy and environmental aspects.

In order to achieve this main objective, the following specific objectives were established:

- Define the main topics, types, and importance of climate-oriented and climate zone research in the building area.
- Assess the existing climate zoning types for the study area by modelling the energy consumption of the main categories of dwellings in current and future periods.
- Identify key aspects that can improve climate zoning for building in southern Chile.
- Analyse the possibility of applying climate zoning methodologies for building from different countries in the study area.
- Propose a new climate zoning and present recommendations for thermal transmittance of building elements through the search and selection of optimal zoning methods.
- Assess environmental and energy effects of climate change for dwelling design and propose a methodology that takes these effects under consideration.

Part I. Background

As a starting point for the research, it was necessary to contextualise it, both scientifically and in terms of application, which has been included in this part of the document.

For this purpose, the first chapter presents a bibliographical review that addresses building design from a climatic point of view. This has allowed the definition of the theoretical framework of the investigation, as well as the scientific evolution of the subject to be addressed, which has facilitated the establishment of the starting point of the research, as well as the key points to be considered in order to achieve the established objectives.

However, building design is carried out in accordance with a regulatory framework that establishes the requirements that buildings must meet in relation to the basic requirements of safety, habitability, and energy efficiency. This regulatory framework, although based on common technical and scientific criteria, is tailored to the social, economic, and environmental conditions of each country. For this reason, it has been necessary - in a second chapter - to include, on the one hand, the definition of the geographical area in which the research is being carried out, the south of Chile, and on the other hand, the reference framework for building design in this area.

CHAPTER 1.-

ANALYSIS OF CLIMATE-ORIENTED RESEARCHES IN BUILDING[1]

[1] The results shown in this chapter were presented in: **Verichev, K.**, Zamorano, M., Salazar-Concha, C., Carpio, M., **Analysis of Climate-Oriented Researches in Building** (2021) *Applied Sciences* 11(7) V., 3251

1.1. Introduction

The scientific production in the field of buildings and climate and climate change has been increasing in recent years, in addition to becoming more interdisciplinary. Among the published aspects is the development of methodologies that allow the use of current meteorological data for the energy simulation of the dwellings (Eguía Oller, Alonso Rodríguez, Saavedra González, Arce Fariña, & Granada Álvarez, 2018; Fabiana Silvero, Lops, Montelpare, & Rodrigues, 2019), as well as the development of works that are aimed at improving the hierarchy of climatic zones in buildings (Bai & Wang, 2019; Verichev & Carpio, 2018), so as to reduce the construction of inefficient houses from an energy point of view, and that take into account the urban, meso- and microclimatic conditions for buildings (Praene, Malet-Damour, Radanielina, Fontaine, & Riviere, 2019; Toparlar, Blocken, Maiheu, & van Heijst, 2018; Walsh et al., 2018; Xiong et al., 2019; X. Yang et al., 2019).

Besides, during last years, in the context of the evolution of knowledge about the climate system, as well as a knowledge evolution about the anthropogenic impact on the climate, research on minimizing energy consumption (EC) in building construction by optimizing the use of materials and GHG emissions has begun (Aslam, Huang, & Cui, 2020; Bahramian & Yetilmezsoy, 2020; Gan et al., 2020). In this sense, the development of climate change projections has sparked interest in conducting research on the change of climate zones for buildings in future climate conditions (Verichev, Zamorano, & Carpio, 2020; Z. J. Zhai & Helman, 2019). Furthermore, papers have been published on the analysis of changes in the total EC of housing, as well as on the possible evolutions of changes in EC for the cooling and/or heating of dwellings in different parts of the world (Dolinar et al., 2010; Jylhä et al., 2015; Rey-Hernández et al., 2018; H. Wang & Chen, 2014; X. Wang et al., 2010). In addition, other research has dealt with changes in the climate values of heating degree-days (HDD) and cooling degree-days (CDD) in the future (Eshraghi, Ansari, Moshari, & Gholami, 2019; Ramon, Allacker, De Troyer, Wouters, & van Lipzig, 2020). Likewise, studies have been carried out on the analysis of adaptation techniques (Far & Far, 2018; F Silvero, Lops, Montelpare, & Rodrigues, 2019) and mitigation (Bollo & Cole, 2019; Geng, Chen, & Yang, 2019) in relation to climate change. The concern about climate change by researchers, public administration, and society in general has promoted new research on the development of state standards and programs to control the negative effects of the building construction industry on the environment and policies to mitigate the effects of climate change (Deetjen, Conger, Leibowicz, & Webber, 2018; Graham & Rawal, 2019; Thonipara, Runst, Ochsner, & Bizer, 2019).

Generally, all studies in building carried out based on climatological parameters, or in the context of climate change effects, can be identified as climate-oriented. Furthermore, for the most part, studies in building are characterized by pronounced localism, as it is generally implemented on a country, region, or city scale. To a large extent, this situation is due to the research focus on the final consumer (government of countries, regions, municipal authorities, local construction companies, etc.). This is a substantial factor, as local building experts have a clear understanding of the particular characteristics of the region in which they work, conduct research, and carry out applied projects. However, this may be a limiting factor if we consider the development of certain unified global techniques and methodologies. The climate factor clearly emerges from localism, which in turn affects the development of climate-oriented scientific works in building.

The studies mentioned above are directly linked to climate, with topics on climate zones for buildings, meteorological data for energy simulations, and change in EC under conditions of global climate change. However, there are also works that are indirectly related to climate, that is, studies that do not directly address climate research, but whose results or methodologies depend on climate or climate zones. For example, research on the composition and structure of the substrate of green roofs, where the authors show that the dependence on the optimal composition and structure of the substrate for better bioproductivity of the plants, is ultimately affected by the climatic zones (Kazemi & Mohorko, 2017); the selection of the best hybrid cooling system to minimise EC and building emissions shows how each climate zone corresponds to a technically different optimal system (Kojok, Fardoun, Younes, & Outbib, 2016); studies on passive building cooling have shown the importance of the climate zone with respect to the various techniques used (Bhamare, Rathod, & Banerjee, 2019); and the neutral temperature of the adaptive thermal comfort model and its relation to the minimum mortality temperature have a clear regional dependence (Y. Jiang, Lu, Wang, & Lin, 2019).

For the above reasons, the dependence of the objectives, methodologies, and/or results of studies on climate is based on the dependence on climate parameters and their variability, both temporal and geographical. In addition, a certain set of climatic parameters (at certain intervals) characterizes some climatic zones. Therefore, the term climate-oriented is directly related to climate zones. Thus, in the works mentioned above, it can be seen that many aspects of building construction depend on climatic zones, specialized building zones, or bioclimatic zones. Therefore, an understanding of all topics, parameters, techniques, and methods of building according to climate zone will help in optimally designing buildings in different parts of the world.

Due to the large number of publications dealing with construction from a climate or climate-oriented point of view, either directly or indirectly, a scientific map of climate-oriented studies in building has been established in this chapter. To do that, a bibliographic and manual analysis of the publications with the most significant impact in recent decades has been performed; it has also identifies the main topics, the typologies of these investigations, and the main types of climatic zoning used in these studies and the principal climate zones in which the investigated works were implemented.

1.2. Material and methods

1.2.1. Bibliometric and bibliographic methods

In recent years, different methods of bibliometrics have been widely used to analyse the development of different fields of science. Bibliometrics is divided into two main areas:

(i) Performance analysis, where several scientific producers are evaluated using bibliographic data and applying bibliometric index (h-index, hg-index, etc.);

(ii) Analysis of science maps, where the structural and dynamic aspects of the field of science and its temporal evolution are studied, while also analysing the intellectual connections and their evolution in the field of knowledge (Moral-Munoz, López-Herrera, Herrera-Viedma, & Cobo, 2019).

To study a scientific map, it is necessary to create and analyse bibliographic networks. In the study of Moral-Munoz *et al.* (Moral-Munoz et al., 2019), a description of the main types of bibliographic networks is presented, including the following:

(i) Co-citation networks – two publications can be considered as co-cited if a third publication quotes both. The strength of the co-citation relationship will depend on the number of publications citing both publications together (Fig. 2). Papers A and B are associated because they are co-cited in a reference list of papers C, D, and E. Therefore, the greater the number of co-citations, the stronger the co-citation relationship (Moral-Munoz et al., 2019; H. Small, 1973).

(ii) Bibliographic coupling networks – in this case, two publications are bibliographically coupled if both publications cite a third (Fig. 2). Papers A and B are bibliographically coupled because they have common cited paper C, D, and E in their reference list. A higher number of references shared by two publications indicates a stronger bibliographic coupling between them (Kessler, 1963; Moral-Munoz et al., 2019; H. G. Small & Koenig, 1977).

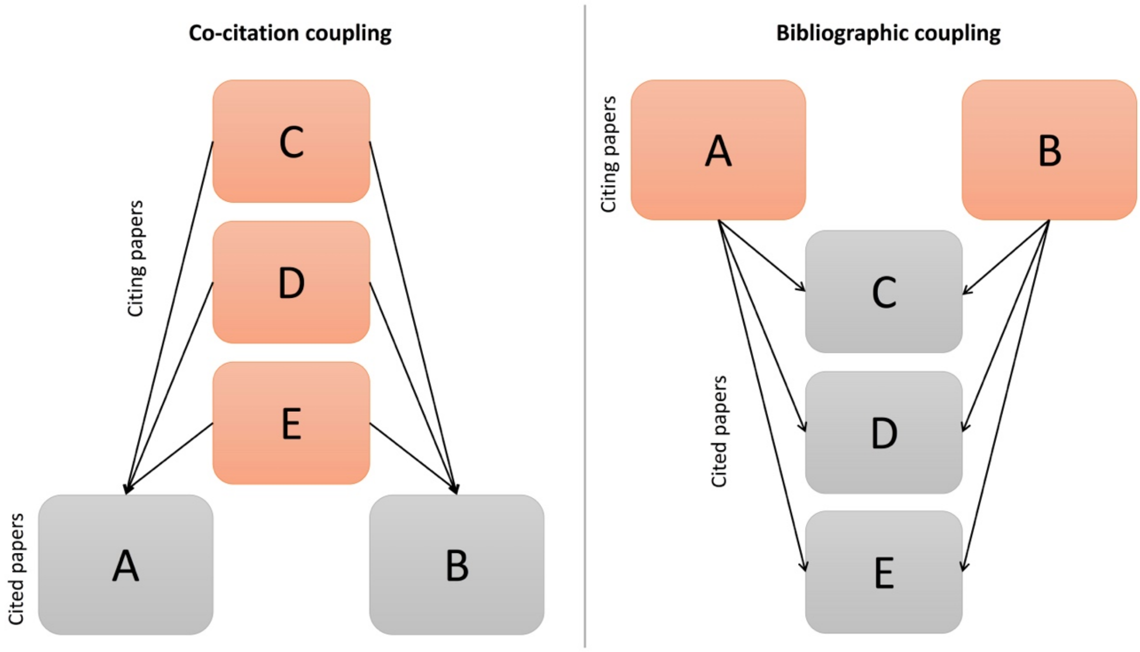


Fig. 2 Bibliographic and co-citation coupling difference.

Small & Koenig, in 1977, clustered journals based on the bibliographic coupling method, demonstrating good results in comparison with the manual classification method (H. G. Small & Koenig, 1977). In addition, the claim that the bibliographic coupling method is capable of grouping documents of similar research types has been confirmed in Jarneving's research (Jarneving, 2007). Furthermore, in the work of Boyack & Klavans (Boyack & Klavans, 2010), the use of bibliographic coupling showed better results in the clustering process, compared to co-citation analysis and direct citation analysis. For these reasons, in this paper, it was decided to use this methodology for science mapping analysis.

1.2.2. Data collection

The study of this chapter is based on the main articles on climate-oriented studies in building. Papers published on the Web of Science (WOS) up to the end of 2019 were analysed. To find the articles, the following formula was used in “advanced search”: TS=("climate zone" and "building") OR TS=("climatic zone" and "building") OR TS=("climate zones" and "building") OR TS=("climatic zones" and "building") OR TS=("climate zone" and "buildings") OR TS=("climatic zone" and "buildings") OR TS=("climate zones" and "buildings") OR TS=("climatic zones" and "buildings") OR TS=("climatic zoning" and "building") OR TS=("climatic zoning" and "buildings").

The initial sample drawn from WOS included a total of 1403 documents. First, manually, the abstracts and keywords of all publications were reviewed, and publications not related to the building scientific field were excluded. After this additional manual examination of publications, a total of 1280 documents remained. To select the publications with the most significant impact, 10% of the most cited papers were used (with more than 35 citations in WOS at the end of 2019). After applying this filter, 128 articles were selected covering the period from 1995 to 2018.

1.2.3. Clustering tools and methodology

In the first stage of data processing, the Bib Excel tool was used to transform the .txt file of the WOS to a Citation Network File (with a number of commonly cited papers in references for each pair of articles). Of the 128 articles that made up the database, only 114 presented common references and therefore formed the basis of our cluster analysis.

To analyse the Citation Network File, it was processed in the program Gephi, version 0.9.2 (Bastian, Heymann, & Jacomy, 2009). Gephi is open-source software for graphics and network analysis, which provides the possibility of visualization and research of all types of complex networks and systems, dynamic and hierarchical graphics. Gephi was implemented for a bibliometric analysis of research in different fields of science, applying different methods for analysis (Bartolini, Bottani, & Grosse, 2019; Leydesdorff & Rafols, 2012; Y. Wang, Lai, Zuo, Chen, & Du, 2016). Note that Gephi is the most reliable software for scientific map analysis (Moral-Munoz et al., 2019). In this research, a 114x114 matrix was formed in Gephi with common references numbers for each pair of papers.

For clustering of the article network, a modularity cluster detection algorithm was used. The cluster definition algorithm is heuristic, based on modularisation optimisation, and was first published in 2008 by Blondel *et al.* (Blondel, Guillaume, Lambiotte, & Lefebvre, 2008). This algorithm (or Louvain's method (Blondel et al., 2008)) has several advantages, such as the ease and speed of implementation and the ability to analyse large and weighted networks. In comparison with other methods, Blondel's algorithm showed better results for the definition of clusters (Blondel et al., 2008; Lancichinetti & Fortunato, 2009). The general methodology of this chapter is presented in Fig. 3.

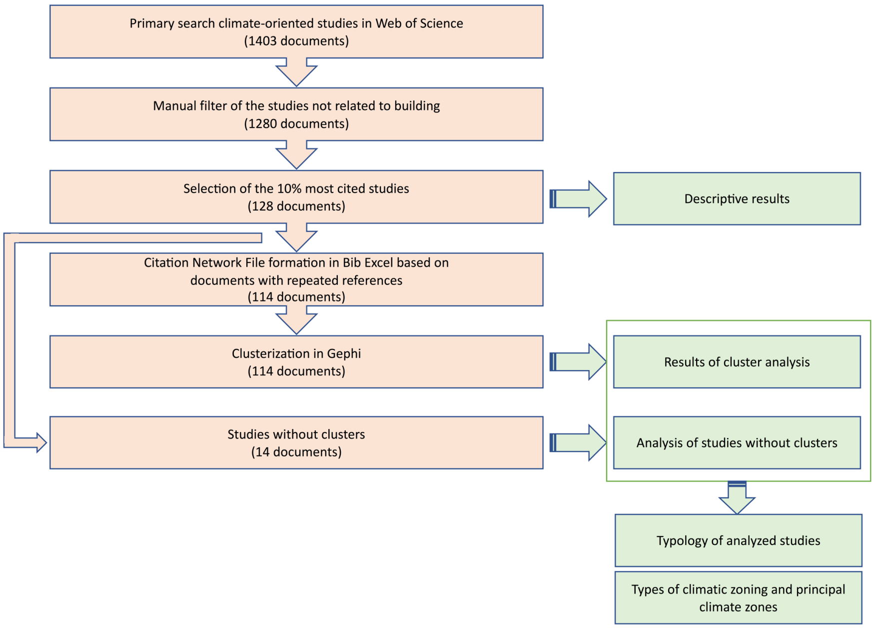


Fig. 3 The general methodology of analysis of climate-oriented research in building.

The scope of the present chapter to identify the scientific map of climate-oriented publications can be summarised as follows:

(i) Only WOS publications were used.

(ii) 10% of the most frequently cited papers were analysed.

(iii) A bibliographic coupling method was used for clustering.

(iv) Works published from 1995 to 2018 were analysed.

1.3. Results and discussion

1.3.1. Descriptive results

The time trend of the 128 publications used in this chapter, all with more than 35 citations, is presented in Fig. 4. It shows an upward trend, with a maximum number of documents published in 2012. The first work was published in 1995, and in the following 15 years (period: 1995 - 2011), 60 papers were published, while in a more recent period of only 7 years (2012 - 2018), a similar number has been published, specifically 68 articles. The typology of the works studied includes 112 full research articles, 10 reviews, 4 article proceeding papers, 1 review book chapter, and 1 editorial; these results once again highlight the intensive research being carried out on the subject under study in the present chapter.

Note that the earliest studies were related to the analysis of the effect of climate change on variations in the EC of buildings (Rosenthal, Gruenspecht, & Moran, 1995), as well as to the analysis of the method of energy conservation by improving the thermal envelope of buildings (Balaras, Droutsa, Argiriou, & Asimakopoulos, 2000). The maximum of mean number of citations in Fig. 4 in 2002 is associated with the publication of one of the fundamental articles on adaptive thermal comfort (R. J. de Dear & Brager, 2002).

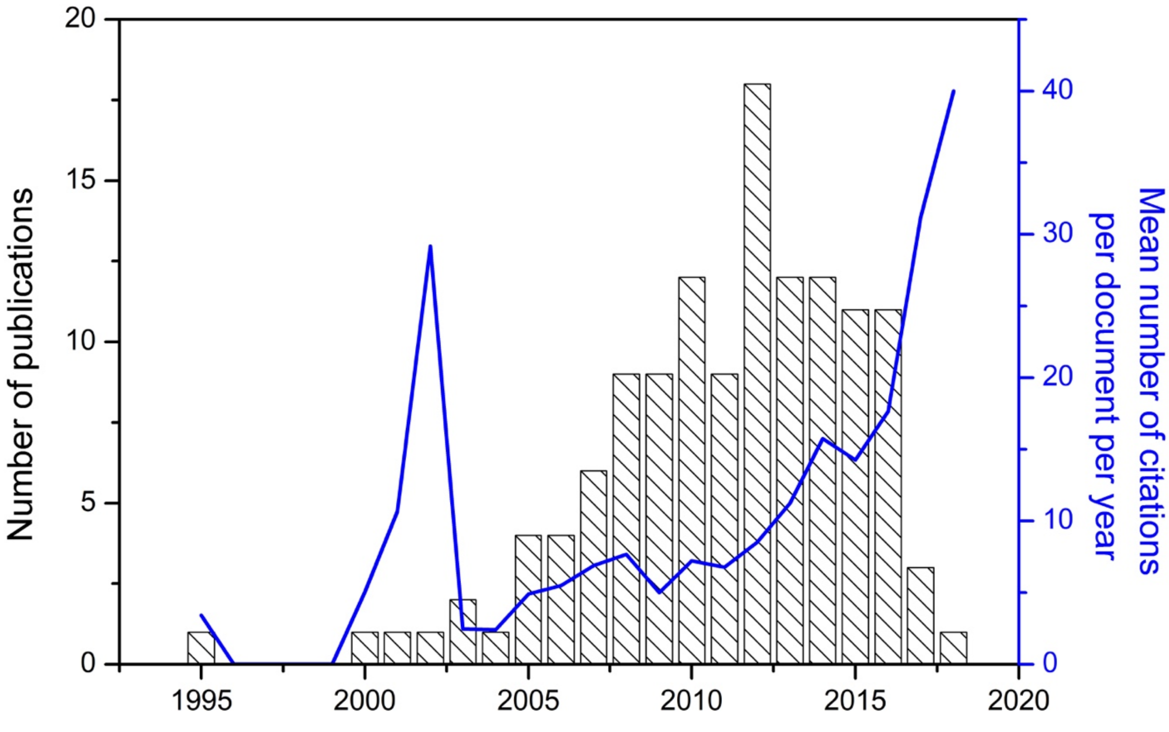


Fig. 4 Temporal evolution of analysed climate-oriented publications.

Note that, in the period up to 2005, principal studies related to the study of microorganisms in the indoor air were conducted (Kemp, Neumeister-Kemp, Esposito, Lysek, & Murray, 2003; Tsai & Macher, 2005). Furthermore, in 2005, some of the main works on the study of cool roofs as energy saving techniques were published (Akbari, Levinson, & Rainer, 2005; Levinson, Akbari, Konopacki, & Bretz, 2005). In 2008, a study on Fanger's thermal comfort analysis was published (J van Hoof, 2008). In 2014, work on the pairing of indoor thermal comfort and an analysis of the energy saving potential was published (L. Yang, Yan, & Lam, 2014). The most recent work analyses the reduction of carbon emissions from office buildings as a result of the effective building energy efficiency policy in China (Ma & Cai, 2018). In general, over the past decades, the dominant theme of most of the papers under study has been energy saving in buildings. At the same time, this topic has gradually absorbed new emerging topics; for example, the topic of adaptive thermal comfort has been integrated into the energy saving concept. Urban heat island mitigation techniques, systems optimization, building envelope optimization techniques, and emission reduction techniques have also become progressively more complex. Meanwhile, the analysis of microorganisms in the indoor air has remained outside the general topic of energy saving.

The papers included in this study collect a total of 8777 citations in WOS, of which 24.6% are concentrated in ten of them, as shown in Table 2.

Table 2 The most cited bibliography, used in the analysed researches.

Title of publ.	Authors	Journal	Type	Year	Tot. cit.	Tot. cit./year	Ref.
Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55	De Dear R.J.; Brager G.S.	Energy and Buildings	Article proceedings paper	2002	496	29.2	(R. J. de Dear & Brager, 2002)
Thermal comfort and building energy consumption implications - A review	Yang L.;Yan H.Y.; Lam J.C.	Applied Energy	Review	2014	308	61.6	(L. Yang et al., 2014)
Solar air conditioning in Europe - an overview	Balaras C.A.; Grossman G.; Henning H.M.; Ferreira C.A.I.; Podesser E.; Wang L.; Wiemken E.	Renewable & Sustainable Energy Reviews	Review	2007	241	20.1	(Balaras et al., 2007)
Forty years of Fanger's model of thermal comfort: comfort for all?	Van Hoof J.	Indoor Air	Review	2008	220	20.0	(J van Hoof, 2008)
The adaptive model of thermal comfort and energy conservation in the built environment	De Dear R.; Brager G.S.	International Journal of Biometeorology	Article	2001	192	10.7	(R. de Dear & Brager, 2001)
Zero energy buildings and sustainable development implications - A review	Li D.H.W.; Yang L.; Lam J.C.	Energy	Review	2013	182	30.3	(D. H. W. Li, Yang, & Lam, 2013)
Determination of optimum insulation thickness for building walls with respect to various fuels and climate zones in Turkey	Bolatturk A.	Applied Thermal Engineering	Article	2006	150	11.6	(Bolatturk, 2006)
Impact of climate change on energy use in the built environment in different climate zones - A review	Li D.H.W.; Yang L.; Lam J.C.	Energy	Review	2012	128	18.3	(D. H. W. Li, Yang, & Lam, 2012)
Energy performance of building envelopes in different climate zones in China	Yang L.; Lam J.C.; Tsang C.L.	Applied Energy	Article	2008	122	11.1	(L. Yang, Lam, & Tsang, 2008)
Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings	Hoyt T.; Arens E.; Zhang H.	Building and Environment	Article	2015	119	29.8	(Hoyt, Arens, & Zhang, 2015)

As can be seen, this generally involves research related to interior thermal comfort, the search of optimal thermal insulation and the use of renewable energy to improve the energy performance of houses.

The 128 publications analysed were produced by 359 authors. Table 3 presents the authors with the most significant impact, the total number of citations, the number of publications of each author used in this study, and the main work of each author. 313 of the identified authors participated in only one publication, and the average citation value per author was 80. Most of the analysed studies are concentrated in China (24%) and the USA (20%), with the rest of the countries being in the minority (7% from Greece, 6% from Spain, 5% from Australia, and the remaining 38% from 22 other countries); in fact, the five authors with the largest number of publications belong to Chinese institutions (Lam J.C, Yang L., Jing Y.Y, Li D.H.W., and Wang J.J.), which comprise 2847 of the 8777 citations.

Table 3 Principal authors of the analysed researches.

Author	Last affiliation (05 Oct 2019)	Num. publ.	Sum. cit.	Year of the first publ.	Title of more cited publ.	Ref.
Lam J.C.	City University of Hong Kong, Kowloon, Hong Kong	8	983	2008	Thermal comfort and building energy consumption implications - A review	(L. Yang et al., 2014)
Yang L.	Xi'an University of Architecture and Technology, Xi'an, China	7	904	2008	Thermal comfort and building energy consumption implications – A review	(L. Yang et al., 2014)
Jing Y.Y.	North China Electric Power University, Baoding, Baoding, China	4	268	2010	Multi-criteria analysis of combined cooling, heating and power systems in different climate zones in China	(Jiang-Jiang, Chun-Fa, & You-Yin, 2010)
Li D.H.W.	City University of Hong Kong, Kowloon, Hong Kong	4	424	2011	Zero energy buildings and sustainable development implications – A review	(D. H. W. Li et al., 2013)
Wang J.J.	North China Electric Power University, Baoding, Baoding, China	4	268	2010	Multi-criteria analysis of combined cooling, heating and power systems in different climate zones in China	(Jiang-Jiang et al., 2010)
Balaras C.A.	National Observatory of Athens, Athens, Greece	3	379	2000	Solar air conditioning in Europe - an overview	(Balaras et al., 2007)
De Dear R.	The University of Sydney, Sydney, Australia	3	326	2001	Thermal comfort in naturally ventilated buildings: revisions to ASHRAE standard 55	(R. J. de Dear & Brager, 2002)
Hong T.Z.	Lawrence Berkeley National Laboratory, Berkeley, United States	3	158	2013	Commercial building energy saver: an energy retrofit analysis toolkit	(Hong et al., 2015)
Mago P.J.	Mississippi State University, Starkville, United States	3	137	2009	Analysis and optimization of the use of CHP-ORC systems for small commercial buildings	(Pedro J Mago, Hueffed, & Chamra, 2010)
Tsang C.L.	City University of Hong Kong, Kowloon, Hong Kong	3	251	2008	Energy performance of building envelopes in different climate zones in China	(L. Yang, Lam, & Tsang, 2008)
Ucar A.	Firat Üniversitesi, Elazig, Turkey	3	169	2009	Effect of fuel type on the optimum thickness of selected insulation materials for the four different climatic regions of Turkey	(Ucar & Balo, 2009)
Wan K.K.W.	City University of Hong Kong, Kowloon, Hong Kong	3	195	2008	Building energy efficiency in different climates	(Lam, Wan, Tsang, & Yang, 2008)

1.3.2. Results of cluster analysis

Next, an analysis of the results of the Citation Network processing in Gephi, as well as the clustering, was carried out, identifying the main directions of scientific development in climate-oriented studies in building. As clustering was based on common references, Table 4 shows the analysis of the most commonly used references in the analysed studies. In total, 114 analysed studies cited 4172 publications. At the same time, work published in ASHRAE Transaction (R. de Dear, Brager, & Cooper, 1998) is presented in the references of 12 analysed studies.

Table 4 Most used articles in references of analysed studies.

Year	Journal/Book	Title of publ.	Num. of rep.	Ref.
1998	ASHRAE Transactions	Developing an adaptive model of thermal comfort and preference	12	(R. de Dear et al., 1998)
2008	Applied Energy	Energy performance of building envelopes in different climate zones in China	9	(L. Yang, Lam, & Tsang, 2008)
1998	Energy and Buildings	Thermal adaptation in the built environment: a literature review	8	(Brager & de Dear, 1998)
2011	Building and Environment	Future trends of building heating and cooling loads and energy consumption in different climates	8	(Wan, Li, Liu, & Lam, 2011)
2002	Energy and Buildings	Thermal comfort in naturally ventilated buildings: revisions to ASHRAE standard 55	7	(R. J. de Dear & Brager, 2002)
1970	Book	Thermal comfort. Analysis and applications in environmental engineering.	7	(Fanger, 1970)
2002	Energy and Buildings	Extension of the PMV model to non-air-conditioned buildings in warm climates	7	(Ole Fanger & Toftum, 2002)
1998	ASHRAE Transactions	Understanding the adaptive approach to thermal comfort	7	(Humphreys & Nicol, 1998)
2005	Renewable Energy	Energy policy and standard for built environment in China	7	(Yao, Li, & Steemers, 2005)
2003	Applied Energy	Towards sustainable-energy buildings	6	(Chwieduk, 2003)
2009	Energy and Buildings	Analysis and optimization of CCHP systems based on energy, economical, and environmental considerations	6	(P J Mago & Chamra, 2009)
2008	Energy and Buildings	Integration of distributed generation systems into generic types of commercial buildings in California	6	(Medrano, Brouwer, McDonell, Mauzey, & Samuelsen, 2008)
2012	Applied Energy	Impact of climate change on building energy use in different climate zones and mitigation and adaptation implications	6	(Wan et al., 2012)
2010	Applied Energy	Multi-criteria analysis of combined cooling, heating and power systems in different climate zones in China	6	(Jiang-Jiang et al., 2010)
2010	Energy	Environmental impact analysis of BCHP system in different climate zones in China	6	(J. Wang, Zhai, Zhang, & Jing, 2010)
2011	Applied Energy	Influence analysis of building types and climate zones on energetic, economic and environmental performances of BCHP systems	6	(J. Wang, Zhai, Jing, & Zhang, 2011)

The map of bibliographic coupling clusters obtained from Gephi analysis (Fig. 5) made it possible to identify the following 9 clusters, in addition to the general outline of the relationship between Citation Network works:

- Cluster 1 – Mitigation of the effects of UHI and cooling of buildings (with the following principal topics: Building cooling, UHI mitigation techniques, Outdoor thermal comfort, General energy saving techniques, and Indoor thermal comfort in UHI conditions);
- Cluster 2 – Indoor air microorganisms;
- Cluster 3 – Combined heating, cooling and power systems;
- Cluster 4 – Economic and energy optimization of the thermal insulation;
- Cluster 5 – Indoor thermal comfort;
- Cluster 6 – Energy optimization of school buildings;
- Cluster 7 – Infiltration and air leakage;
- Cluster 8 – Windows and façade optimization;
- Cluster 9 – Energy simulation, conservation and meteorological data (with the following principal topics - Simulation of EC, Multi-parametric and multi-objective optimizations, Schedule occupancy optimization, Heat and energy recovery ventilators, HVAC-systems optimization, Indoor thermal comfort models

implementation for energy simulation, Climate change and EC, Building climate zones, and Meteorological data for simulation).

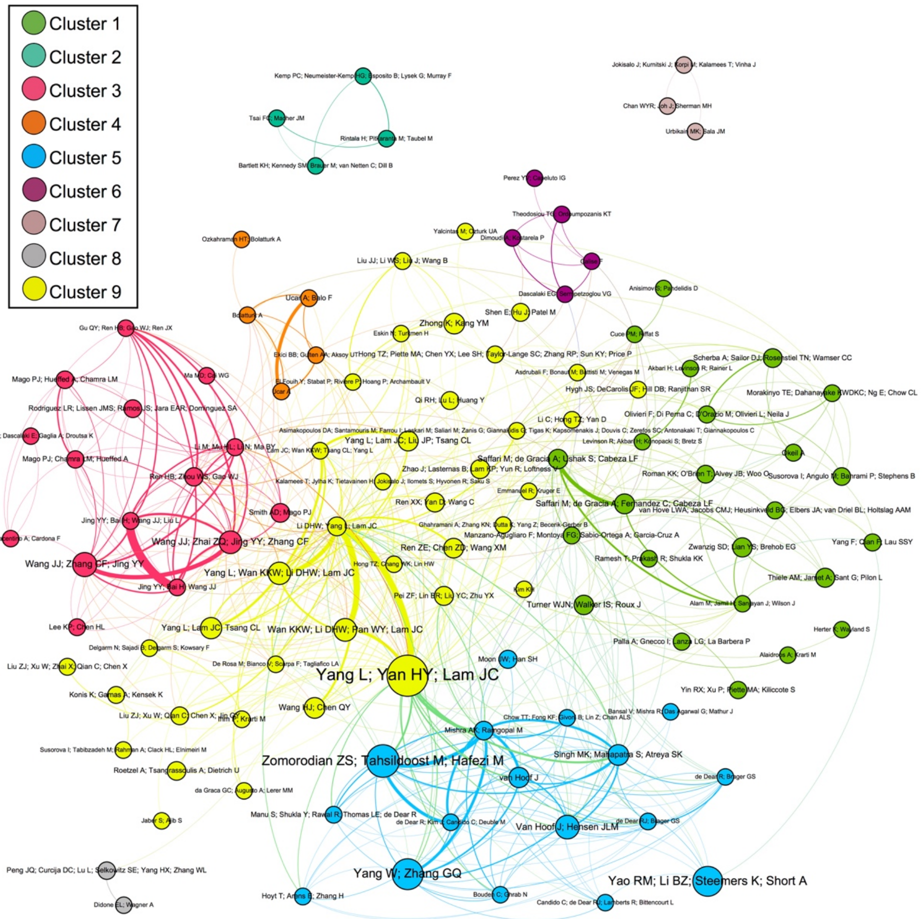


Fig. 5 Map of bibliographic coupling clusters.

In this clustering, 114 publications have been used, with 517 interconnections (edges) of repeated references in each pair of papers, varying from 1 common reference to 41. Fig. 5 shows that, of all the clusters identified, 7 are connected to each other, and 2 are isolated; depending on the number of references in common, the thickness of the edge is greater if there are more references in common between two works. There is a greater number of common references in studies by the same authors, e.g., (Yang L; Yan HY; Lam JC) (L. Yang et al., 2014) and (Li DHW; Yang L; Lam JC) (D. H. W. Li et al., 2012). On the other hand, the size of the circle of each article depends on the degree of involvement of each work in the Citation Network of the study; thus, the work of (Yang L; Yan HY; Lam JC) (L. Yang et al., 2014) is grade 51, which means that 48 study network papers are used in his references, and 3 study network papers cite this work; instead, the research of (Ozkahraman HT; Bolatturk A) (Ozkahraman & Bolatturk, 2006) is grade 1 and located on the periphery of the network, which means that only 1 study in the network uses this work in its references. Given that the present study used works with high citation numbers in the scientific environment, the main emphasis in the analysis of the results will focus on the clustering and the definition of the main themes of the studies, and not on how these works relate to each other in this research network.

In general, the seven clusters have a clear correspondence with one single scientific topic. However, Cluster 9 includes ten themes, due to its central position among other clusters; therefore, the themes of this cluster can overlap with the topics of other clusters. In addition, Cluster 1 includes five themes.

During the analysis of the publications, it was observed that most of the works are within an overall theme of energy conservation in the buildings. Outside the subject of energy conservation is the Indoor air microorganisms theme (Cluster 2). Moreover, the Indoor air microorganisms theme is isolated, just as most of the work of Indoor thermal comfort is outside the subject of energy conservation; this is because, although research has recently been carried out on the application of thermal comfort models in the process of energy simulation and for the evaluation of the energy efficiency of buildings, most of the studies in this cluster focused on the development of thermal comfort models. The topic of outdoor thermal comfort (Cluster 1), is also vaguely related to the topic of energy conservation. The economic and energy optimization of the thermal insulation (Cluster 4), is difficult to relate completely to the topic of energy conservation, as the basis of the works on this theme is the methodology for finding an economic optimum between the insulation material and the economic costs of heating and cooling in buildings.

It can be said that the definition of clusters using Gephi and the bibliographic coupling method showed good results for identifying peripheral and isolated topics. However, in the case of centrally located topics and overlapping topics, additional manual analysis of the content of the clusters is required. Therefore, a detailed analysis of each cluster will be presented below.

1.3.2.1. Cluster 1 –Mitigation of the effects of UHI and cooling of buildings

This first cluster includes a total of 24 investigations (Table A. 1). These include general methodologies for energy conservation in buildings, techniques for mitigation the various effects of urban heat islands (UHI), the improvement of outdoor thermal comfort in UHI conditions, and techniques for reducing EC for cooling in buildings.

The first and oldest works of this cluster were focused on the idea of energy conservation. They analysed the application of cool-roof energy conservation techniques for non-residential and commercial buildings in different cities and in different climate zones, showing energy simulation results (Akbari et al., 2005; Levinson et al., 2005). Subsequently, studies appeared that focus on the search for optimal bioclimatic architectural strategies (Manzano-Agugliaro, Montoya, Sabio-Ortega, & Garcia-Cruz, 2015) as well as the optimal design of residential building envelop systems (Alaidroos & Krarti, 2015), all of this with the general aim of reducing EC in housing and improving indoor thermal comfort.

Mitigation techniques were developed, ranging from cool-roofs, green roofs, and green façades, to the application of phase change materials (PCM) for building envelopes and the search of the optimal PCM for different cities and climate conditions. These generally show an evolution from field studies of the thermal effect and the radiation balance of various UHI mitigation techniques to complex computational simulations of the energy saving potential, considering indoor thermal comfort. Thus, in 2010, a paper was published on the search for optimal building shapes (Okeil, 2010) with the main purpose to mitigate the effect of UHI using simulation with the ENVI-Met tool, which showed that the shape of buildings can improve ventilation in the streets, and the use of green-roofs, will help mitigate the effect of UHI. In this respect, research on techniques for mitigating the effect of UHI was subsequently carried out. Thus, in 2011, based on Energy Plus simulations in 6 ASHRAE climate zones in the USA, it was determined *"that white and green-roofs are effective strategies for UHI mitigation"* (Scherba, Sailor, Rosenstiel, & Wamser, 2011); in Italy, based on field experiments and computer simulation, a numerical model for calculating the thermal resistance of green roofs was presented (Olivieri, Di Perna, D'Orazio, Olivieri, & Neila, 2013); finally, numerical models were developed for calculating the thermal resistance of green façades (Susorova, Angulo, Bahrami, & Stephens, 2013). Continuing with the application of UHI mitigation techniques in countries such as the USA and Australia (Roman, O'Brien, Alvey, & Woo, 2016), the use of PCMs in building envelopes, which can generate potential annual energy savings of 17-23%, is emerging (Alam, Jamil, Sanjayan, & Wilson, 2014). In this regard, it has become clear that *"PCM performance highly depends on the weather conditions, emphasizing the necessity to choose different PCMs at different climate zones"* (Zwanzig, Lian, & Brehob, 2013). More recent work focuses on finding optimal PCM melting temperatures for different cities and climate zones (Saffari, de Gracia, Fernandez, & Cabeza, 2017), as well as combining the use of PCM with indoor thermal comfort models in energy simulations (Saffari, de Gracia, Ushak, & Cabeza, 2016).

This cluster also includes two publications that address the study of outdoor thermal comfort in UHI conditions, as well as the development of methods to mitigate the thermal and energy effects of UHI (van Hove et al., 2015; F. Yang, Qian, & Lau, 2013). In both investigations, the authors point out the importance of the urban wind environment for outdoor thermal comfort in two cities located in different climate zones. By 2017, estimates were already being made of the effect of green roofs on outdoor/indoor temperature and cooling demand under four different climate conditions and urban densities with ENVI-met and Energy Plus tools (Morakinyo, Dahanayake, Ng, & Chow, 2017). In this sense, studies have evolved from focusing solely on the dwelling to an analysis of buildings with an aspect of interaction with the urban environment, e.g., on the scale of streets and neighbourhoods.

Additionally, because the effect of the increased EC of buildings in UHI conditions is a problem generally in cities with hot climates and mostly related to cooling, this cluster presents research on energy reduction techniques for cooling. In 2010, two studies were published by different scientific groups in California on economic methods for energy conservation. In these cases, the critical-peak pricing effect (Herter & Wayland, 2010) was studied in the case of cooling energy for residential housing. Furthermore, the optimisation of HVAC-system operation settings (pre-cooling strategies) (Yin, Xu, Piette, & Kiliccote, 2010) for the minimisation of EC in commercial buildings was analysed. In addition, the use of pre-cooling strategies was also used for residential buildings (Turner, Walker, & Roux, 2015).

1.3.2.2. Cluster 2 – Indoor air microorganisms

The second cluster, with four papers, deals with Indoor air microorganisms and includes studies on the presence of bacteria, fungi, and microbes inside the office, school, and residential buildings, as a consequence of the variability of these microorganisms, which is related to climatic zones and ventilation techniques, as well as solutions to reduce their presence.

Initially, airborne fungi species and culturable bacteria content analysis research focused on office buildings. In 2003 it was shown that an HVAC system helps to minimise the concentration of airborne fungi species in the indoor air of New York offices, whereas this is not the case in Perth (Kemp et al., 2003). In addition, the seasonal and climatic dependence on the content of culturable airborne bacteria in office indoor air of 100 office buildings in 10 US climate zones was revealed (Tsai & Macher, 2005).

In another study, airborne bacterial concentration was analysed in 39 schools in Canada, showing a direct relationship between the concentration of airborne bacteria and the concentration of CO_2 in school classrooms, demonstrating the importance of implementing ventilation in school facilities in the climate zone studied (Bartlett, Kennedy, Brauer, van Netten, & Dill, 2004). Finally, in 2012, house dust microbial communities were investigated, and conclusions were drawn that residences located in a temperate climate zone showed higher dust microbial diversity than in tropical climate zone (Rintala, Pitkaranta, & Taubel, 2012).

1.3.2.3. Cluster 3 – Combined heating, cooling and power systems

The third cluster presents 15 investigations, listed in Table A. 2, dealing with climate-dependent optimizations and analysis of energy saving potential of combined heating, cooling, and power systems (CHCP).

Initially, the primary interest of the scientists was to investigate the energy effects of the use of CHCP systems in airport buildings due to a problem related to the high level of EC in these types of buildings, while noting the good potential for energy savings from using these systems in more southerly climatic zones (Cardona, Piacentino, & Cardona, 2006). Thus, in the oldest study of the cluster, the problem of using systems with the right power in the aspect of energy conservation in airport buildings was raised. Systems optimization measures at Greek airports could result in potential energy savings of 15-20% for the southern climates and 35-40% for the northern climates (Balaras, Dascalaki, Gaglia, & Droutsa, 2003).

Subsequently, studies already focused on office buildings were addressed. Thus, in 2009, in the USA, a method was demonstrated to optimize a combined heating and power system (CHP) in this type of building, and in the context of three objectives: energy saving (ES), operation cost reduction (OCR), and environmental impact minimization (EIM) – only for carbon emissions; it was shown that electricity and natural gas CHP system optimisation is dependent on climate zones and operational mode (P J Mago, Chamra, & Hueffed, 2009). In the case of a building in Beijing, solar CHCP systems were considered, and the OCR optimisation objective was extended in the context of LCA methodology. Moreover, the EIM objective was extended to global warming, the chemical composition of precipitation, and the respiratory effect of pollutants, and the results indicate that the energy saving and pollutant emissions reduction potentials of the FTL operation mode are better than that of the FEL mode (Jing, Bai, Wang, & Liu, 2012). The same authors of the previous study used a similar approach for multi-objective optimisation of the electricity and natural gas CHCP system in a commercial office building in Beijing. In this research, the optimal equipment size and operation mode was obtained. The authors found that *"if energy benefits are paid more attentions, following the thermal load (FTL) mode is the first choice, while if environment performance is more valuable, following the electricity load (FEL) mode is the good operation strategy"* (Jing, Bai, & Wang, 2012). In the two papers presented above for Beijing, the authors note that their conclusions were obtained for the specific climatic conditions of this city.

In another investigation, the application of CHP systems with Organic Rankine Cycle (ORC) was analysed in small commercial office buildings in six climate zones in the USA. The authors show that the CHP–ORC system help reduce the primary EC cost and carbon dioxide emissions in comparison with the same building, operating solely with a CHP system in all climatic zones of study (Pedro J Mago et al., 2010).

In the case of hotel buildings, optimisation methodologies aimed at three objectives (ES, OCR, and EIM) were presented for CHCP systems. The authors concluded that CHCP systems are most relevant in the aspect of primary energy conservation and emission reduction in a cold climate with high heating energy needs (Jiang-Jiang et al., 2010). On the other hand, in the USA, it proved effective in the hybrid method for operating a CHP system of a hotel building (which either follows the thermal or the electric demand), by comparing the energy simulation results of this method with FEL and FTL modes of operation strategies in 16 climate zones. It was shown that the choice of the CHP system operation method will depend on the climate zone for this type of building. Therefore, in all climatic zones, the efficiency of the system with the hybrid operational mode was greater than with FEL and FTL. However, the FEL operational mode is more suitable for warm climatic zones of ASHRAE (1A, 2A, 2B, 3A, and 3B) and FTL for cold climatic zones (Smith & Mago, 2014).

In the research of Wang *et al.*, the authors developed and compared the use of optimal CHP systems for four types of buildings (hotel, school, office, and hospital) in five cities in China, with different climates in the context of three objectives (ES, OCR, and EIM). The authors concluded that energy demands depend on the type of building, which also affects the optimal design of the CHP. In general, throughout the year, the CHP system in office buildings consumes less energy, spends less, and emits less CO2 among the four categories of buildings. In terms of saving primary energy, CHP systems are optimal for severe cold climates; in terms of reducing carbon emissions, they are optimal for mild climates (J. Wang et al., 2011).

In 2012, the possibility of applying CHCP systems in a multi-storey residential building, under the climatic conditions of Shanghai city, was analysed. The authors summarised that, from an economic point of view, the introduction of these systems is not profitable for residential buildings and that a reduction in natural gas prices may make it possible to use these systems in such buildings (Gu, Ren, Gao, & Ren, 2012). On the other hand, in Spain, the design of the integrated hybrid solar thermal (PV) micro-CHP system was analysed and applied to an apartment building in five climate zones. In this paper, a discussion was presented on the problems of using micro-CHP systems in residential buildings, and it was concluded that CHP systems are optimal for cold climate zones (Romero Rodriguez, Salmeron Lissen, Sanchez Ramos, Rodriguez Jara, & Alvarez Dominguez, 2016).

The evolution of the application of CHCP systems for different types of buildings is remarkable. Initially, these systems were used for airport buildings and other types of public buildings. Recently, researchers have been analysing the possibility of applying these systems to residential buildings. In addition, it is significant that the timing and mode of operation of these systems depend on the type of building, climate zones, and target (energy saving, economic, or ecological) that is most desired with the use of CHCP systems.

1.3.2.4. Cluster 4 – Economic and energy optimization of the thermal insulation

In the fourth cluster, five studies are presented that develop a methodology for determining the optimum thickness of thermal insulation based on minimising the parameters that affect it.

Thus, the first paper presented a methodology for finding the optimal thickness of thermal insulation for exterior walls in a cold climate zone in Turkey. This methodology was based on an approach of minimising the economic costs of heating as well as the cost of thermal insulation (Ozkahraman & Bolatturk, 2006). Following the methodology of the previous study, subsequent work searched for the optimum thickness of the exterior wall insulation, considering the economic-energy balance using (i) heating degrees-days, (ii) the cost of the insulating material, and (iii) the cost of fuel used to heat the house for a decade (Bolatturk, 2006). In subsequent studies, the methodology was extended by adding the search for the optimum fuel for different climate zones (Ucar & Balo, 2009), as well as the search for the optimum thickness of the thermal insulation of the roof, evaluating also the effect of the thermal insulation on the environment, thus reducing CO_2 and SO_2 emissions (Ucar, 2009) and, finally, extending the number of materials analysed for use as thermal insulation, determining, for each climate zone in Turkey, the optimum material and structure in the external walls (Ekici, Gulten, & Aksoy, 2012).

1.3.2.5. Cluster 5 – Indoor thermal comfort

The fifth cluster is composed of 17 papers on indoor thermal comfort, which generally deal with the concept of the adaptive thermal comfort model and its evolution over time, the conventional thermal comfort model, and the potential for energy savings in the application of thermal comfort models in buildings. All studies of this cluster are presented in Table A. 3.

The adaptive thermal comfort (ATC) model for naturally ventilated buildings, developed by de Dear and Brager, as an alternative to the conventional model of thermal comfort (R. de Dear & Brager, 2001), with all the limits of its application, the energy saving potential, and the problems of its development (R. J. de Dear & Brager, 2002), was adopted as an amendment to the ASHRAE 55 Standard and then went through different stages of evolution from its conceptual formation to its application in buildings to minimise EC.

First, it was found that the ATC model has a clear dependence on local climatic conditions and the thermal preferences of the population in different regions of the world. Generally, the ATC model is more applicable to regions of the world with a warm climate (Bouden & Ghrab, 2005; Candido, de Dear, Lamberts, & Bittencourt, 2010; W. Yang & Zhang, 2008). These studies showed that the effect of indoor air speeds on thermal comfort in buildings with natural ventilation requires detailed research for different climate zones (Candido et al., 2010; W. Yang & Zhang, 2008).

The application of the ATC model in colder climate conditions was also considered with estimates of potential energy savings (Yao, Li, Steemers, & Short, 2009). It has been shown that the ATC model can only be used in the summer period to natural ventilated office space under Dutch climatic conditions, with a cooling energy saving potential of up to 10%. (Joost van Hoof & Hensen, 2007). For conference and exhibition building in Beijing, a hybrid HVAC system operated with natural ventilation cooling and with the application of a high standard level of the ATC model can be used between 63% and 66% of the hours in July and August, and that can help to reduce EC (Yao et al., 2009).

This cluster presents studies not only on the ATC model but also on the conventional model of thermal comfort. Thus, in 2008, although the author accepts the best applicability of the ATC model for naturally ventilated buildings, van Hoof conducted a review on the predicted mean vote (PMV) model of thermal comfort created by Fangér, demonstrating its strengths and weaknesses. Possible methods of optimization and improvement of the PMV model were also analysed (J van Hoof, 2008). Later, the authors of a study carried out in Hong Kong concluded on the importance of taking into account air velocity for thermal comfort in an air-conditioned office building and recommended the use of air-conditioning systems with individual control for this type of building (Chow, Fong, Givoni, Lin, & Chan, 2010).

The existence of two models of thermal comfort, of course, leads to the development of research in terms of comparing them with each other. For example, in India, for residential buildings, it was concluded that the ATC model is more suitable for reflecting the thermal preferences of the population than the PMV model (M. K. Singh, Mahapatra, & Atreya, 2011). A good comparative study of the two models was published in 2013, on field studies in thermal comfort research, presenting all research according to the four Köppen climate zones. The authors concluded that the conditioned spaces have narrower comfort zones compared to free-running buildings. In all climate zones, the most popular adaptation methods are related to the modification of air movement and clothing of the building occupants (Mishra & Ramgopal, 2013). Additionally, there were still attempts to develop a single ATC model for air-conditioned and natural ventilated office buildings (Manu, Shukla, Rawal, Thomas, & de Dear, 2016).

Most of the above studies focus on office and residential buildings. However, on the other hand, school buildings also receive significant attention from thermal comfort researchers. The interest in studying thermal comfort in schools is because children spend most of their time there, and their academic performance and emotional health depend on thermal comfort. In one of these works, the acceptable temperature range for Australian school children was analysed. This research was carried out in nine schools, in three climate zones, with different HVAC systems. It was identified that the comfortable thermal sensation of the children was between 1 and 2°C lower than the thermal sensation of the adults. Within this research, a review of work on thermal comfort in schools and in different geographical areas is presented (R. de Dear, Kim, Candido, & Deuble, 2015). Furthermore, in different countries of the world, there are policies to optimize energy costs in educational institutions, which depend on indoor thermal comfort (Zomorodian, Tahsildoost, & Hafezi, 2016). Generally, in previous investigations, it was concluded that thermal comfort depends on the type of building and the age and gender structure of the building users.

Following, after the stages of development and evolution of the models, other studies on the practical application of the thermal comfort models can be found, in which the adjustment of the thermostat configuration based on the thermal comfort models is discussed, to minimize the EC of the buildings in different climatic zones (Hoyt et al., 2015; Moon & Han, 2011). Finally, in one study, the use of an earth-air-tunnel heat exchanger is analysed for the minimization of the EC maintaining thermal comfort, according to the ATC model of the ASHRAE standard (Bansal, Mishra, Das Agarwal, & Mathur, 2012). It can be said that the choice of using an ATC model, a conventional model, or a combination of both for the operation of an HVAC system to minimize EC depends on the climate zone in which the building is located.

1.3.2.6. Cluster 6 – Energy optimization of school buildings

The sixth cluster consists of five articles dealing with the energy optimisation of school buildings, mainly based on the objective of maintaining indoor comfort conditions and focusing on a holistic approach (energy efficiency, thermal comfort, and indoor air quality).

This cluster addresses energy-efficient strategies in school buildings and different climate zones, based on aspects such as maximising energy conservation, improving indoor air quality, and visual comfort (Theodosiou & Ordoumpozanis, 2008). The studies have shown that this requires optimising the design parameters of the building, its shape, orientation, thermal insulation, and HVAC systems for different climate zones (Dimoudi

& Kostarela, 2009), light control, infiltration, glazing, night ventilation, and size of windows (Perez & Capeluto, 2009), in addition to the use of renewable energy (usually solar), to minimise EC in buildings (Calise, 2010; Dascalaki & Sermpetzoglou, 2011).

1.3.2.7. Cluster 7 – Infiltration and air leakage

The low number of works in this cluster, with only three publications, presents studies on the infiltration of residential buildings in general, as well as infiltration specifically of windows and exfiltration of dwellings. In this cluster, there are general conclusions on the need to develop studies on infiltration and exfiltration in different regions of the world for different types of housing and their effect on energy efficiency.

In Finland, the relationship between infiltration and the EC of the heating and ventilation system of a single-family house was analysed. It was determined that infiltration causes 15-30% of the heating and ventilation energy use of the dwelling. In addition, the authors proposed a climate zoning methodology for infiltration (Jokisalo, Kurnitski, Korpi, Kalamees, & Vinha, 2009). In Spain, the effect of window infiltration on the process of energy certification of windows was analysed. Two energy balance equations through the window were presented for two climate zones in Spain, depending on window leakage at a pressure difference of 75 Pa and outdoor temperature difference of 20 °C. Based on the energy balance equation, it was possible to carry out an energy qualification of the windows (Urbikain & Sala, 2009). The last work carried out in the USA analysed air leakage in 134,000 houses. It was established that the built year and climate zone are the two most influential parameters on air leakage. This is a good methodological work to understand the air leakage concept in relation to buildings (W. R. Chan, Joh, & Sherman, 2013).

1.3.2.8. Cluster 8 – Windows and façades optimization

The eighth cluster is the smallest of those analysed and is made up of two studies about the energy saving potential of semi-transparent photovoltaic panels for windows and façades. One of these presents a possible energy conservation evaluation methodology with semi-transparent PV windows in offices in two cities in Brazil and one in Germany (Didone & Wagner, 2013). The second one presents a methodology for finding the optimal design of a ventilated photovoltaic double-skin façade to minimize

EC in housing. (J. Peng et al., 2016). In both cases, the energy saving efficiency of these systems was directly related to the climate zones.

1.3.2.9. Cluster 9 – Energy simulation, conservation and meteorological data

This cluster, with 39 publications, is the largest, has a central location among the other clusters (Fig. 5), and deals with energy conservation. All the studies in this cluster are presented in Table A. 4 and include studies on the simplification of methodologies for estimating EC in buildings (de Rosa, Bianco, Scarpa, & Tagliafico, 2014; Hygh, de Carolis, Hill, & Ranjithan, 2012), the relationship between thermal comfort (L. Yang et al., 2014) and visual comfort (E. Shen, Hu, & Patel, 2014) with energy conservation in buildings, and comparisons of the energy efficiency of simulated dwellings according to the use of national building standards, both in Italy and Spain, for different building climate zones, showing the most favourable energy regulations (Asdrubali, Bonaut, Battisti, & Venegas, 2008). Due to its size, and to facilitate the analysis of the results, this cluster has been manually divided into five sub-themes, which will be analysed below: (i) Multi-parametric and multi-objective optimizations; (ii) Heat and energy recovery ventilators; (iii) Schedule occupancy and occupant behaviour; (iv) Renewable energy systems; (v) Meteorological data and climate change.

1.3.2.9.1. Sub-theme 1 – Multi-parametric and multi-objective optimizations

This first sub-theme presents 13 studies on the optimisation of buildings for energy conservation through four different approaches in the use of energy-efficient measures (Table 5): (i) building envelopes; (ii) architectural parameters (building orientation and geometry); (iii) building service systems and equipment; (iv) internal conditions (thermal/lighting comfort; building occupation; occupant behaviour; indoor environmental conditions).

It can be seen that the older publications considered a limited number of parameters for optimising buildings and only with an energy purpose. With the progress of research, the number of parameters and measures analysed has increased significantly, and secondary objectives of optimisation have also been developed, be they economic, ecological, or health-oriented. These objectives were later integrated with the energy aspect of the optimisation. Recently, there has been a trend towards a decrease in the number of parameters and optimisation techniques, through the search for more efficient methods and parameters for different types of buildings, in different climate zones (D. H. W. Li et al., 2013).

Table 5 Principal studies of the multi-parameter optimizations.

Parameters for optimisation	Tools	Year	Ref.
Insulation and thermal mass; aspect ratio; the colour of ext. walls; glazing system; windows size; shading devices	Energy Plus and validation with measured data	2008	(Eskin & Tuerkmen, 2008)
Shape coefficient; building envelops (wall, roof)	Num. model - Overall thermal transfer value method	2008	(L. Yang, Lam, & Tsang, 2008)
Passive solar design; internal loads (lightning and equipment); operations of fans and pumps; wall insulation	Simulation tool DOE-2.1E	2008	(Lam et al., 2008)
Window design; 4 types of glazing	TRNSYS software Economic model life cycle cost (LCC) criterion	2011	(Jaber & Ajib, 2011)
Transparent composite façade system vs glass curtain wall system	DOE-2 (eQuest) Economic model LCA	2011	(K.-H. Kim, 2011)
Orientation; wall and roof ins.; win. size; WWR; glazing; lighting; infiltration; cooling Temp.; refrigerator energy effic. lev.; boiler type; cooling sist. type	DOE-2 LCC	2012	(Ihm & Krarti, 2012)
Win. orientation; WWR; width to depth ratio (W/D)	Energy Plus	2013	(Susorova, Tabibzadeh, Rahman, Clack, & Elnimeiri, 2013)
Building occupation; ATC model; CO_2 emission	Energy Plus	2014	(Roetzel et al., 2014)
6 principal parameters: climate; envelope; equipment; operation and maintenance; occupation behaviour; indoor environmental conditions	Energy use audit	2014	(C. Li, Hong, & Yan, 2014)
Energy conservation tool for optimizing existing buildings and to design new buildings. 100 configurable energy conservation measures; IEQ	CBES toolkit Energy Plus	2015	(Hong et al., 2015)
Multi-criteria optimization; orientation; win. size; overhang specification	Multi-objective non-dominated sorting generic algorithm and Energy Plus	2016	(Delgarm, Sajadi, Delgarm, & Kowsary, 2016)
Tool for multi-criteria optimization; passive environmental design strategies; building geometry; orientation; fenestration configuration y others.	Passive Performance Optimization Framework Energy Plus	2016	(Konis, Gamas, & Kensek, 2016)

1.3.2.9.2. Sub-theme 2 – Heat and energy recovery ventilators

This sub-theme presents three papers related to heat and energy recovery ventilators. In the case of heat recovery ventilators, in countries such as France and China, it has been shown that the energy efficiency of an optimal ventilator depends on the climate zone and the type of building (El Fouih, Stabat, Riviere, Hoang, & Archambault, 2012; Ke & Yanming, 2009). Besides that, for an energy recovery ventilator, the seasonal dependence of weighted coefficients (latent and sensible heat efficient) of enthalpy efficiency in different cities was demonstrated (J. Liu, Li, Liu, & Wang, 2010). These conclusions are derived from the direct dependence of the energy efficiency of these ventilators on the outside temperature, the moisture content of the air and the latent and sensible heat content.

1.3.2.9.3. Sub-theme 3 – Schedule occupancy and occupant behaviour

The third sub-topic includes three papers and focuses on assessing the impact of building occupancy on EC and finding models of schedule occupancy closer to the real occupancy in residential (X. Ren, Yan, & Wang, 2014) and office buildings (Zhao, Lasternas, Lam, Yun, & Loftness, 2014). In the case of offices, it was shown that the improvement of the schedule occupancy model led to a decrease in the EC of the HVAC system during simulations in hot climate types and an increase in cold climate types. It also highlights the importance of selecting daily optimal setpoint temperatures for HVAC and demonstrates the potential for energy saving in different climates. For small, medium, and large office buildings, setpoint temperatures for an HVAC system in the range of 22.5 ± 3 °C would lead to 10.09–37.03%, 11.43–21.01%, and 6.78–11.34 % energy saving, respectively, depending on the climate zones (Ghahramani, Zhang, Dutta, Yang, & Becerik-Gerber, 2016).

1.3.2.9.4. Sub-theme 4 – Renewable energy systems

The fourth sub-theme, with four papers, deals with energy saving techniques in buildings from the use of renewable energy-based systems such as solar thermal systems, photovoltaic systems (da Graca, Augusto, & Lerer, 2012), solar-assisted liquid desiccant air-conditioning systems (Ronghui, Lin, & Yu, 2014), ground-source heat pumps (Z. Liu, Xu, Qian, Chen, & Jin, 2015), and hybrid ground-source heat pumps with an auxiliary heat source (Z. Liu, Xu, Zhai, Qian, & Chen, 2017). In this work, a clear dependence was shown on the possibilities and limits of the application of the above systems in the different climate zones.

1.3.2.9.5. Sub-theme 5 – Meteorological data and climate change

This fifth sub-theme shows 9 papers linking energy conservation and meteorological data. To simulate EC, meteorological data is needed, so the quality and selection of the data are important.

Results of the use of typical meteorological year (TMY) data for energy simulation were compared with the use of real measurement data over a period of 30 years (L. Yang, Lam, Liu, & Tsang, 2008), with the use of typical principal component year (TPCY) data (L. Yang, Wan, Li, & Lam, 2011), and with the use of actual meteorological year (AMY) data (Hong, Chang, & Lin, 2013). It was concluded that, in the era of availability of meteorological data and the increasing power of computer technology, it is necessary to use real meteorological data from different years to simulate the EC of households in order to obtain more realistic results or, as in Finland, to develop individual methodologies to create energy reference year data for energy simulations in different climate zones (Kalamees et al., 2012).

The simulation of EC for the present, meanwhile, has generated scientific interest in the study of future EC. This interest has a basis in the development of climate models and forecasts, as well as the unification of climate change projections. Thus, in 2011, researchers presented construction methods for adapting designed residential buildings to climate change (Z. Ren et al., 2011). In 2012, other authors pointed out the importance of the ability to analyse how buildings will respond to future climate changes and assessed possible quantitative changes in energy use and carbon footprints. In addition, they discussed possible climate change mitigation and adaptation strategies (Wan et al., 2012).

In the USA, changes in EC in different types of buildings and climate zones were assessed according to IPCC climate change projections. It was found, by the 2080s, residential EC will increase in climate zones 1-4 of ASHRAE and decrease in climate zones 6-7 of ASHRAE (H. Wang & Chen, 2014). Similarly, in Greece, the effect of climate change on the EC of buildings will be more noticeable in warmer climate zones (Asimakopoulos et al., 2012).

1.3.3. Studies without clusters

As noted above (Fig. 3), 14 papers were left out of the clustering, which are presented in Table A. 5.

In general, these studies are related to the topics that have been identified in the previous analysis of the clusters, such as thermal comfort and energy saving, CHCP and renewable energy systems, multi-criterial optimization for energy saving, climate change and change of EC, etc.

Nevertheless, there are interesting researches, for example, on energy efficiency, where, with a group of analytical hierarchical processes, it was possible to identify 17 basic parameters out of 83 parameters that should be used to assess the energy efficiency of residential buildings in the hot summer and cold winter zones in China (Y. Yang, Li, & Yao, 2010). Likewise, studies are also presented on climatic building zones in Spain (de la Flor, Domínguez, Félix, & Falcón, 2008) and on the development of bioclimatic zones in India, with potential for the development of passive solar design strategies for residential buildings (M. K. Singh, Mahapatra, & Atreya, 2007).

1.3.4. General analysis of the typology of climate-oriented research

After a detailed description of the content of each cluster and a complete in-depth analysis of the papers in these clusters, it was concluded that there are seven main Types of climate-oriented studies in building (I-VII). 120 of the 128 studies analysed could be classified into a particular type. To facilitate an understanding of these seven types of studies, a schematic diagram is shown in Fig. 6.

In the first macro-group, comparative works were classified. These were carried out to demonstrate differences between various climatic zones or geographical locations, as well as to develop general conclusions and patterns:

I. In 41.6% of the analysed studies, the research involves studies in a single geographical location for each climate zone studied. The results and conclusions obtained for each geographical point are extrapolated to the whole climate zone, and this logic applies to all climate zones of the study. The results for the climate zones are then compared with each other or are used for developing general conclusions.

II. In 26.7% of the studies analysed, the research involves studies in more than one geographic location for each climate zone studied. The results and conclusions obtained for different geographical locations are extrapolated to the whole climate zone, and this logic applies to all climate zones of the study. The results for climate zones are then compared with each other or are used to develop general conclusions.

III. 6.7% of the studies analysed compares results in different geographical locations to obtain general conclusions, without focusing on climatic zones.

In the second macro-group are investigations on the development of recommendations, standards, and conclusions for a specific area or geographical location:

IV. In 10% of the studies analysed, conclusions were drawn for a climatic zone, extrapolating results and conclusions from a representative geographical location.

V. In 5.8% of the analysed studies, conclusions were drawn for one climate zone, extrapolating results and conclusions from several representative geographical locations.

VI. 4.2% of the studies analysed were designed to obtain conclusions and results for a specific geographical location, without focusing on climatic zones.

Finally, the last group of studies:

VII. 5% of the studies analysed focused on the development of climate zones, including the analysis and identification of urban climate zones.

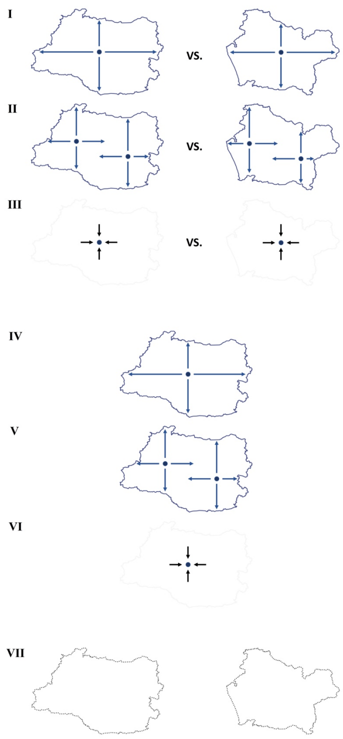


Fig. 6 Seven main types of climate-oriented researches in building.

Fig. 7a shows the time distribution graph of the main types of climate-oriented research. It can be observed that, in general, up to 2006, comparative works of Types I, II, and III prevailed. After 2006, studies of Types IV, V, VI, and VII started to appear. The maximum variability of climate-oriented research type in building was in 2010. This may be connected to the logical feasibility of doing comparative work first, looking for common patterns and differences in results in order to develop conclusions. This type of works leads to the need to generate studies to develop and establish standards and techniques, to find optimal systems and their correct functioning for certain geographical points and/or climate zones. For this reason, the studies corresponding to Types IV, V, and VI appeared later. Similarly, there is a need for works on the development of climate zones; as these are more specific investigations, they require more involvement from specialists in different areas of science and the use of multiple climatological and meteorological data. Finally, these studies require more time and computing resources. Actual examples of Type VII are studies on the definition of new climatic zones for building construction (J. Shi & Yang, n.d.; L. Yang et al., 2020) and urban local climate zones (Kotharkar, Ghosh, & Kotharkar, 2021).

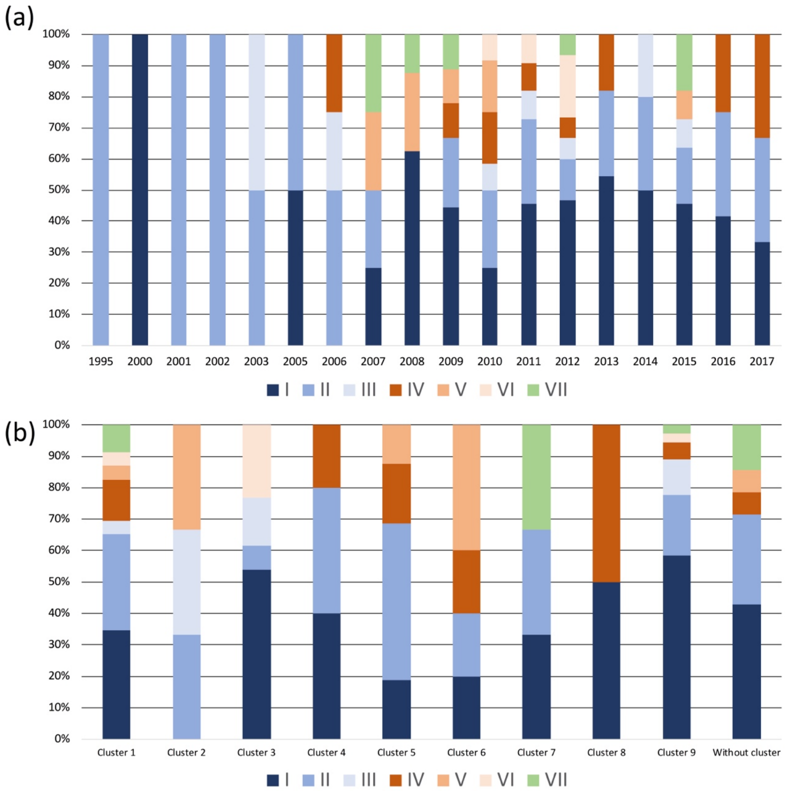


Fig. 7 Temporal distribution of the seven main types (a) and content of each of them in the nine clusters analysed (b).

Fig. 7b shows the remarkable difference in variability of the types of climate-oriented research in the clusters. Additionally, the types of analysed studies are presented in Tables A. 1 – A. 5. Cluster 1 presents the largest variability in the types of climate-oriented research, from research on the establishment of urban climate zones to the qualification of the application of UHI mitigation techniques for certain specific geographical locations. Among the other clusters with a large number of studies, Clusters 3 and 9 are mostly characterised as comparative studies (>75%) and Type I (>50%). This is due to the particularities of this works, which are based on the use of meteorological data for a single reference point, extrapolation of the results to a climatic zone and comparison with other zones. In addition, Cluster 3 has a higher number of Type VI studies, which corresponds to research carried out in a single geographical location without focusing on the climatic zone. In comparison, Cluster 5 has 32% of the Type IV and V studies, generally associated with the development of ATC models for different climate zones and specific regions based on a single or several geographical locations.

In general, it can be concluded that, among all the investigations analysed, those corresponding to Type I are more representative, so concerns arise about the adequacy of the extrapolation of the results and the local conclusions for the whole climate zone.

Certainly, the practice of using one geographical point to cover a specific climate zone should no longer be used for climate-oriented research in building. Type II and V studies must be carried out in a more frequent manner. For example, recently, Type V researches related to the assessment of the energy demand of buildings in various countries were published (Ascione, Bianco, Mauro, Napolitano, & Vanoli, 2021; Bienvenido-Huertas, Sánchez-García, Rubio-Bellido, & Pulido-Arcas, 2021). Additionally, recent work corresponding to Type II about the procedure for selecting glazing at different points of the same bioclimatic zone has been published (Ávila-Delgado, Robador, Barrera-Vera, & Marrero, 2021).

Furthermore, the typology presented for climate-oriented researches in building can be applied and used in future research, not only in the scientific area of buildings.

1.3.5. General analysis of types of climate zoning and climate zones used in climate-oriented research.

As climate-oriented research was analysed, the main types of climate zoning used in the reviewed studies are presented. In addition, the climate zones most commonly engaged in the research were analysed. Fig. 8 shows an overview of the different types of climate zonings analysed in this study. It can be seen that most of the works included climate zonings from the National Building Codes (BCs). In 120 studies, where it was possible to identify the type of zoning, the National BC climate zonings were used 74 times. The total number of times zonings were used exceeds the number of studies, because some research has included more than one type of climate zoning. Additionally, the types of zoning and principal zones of the studied research are presented in Tables A. 1 – A. 5.

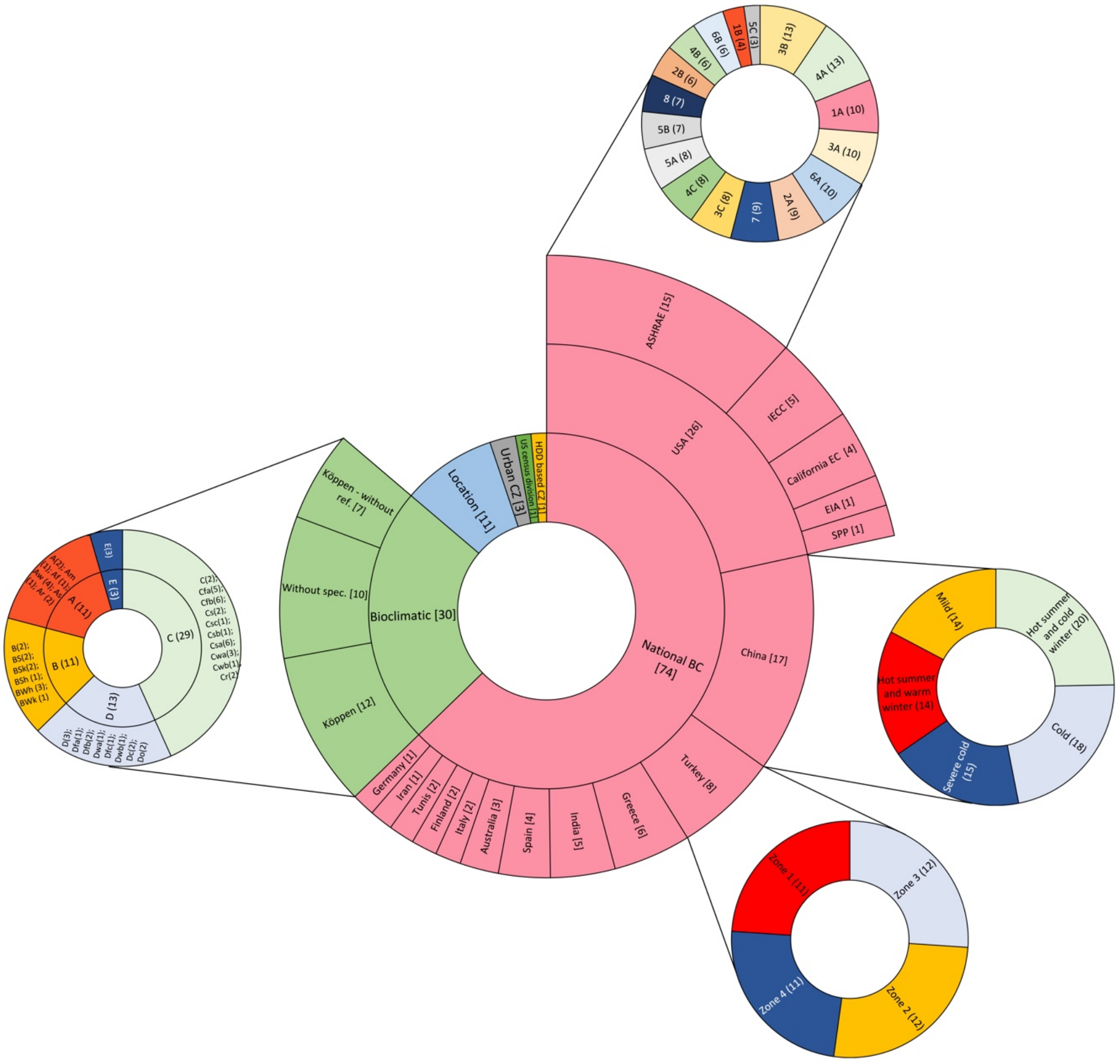


Fig. 8 Main climate zonings [number of times of use] in analysed works and the most used climate zones (the number of geo-graphical points corresponding to each zone).

Among the most popular National BC climate zonings were China (used 17 times in the studies reviewed); the USA, specifically ASHRAE zones (15); and Turkey (8). It can be noted that, in the USA, some research has included the use of climate zones of the International Energy Conservation Code (IECC), the California Energy Commission (EC), the U.S. Energy Information Administration (EIA), and the Statewide Pricing Pilot (SPP) and climate zones of the California Public Utilities Commission. The IECC zones were generally used for studies related to energy analysis. The California EC zones were applied for state-oriented work in California.

Within the climate zones of National BC, China's "Hot summer and cold winter" climate zone was the most popular in the works analysed. This zone includes the cities of Shanghai, Nanjing, Nanchang, Wuhan, and Hefei, among others. Beijing, in contrast, is in the "Cold" zone. Note that Chines studies show a clear tendency to use representative geographical locations for each climate zone. China's research usually attempts to cover the whole country, using at least one representative location for each of its 5 climatic building zones.

In the case of the USA and the ASHRAE zones, the climate zones most commonly used in the studies are 3B and 4A. Zone 3B represents the cities of Los Angeles, San Diego, and Sacramento, among others. On the other hand, zone 4A represents the cities of New York, Washington and Philadelphia, among others. Zones 1A, 1B, and 5C are less represented. Moreover, there are no works with climate zones 0. This is related to the climatic reality of the USA, as there are no such zones in the territory of this country. For this reason, for some studies, geographical points from other countries of the world are used to cover the areas that are missing. Additionally, note that due to the clear ASHRAE zoning methodology, it is possible to identify ASHRAE zones in other geographical locations around the world. Among all the studies analysed in this research with National BC zones, only ASHRAE zones have this characteristic. For example, recent work on the analysis of the applicability of ASHRAE climate zones in the territory of China (Bai, Yang, Song, & Liu, 2020).

In the case of Turkey, almost all the works generally involve the 4 climate zones of Turkish Thermal Insulation Standard TS 825. In this standard, zone 1 represents cities with warmer thermal conditions - Antalya and Izmir, among others. Zone 4 represents cities with colder thermal conditions - Erzurum and Kars, among others. Istanbul and Ankara are categorised in zones 2 and 3, respectively. The papers corresponding to the Cluster 4 were totally realised under Turkish climate zones. At the same time, the methodology of this cluster has firmly entered the scientific field of building construction, which is reflected in its use for actual research (Akan, 2021; Aydin & Biyikoğlu, 2021).

Other National BC climate zonings exist; for example, in studies in Greece, climate zones from Buildings' Thermal Insulation Regulation (TIR) and the Hellenic Regulation on the Energy Performance of Buildings (REPB) were used. Mostly these zones have been used in the research grouped in Cluster 6. The climate zones of Energy Conservation BC of India were used in 3 investigations belonging to Cluster 5.

Moreover, in the climate-oriented studies, bioclimatic zones were used 30 times, generally, from the Köppen or Köppen-Geiger classification. The papers reviewed did not necessarily include bibliographical references that would allow the type of classification to be identified. In certain cases, it was difficult to establish the type of classification, because a quantitative description of the climate was used, for example, "warm climate" or "temperate climate". However, among the works where the zones could be identified, the most used Köppen zones in the climate-oriented works analyzed were identified (Fig. 8). It can be seen that the climate type C (Temperate climates) is the most popular, analysed in 29 geographical locations, where Cfb (Oceanic climate or Marine west coast climate) and Csa (Mediterranean hot summer climates) are the Köppen subzones most commonly used. Zone Cfb represents cities located on the Atlantic coast of northwest Europe, southwest Australia and New Zealand. Zone Csa represents cities located in the Mediterranean Sea region, part of the Pacific coast of the USA and part of Australia. Additionally, it can be said that Köppen's climate zone E (Polar and alpine climates) is less represented in the climate-oriented building studies analysed. On the other hand, 11 studies involved specific geographical locations, 3 of which dealt with urban climate zones (Fig. 8).

The distribution of climate zoning types used in the different clusters is presented in Fig. 9. It can be seen that, among the clusters with a large number of investigations, i.e., Clusters 5 and 1, there is a higher percentage of work based on bioclimatic zones, compared to Clusters 3 and 9, plus the "without clusters" investigations, which are related to energy simulations based on National BC climate zones. This is because, in the case of simulation-related research, building regulations strictly related to climatic building zones must be applied, as, for example, in current research of the assessment of the profile of the use of the HVAC system based on the Spanish national BC in the aspect of energy efficiency of residential buildings (Bienvenido-Huertas, 2020). In the case of thermal comfort studies, urban areas studies, and outdoor comfort works can be carried out using bioclimatic zones, such as, for example, in actual studies about adaptive comfort in temperate and tropical climates (Guevara, Soriano, & Mino-Rodriguez, 2021; Shrestha, Rijal, Kayo, & Shukuya, 2021).

Note that most of the studies have a well-determined local view, these were carried out in climate zones established under the National BCs of different countries. In general, it can be said that differences were revealed both in the typologies of studies and in the types of climate zoning used in the works of various clusters and topics.

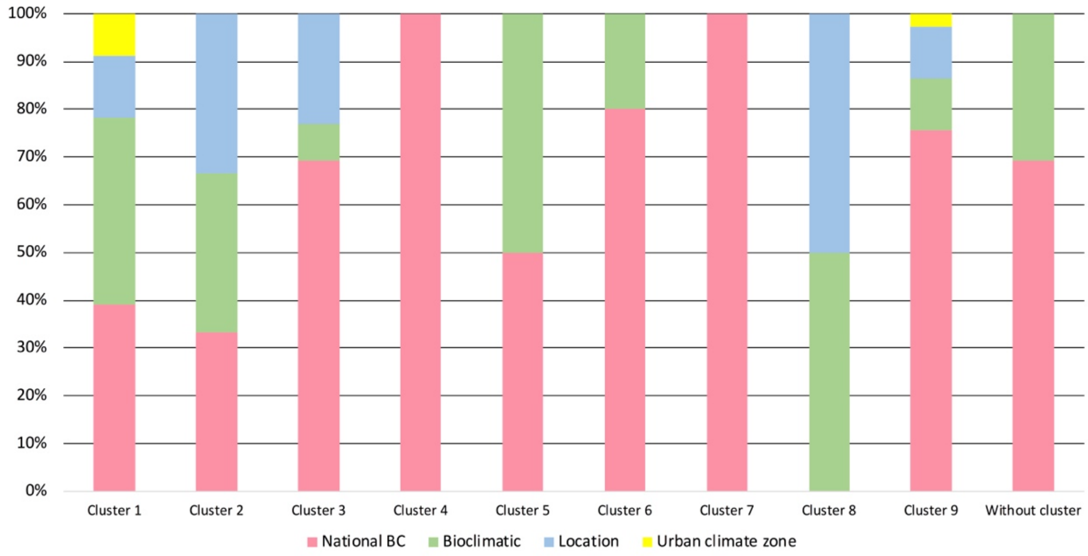


Fig. 9 Main climate zonings for the clusters.

1.3.6. Future lines of research and recommendations

The following are the main recommendations for future climate-oriented studies, both in the scientific field and in decision-making in public administration in building, considering the trends and knowledge gaps observed:

- In issues connected with UHI, it was found that there is a need to develop research and analyse the effect of UHI on EC for the heating and cooling of dwellings in regions with cold climatic conditions and on climatic zoning for building.
- The topic of Indoor air microorganisms should be integrated with that of thermal comfort, and IEQ control should be applied to different types of buildings.
- In the area of thermal comfort, it is important to carry out research on the development of adaptive thermal comfort models for different age groups, for different types of buildings, and in different geographical areas, and to a greater extent applicate in the practice of the thermal comfort models for functioning HVAC systems.
- As far as visual comfort is concerned, it is important to carry out studies on different types of buildings and climate zones. The use of visual comfort is also an objective in the multi-objective energy optimisation of school buildings.
- In terms of different building systems, it is important to develop comparative work in search of optimal parameters and of operating modes for CHCP systems for

different types of buildings in various climate zones, to analyse hybrid building HVAC systems and energy saving capabilities in different climate zones, study possibilities for the integration of renewable energy systems; and analyse and map renewable energy capacities, which can be used for air conditioning, domestic hot water, and electrical energy in buildings in different regions of the world.

- In climate zoning, the need for research on dynamic building standards, that consider the effects of future climate change is notable. On the other hand, it is important to carry out studies on the climatic zoning of infiltration and to analyse further the energy effects of infiltration in different regions of the world.

It is possible to implement all the recommendations presented above under actual climatic conditions and taking into account the effect of climate change in future periods. In general, a significant amount of research related to climate change, the dynamics of climatic zones, and modifications in meteorological parameters can be implemented. At the same time, note that the Sixth Assessment Report (AR6) of the IPCC is expected to be published in the coming years. This document will present new climate change assumptions, which will be based on four geophysical RCP scenarios of the AR5 and five new Shared Socio-Pathways (SSP) scenarios (O'Neill et al., 2014). The development of Phase 6 of the Coupled Model Intercomparison Project (CMIP6) is also expected (Eyring et al., 2016). Approximately 70 climate modelling centres are involved in this project. The quality of climate modelling is expected to improve significantly. So far, a small number of climate modelling centres have completed the calculations. The first studies in the field of energy using new climate change scenarios have already been published (Edelenbosch, van Vuuren, Blok, Calvin, & Fujimori, 2020; Zheng, Huang, Zhou, & Zhu, 2020). Therefore, it is recommended that the possibility of using new SSP scenarios and climate modelling data from CMIP6 in future research in building be noted, as most studies are now carried out considering the effect of climate change.

1.4. Conclusions

The bibliographic and manual analysis carried out, on the climate-oriented publications with the highest impact in building, has demonstrated reliable results in the scientific map definition in this topic. The main conclusions have been presented below.

Firstly, a broad spectrum of issues directly and indirectly related to climate and climatic zones in building was defined. Thereby, the climatic factor was identified in many aspects of the building construction – not only in studies on building climate zones and on the analysis of the effects of climate change, but also in studies on the optimization of various building systems in different climate zones.

88% of all climate-oriented studies, to one degree or another, are within the scope of the overall topic of energy conservation. In consequence, understanding the fact that energy conservation is directly or indirectly related to climate and climatic zones in buildings will help specialists in architecture and civil engineering design climate-appropriate housing in various aspects, for different regions of the world. In other words, it will be helpful to consider, at the design stage, many parameters, techniques, and methodologies of buildings influenced by the climate factor. Additionally, the possibilities for the adaptation and mitigation of buildings in the context of climate change can be maximised.

The predominant type of studies analysed (41.6%) was comparative studies, carried out for different climate zones, with one representative geographical location in each zone. From the point of view of the specific climate zones and the EC of dwellings, the prevalence of National BC climate zones and bioclimatic zones was revealed. Therefore, the correct definition of climate zones for building and the correct building recommendations for different geographical locations will enable the implementation of energy efficient dwellings.

One-third of the all research analysed was carried out in the climatic building zones of three countries – China, the USA, and Turkey, generally in regions with a large population. In addition, it was found that the only National BC climate zoning that was used in other countries outside of its original country, USA, was ASHRAE, which leads to the conclusion that there is a possibility to use ASHRAE zones in other study areas.

Finally, this study is a significant contribution not only for buildings construction, because it facilitates the establishment of a typology of climate-oriented studies that can be used in future research related to other applications.

CHAPTER 2.-

STUDY AREA AND TECHNICAL REGULATIONS APPLICABLE TO BUILDINGS

2.1. Definition of study area

Chile is geographically divided into 16 regions, going from a warm climate in the north to a cold climate in the south. As justified in the introduction, in this work the five southernmost regions will be analysed – La Araucanía region, Los Ríos region, Los Lagos region, Aysén del General Carlos Ibáñez del Campo region (Aysén) and Magallanes y de la Antártica Chilena region (Magallanes) whose capitals are Temuco, Valdivia, Puerto Montt, Coyhaique and Punta Arenas respectively. This is due to the fact that, despite the current binding construction regulation, residential buildings in these regions are characterized by a high level of energy demand for heating and an absolute predominance of heating EC in the matrix of total EC by houses. In most cases, this energy demand is covered by the use of biomass for heating, which provokes environmental and sanitary-epidemiological problems. Therefore, improving climatic zoning for building construction and building guidelines in these regions can help in solving or reducing the scale of these problems.

Fig. 10 shows the study area (red fill colour) comprising five regions in southern Chile, framed between latitudes 37.5°S and 56°S and Table 6 provides general information on the population, area and administrative divisions of each region. In total, the studied regions occupy 45% of the total area of Chile and 14% of the population of the country live in these regions. In the following sections the most important aspects related to the orography and bioclimatic characteristics of the study area are collected.

Table 6 Statistical characteristics of the studied regions (Chile, 2018b; INE, 2018).

Regions	Area, km^2	% of total country	Population	% of total country	Administrative divisions (communes)
La Araucanía	31,842	4.21	957,224	5.45	32
Los Ríos	18,429	2.44	384,837	2.19	12
Los Lagos	48,583	6.43	828,708	4.72	30
Aysén	109,025	14.42	103,158	0.59	10
Magallanes	132,034	17.46	166,533	0.95	11

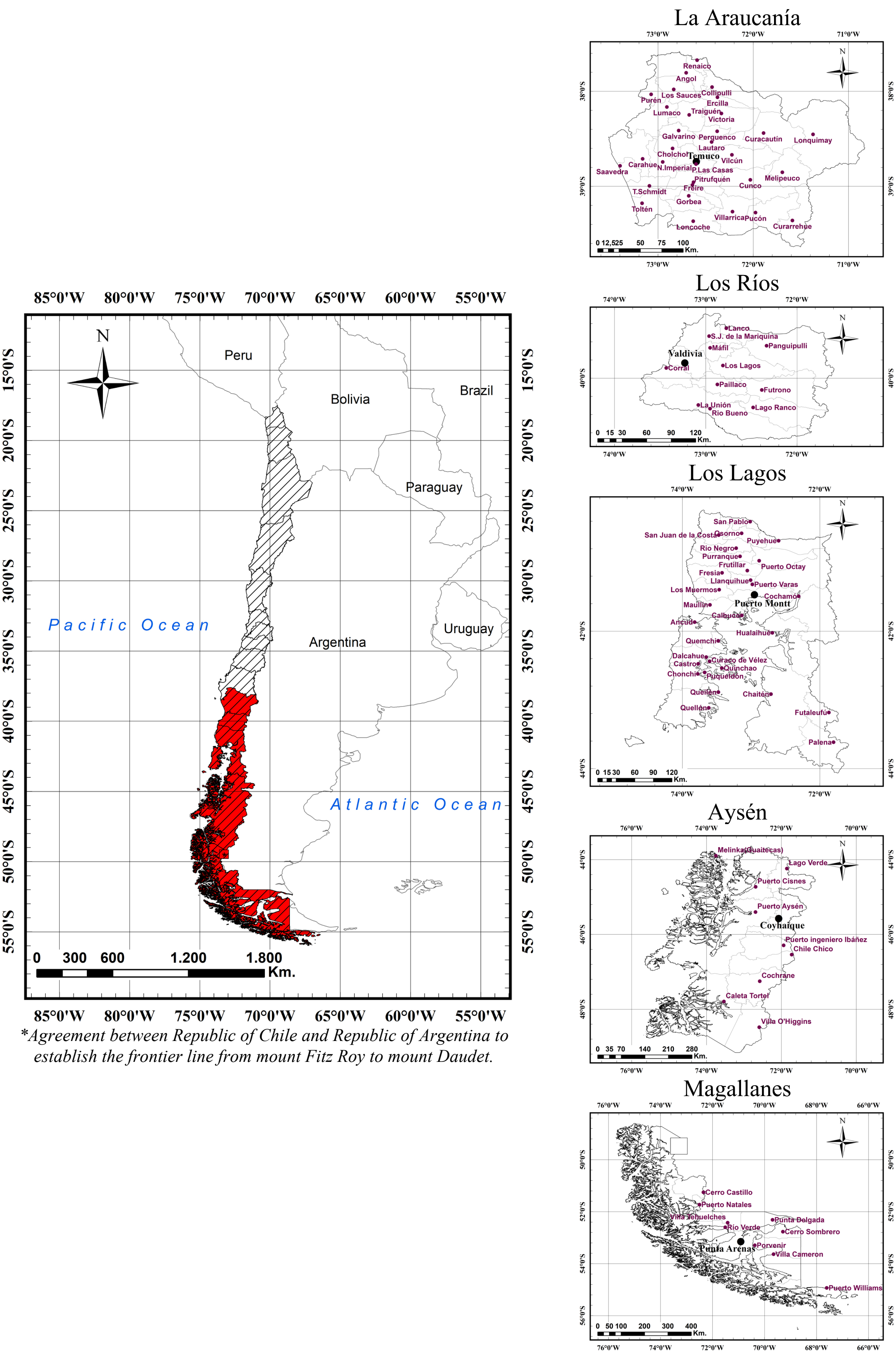


Fig. 10 Maps of general location of study area and regions with a principal cities of communes.

2.1.1. Orographic characteristics

The orography of the north part of the study area (from the north to Puerto Montt city) is characterised by the presence of the Coastal Mountain Range with heights of up to 1,000 m, an intermediate depression with heights of up to 300 m and the Andes Mountain Range with heights of up to 3,000 m. To the south of the continental part of the Los Lagos region is Chiloé Island (southwest) with heights of up to 800 m and the continuation of the Andes Mountain Range (southeast) (Chile, 2019a).

The relief system of the regions Aysen and Magallanes is highly complex, characterised by significant differences in absolute altitude and by the presence of perennial ice and snow cover. In the Aysén region, the main parts of Chile's relief are maintained: Coastal Range, Longitudinal Valley, Patagonian Andes Mountains, with a maximum altitude of 4,058 m. Compared to the three northernmost regions, the longitudinal valley of this region is characterised by higher absolute heights. In the south of the region, this valley borders the Patagonian Andes and the ice fields that also occupy the northern part of the Magallanes region. In the Magallanes region, two main elements characteristic of the relief of the northern regions are disappearing: The Coastal Range and the Longitudinal Valley. The relief units of the Magallanes region are, from west to east: Western Archipelago Mountain Range, Patagonian Andes Mountain Range and Eastern or Trans-Andean Patagonia. Eastern Patagonia extends to the east of the Patagonian Range, up to the border with Argentina. It is also known as the Eastern Trans-Andean Plateau and Magallanic Cold Steppe. Its topography is flat or semi-flat with an average altitude of 500 m, thus improving the natural conditions for human settlement.

2.1.2. Bioclimatic characteristics

According to the Köppen-Geiger climate classification (Sarricolea, Herrera-Ossandon, & Meseguer-Ruiz, 2017), five regions of study were:

(i) 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 (Puerto Saavedra). Temuco, the capital city of the region, has a Mediterranean climate (warm summer). The lower ranges of the Andes Mountains have a Mediterranean climate (warm summer) influenced by the mountains, and a Mediterranean climate (mild summer) (Sarricolea et al., 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). In parts of the north-eastern mountains, the average temperature of the coldest month can reach +3.2°C.

(ii) 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. The central part of the region is characterised by a marine west coast climate (warm and dry summer). The lower ranges of the Andes Mountains have a Mediterranean climate (warm summer) influenced by the mountains and a Mediterranean climate (mild summer) (Sarricolea et al., 2017). 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 (Chile, 2019c).

(iii) Los Lagos: This region is entirely located in a marine west coast climate, except the mountain areas. Osorno has a marine west coast climate (warm and dry summer). On the other hand, the capital city Puerto Montt has a marine west coast climate (warm summer) influenced by the ocean. The south of Puerto Montt has a marine west coast climate (warm summer) (Sarricolea et al., 2017). 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 (Chile, 2019c). In the southeastern part of the region the average temperature of the coldest month can reach + 3°C.

(iv) The Aysén: This region is characterised by the prevalence of Marine climate of the western coasts and the Tundra climate in mountainous areas. Mediterranean climate occurs to a lesser degree in the border areas with Argentina. The main characteristics of the temperature regime of this region: according to the climate maps presented on the website of the Chilean Meteorological Office (Chile, 2019c), the coastal zone of the Aysén region is characterized by average monthly minimum temperatures during the cold period from -1°C to +5°C and by average monthly maximum temperatures during the warm period from +14°C to +18°C. In the distant part of the region from the ocean, the monthly average minimum temperatures during the cold period vary from -6°C to 0°C, and the monthly average maximum temperatures during the warm period vary from +10°C (in high mountains areas) to +21°C.

(v) The Magallanes: This region is characterised by the prevalence of Tundra climate in the southern part of the region and mountainous areas in the north of the region. In addition, it is characterised by the presence of a Cold semi-arid climate in the border areas with Argentina. The northwest coast of the region is characterised by the mixture of Marine climate of the western coasts and Tundra climate. In the northern part of the Magallanes region, when moving from the ocean to the high mountainous area, there is a change in the minimum monthly average temperature during the cold period in the range from +3°C to -7°C. In the warm period of the year, the maximum monthly average temperature varies in the interval of +14 to +10°C. In the southern part of the region, when moving away from the ocean from south to north, the average monthly minimum temperature in the cold period varies from +1°C to -2°C, and the average monthly maximum temperature in the warm period varies from +10°C to +15°C.

2.2. Technical framework for building in Chile

One of the fundamental historical purposes of building is to provide adequate, stable, and permanent living conditions for its inhabitants, with priority given to thermal comfort, a basic and essential requirement for human activity. For this reason, in 1977, the Chilean standard N.Ch 1079-1977 Architecture and construction - Housing climate zoning for Chile and recommendations for architectural design was approved, declared Official of the Republic by Decree No. 1474, dated 10 October 1977, of the Ministry of Public Works of Chile, published in the Official Gazette of November 17th, 1977. Subsequently, following the increase in GHG emissions and their serious effects on the climate, it was concluded that not only did the required indoor thermal comfort parameters have to be achieved, but that this had to be done with as little use of energy as possible. For this reason, since 1994, the Ministry of Housing and Urban Development (MINVU) implemented the Thermal Regulation (RT) program, which has the following objectives:

(i) Improve the quality of life of the population through better thermal comfort and the benefits that this brings such as greater habitability, better health, less pollution, and greater durability of the housing.

(ii) Optimise and/or reduce fuel consumption for heating and cooling of dwellings.

(iii) Promote and stimulate productive, industrial, academic, trade union and applied research activities.

To achieve the above objectives, a regulatory strategy has been defined based on the following three sequential actions:

(i) Minimise energy demands as much as possible.

(ii) Utilise and optimise internal and external revenues.

(iii) If heating or cooling is required, use non-polluting, efficient, and low-cost systems.

In 2002, the first stage of the Thermal Regulation with the thermal insulation requirements for roofing was published. In 2007, with the second stage, its application was extended to exterior walls, ventilated floors, and windows. At this phase, the Thermal Regulation Application Manual (RT) (Chile, 2006a) of the General Ordinance of Urban Planning and Housing (OGUC) (Chile, 2009) was published. The RT OGUC is the mandatory building code for all the dwellings built in the country and contains thermal zones for building and construction requirements for each zone. In this document, a thermal zone is the literal translation of the spanish term "zona térmica", which is equal to the term “climatic zone” for building.

As a third stage of the regulation, the Energy Certification of buildings was originally projected. Over time, MINVU has changed its plans and suspended the Certification in favour of a less rigorous Qualification process. Thus, since 2013 there has been the Energy Qualification of Dwellings, a voluntary process for dwellings built after the entry into force of the second stage of the Thermal Regulations.

At the same time, in 2008, the National Institute for Standardisation (INN), the entity in charge of the study and preparation of technical standards at the national level, published N.Ch 1079-2008, based on N.Ch 1079-1977, the background information provided by the Meteorological Directorate of Chile and other information provided by some members of the Committee of this regulation. This standard replaced N.Ch 1079-1977, and its purpose is to establish a housing climate zoning for Chile in order to facilitate an adequate architectural design of dwellings in different parts of the country, but without a clear focus on the energy efficiency of the dwellings.

In 2018, MINVU published the Sustainable Construction Standards (ECS) for dwellings in Chile, to promote new construction standards that consider the improvement of the thermal quality of the envelope of residential buildings throughout Chile. The aim is to reduce heating EC by 30% in the central and southern parts of the country. These standards consist of six volumes that cover multiple aspects of building: Volume I - Health and Welfare; Volume II - Energy; Volume III - Water; Volume IV - Materials and Waste; Volume V - Environmental Impact; Volume VI - Immediate Environment. Volume II - Energy of the ECS contains information on thermal zones for buildings. Of course, these standards have been significantly improved in terms of the possibility to implement energy efficient buildings, as well as to introduce more thermal zones, with improved recommendations for the thermal transmittance of more building construction elements and taking into account more parameters that have an impact on the ECS of buildings. But, compared to RT OGUC, these standards are not mandatory.

In the following section, the two types of thermal zoning for the study area will be analysed in more detail.

2.3. Thermal zones of RT OGUC and ECS in study area

The RT OGUC of the MINVU includes seven thermal zones for building. They are presented based on annual values of heating degree-days with a base temperature of 15°C (HDD15°C). Table 7 shows the intervals of the annual HDD15°C values that are used for the determination of thermal zones of RT OGUC; it also includes the values of thermal transmittance (U-values) and maximum percentage area of glazed surfaces according to RT OGUC standards that the dwellings in each thermal zone must meet.

RT OGUC has been criticised in several aspects (Bustamante, 2009; Bustamante et al., 2009; F. Ossio et al., 2012; Felipe Ossio et al., 2012; Rouault et al., 2019; Verichev & Carpio, 2018; Verichev, Zamorano, & Carpio, 2019b). Among the reasons given in the studies mentioned above, it is stated that the RT OGUC does not consider meso- and microclimatic specifications for the study area, but the administrative division. In fact, in Fig. 11, a map of the distribution of thermal zones in the study area is presented according to the official RT OGUC document, where clear coherence between the boundaries of thermal zones and the administrative division can be seen. RT OGUC has low building standards that do not facilitate the implementation of energy efficient buildings in many regions of the country. Also, RT OGUC building standards do not cover all structural elements of buildings. Because of all the above, this is why in 2018, the MINVU published the ECS for dwellings in Chile (Chile, 2018c).

Table 7 Thermals zones of Chile, thermal transmittance (U-value) and maximum percentage area of glazed surfaces according to RT OGUC for each thermal zone.

Thermal zone		1	2	3	4	5	6	7
Value of annual HDD15°C		≤ 500	>500 ≤750	>750 ≤1000	>1000 ≤1250	>1250 ≤1500	>1500 ≤2000	> 2000
Walls	U [W/m²·K]	4.0	3.0	1.9	1.7	1.6	1.1	0.6
Roof	U [W/m²·K]	0.84	0.60	0.47	0.38	0.33	0.28	0.25
Floor	U [W/m²·K]	3.60	0.86	0.70	0.60	0.50	0.39	0.32
Monolithic glass [%]		50	40	25	21	18	14	12
Hermetic double	3.6 ⩾ U [W/m²·K] > 2.4	60	60	60	60	51	37	28
glazed windows [%]	U [W/m²·K] > 2.4	80	80	80	75	70	55	37

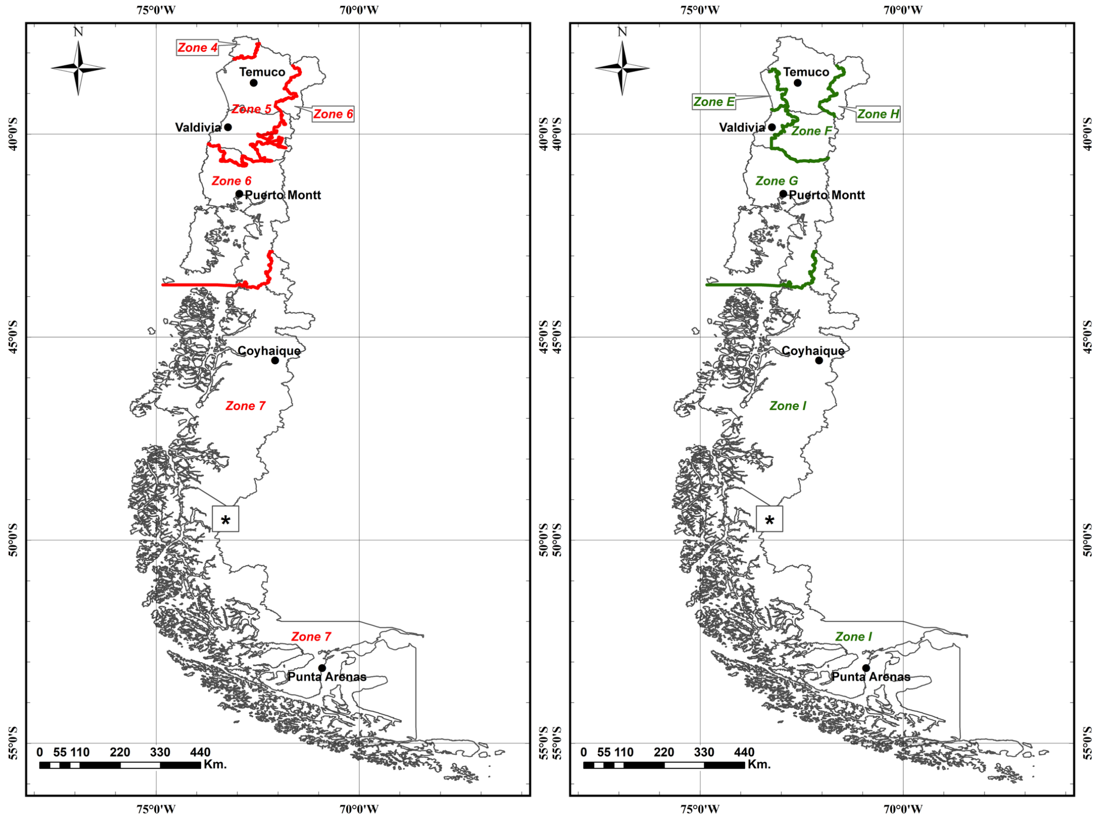
If the maximum permissible U-values of the ECS are compared with those of the RT OGUC, it can be seen that these have been improved, also resulting in a larger number of climate zones, identified with letters from A to I (from warmer to colder zones) which characteristics of building norms have been included in Table 8.

Also, ECS has further requirements for the construction - minimum thermal mass required for the building for thermal zones, maximum allowable air infiltration class for the thermal envelope of buildings, minimum air tightness degree for door and window complexes, maximum allowable energy demand for cooling and heating for current and future periods and so on.

Table 8 Thermals zones of Chile, thermal transmittance (U-value) according to ECS for each thermal zone.

Thermal zone	A	B	C	D	E	F	G	H	I
Walls U [W/m²·K]	2.10	0.80	0.80	0.80	0.60	0.45	0.40	0.30	0.35
Roof U [W/m²·K]	0.84	0.47	0.47	0.38	0.33	0.28	0.28	0.25	0.25
Floor U [W/m²·K]	3.60	0.70	0.87	0.70	0.60	0.50	0.39	0.32	0.32
Floor soil contact R100 [m²·K/W]*100	-	45	45	45	45	91	91	91	91
Door U [W/m²·K]	-	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70
Maximum percentage and maximum U-value of glassed surface per orientation									
U [W/m²·K]	5.80	3.60	3.60	3.60	3.00	3.00	2.40	2.40	2.40
N orientation	50%	60%	50%	50%	50%	50%	40%	30%	30%
S orientation	40%	60%	50%	40%	40%	35%	30%	10%	10%
W or E orientation	30%	40%	40%	30%	30%	25%	15%	10%	10%

Despite the improvement brought about by the approval of the ECS standards, there is a problem with these norms, which is the lack of a clear written methodology for defining the thermal zones, which makes it impossible to use these standards for studies on the temporal evolution of zones in the context of climate change, the updating of zones or the detail of zones according to meso- and microclimatic variations. Furthermore, as can be seen in the maps in Fig. 11 for the two most extreme regions of southern Chile, Aysén and Magallanes, there is no change in the spatial distribution of ECS zones, and there is a clear correspondence between the RT OGUC thermal zone 7 and the ECS thermal zone I. This means that neither of the two classifications captures the evident bioclimatic variability observed in these regions, which has consequences for the energy efficiency of buildings located in these regions.



*Agreement between Republic of Chile and Republic of Argentina to establish the frontier line from mount Fitz Roy to mount Daudet.

Fig. 11 Thermal zones by the RT OGUC (left) and ECS (right). RT OGUC zone definition depends on annual value of HDD15°C (Table 7).

Part II. Key aspects of climate zoning for building in the south of Chile

The bibliographic revision in Chapter 1 has shown that houses with better energy efficiency needs the correct definition of architectural standards, construction standards, and appropriate materials for each building climatic zone (Asdrubali et al., 2008; De Boeck, Verbeke, Audenaert, & De Mesmaeker, 2015; Gill, Tierney, Pegg, & Allan, 2011; Marin et al., 2016; Saffari, de Gracia, Ushak, & Cabeza, 2017). To reach this objective, different countries commonly develop their own climatic zoning systems for buildings (Walsh et al., 2017b), taking into account effects of individual climatic characteristics, specific characteristics of the constructions, levels of housing comfort and, sometimes, climate change projections (Pajek & Košir, 2018; Sánchez-García et al., 2017).

On the other hand, the effect of climate change on the boundaries of climate zones for building is already being reported in the scientific literature. Studies analysing the impacts of climate change on cooling and heating EC in the future conclude that in the future, for all geographical regions, the heating EC of buildings will decrease, and the cooling EC will increase in conjunction with an increase in days of interior thermal discomfort. In consequence, it can be seen that much attention in studied literature is paid to the analysis of changes in EC under conditions of climate change, and the evolution of climatic zones for building is considered to a minimum extent.

Therefore, this second part of the document aims to identify the key aspects that should be considered when addressing a new climate zoning in the study area. To this purpose, the first chapter will focus on the analysis of the evolution of the existing climatic zones for building in the La Araucanía, Los Ríos and Los Lagos regions of the studied area in climate change conditions; this is aimed to analyse the conformity level of the present regulations to future climatic conditions, as well as to estimate possible future changes in the heating EC.

The second chapter will focus on finding a method to improve the current zoning in the Aysén and Magallanes regions in a meso- and microclimatic aspects, by validating the method of simulating the EC of a house in multiple geographical locations. The division of the study area into two parts resulted from several factors:

(i) firstly, this is the latitudinal division, which in turn determines the solar climatology of the two parts of the study and the predominant synoptic processes affecting the formation of certain types of climate; thus, the three northern regions are characterised by the predominance of the Marine west coast climate (with warm summer);

(ii) another aspect is the orographic similarity of the three northern regions;

(iii) the permanent ubication of the regions of Aysén and Magallanes in the same building thermal zone;

(iv) finally, the traditional economic and geographical division of the country has been taken into account, according to the Promotion Production Agency (CORFO), which places the regions of La Araucanía, Los Ríos and Los Lagos as the natural region "Zona Sur" and the regions of Aysén and Magallanes as the natural region "Zona Austral" (CORFO, 1962).

CHAPTER 3.-

EFFECTS OF CLIMATE CHANGE ON VARIATIONS IN CLIMATIC ZONES AND HEATING ENERGY CONSUMPTION OF RESIDENTIAL BUILDINGS IN THE SOUTHERN CHILE[2]

[2] The results shown in this chapter were presented in: **Verichev, K.**, Zamorano, M., Carpio, M., **Effects of climate change on variations in climatic zones and heating energy consumption of residential buildings in the southern Chile** (2020) *Energy and Buildings* 215 V., 109874

3.1. Introduction

In the case of Chile, some studies have been published in relation to the heating and cooling EC in buildings. Thus, a study has been developed to determine the interior comfort in a social residential building in the city of Concepcion, as well as the change of thermal comfort for scenario A2 were analysed (Rubio-Bellido, Pérez-Fargallo, Pulido-Arcas, & Trebilcock, 2017). Different types of buildings, such as office buildings, have been analysed for the years 2020, 2050 and 2080 under the influence of A2 climate change scenario in nine cities (Rubio-Bellido, Pérez-Fargallo, & Pulido-Arcas, 2016). Finally, the change of thermal zones (synonymous with climatic zones) for building in La Araucanía, Los Ríos and Los Lagos regions has been studied based on data of the last decade from 35 meteorological stations (Verichev & Carpio, 2018). However, a limited number of meteorological data and the focus on national building codes cause almost all of the studies carried out to be directed to a certain number of cities or geographical points, and there are not many that analyse the changes of climatic zones for building and spatial distribution of theoretical EC in large geographical areas, such as in studies of cartographic analysis of real and theoretical EC of the dwellings (Martín-Consuegra, Aja, José, & Alonso, 2016; Taylor et al., 2014; Walsh et al., 2018).

Therefore, in this chapter, the thermal zoning of RT OGUC for Chile have been reviewed and, aa energy simulation of a single-family dwelling has been implemented in La Araucanía, Los Ríos and Los Lagos regions in the South of the country, increasing significantly the number of geographic points with metrological data, compared to other studies. Also, the evolution of the existing climatic zones in climate change conditions has been analysed to know the conformity level of the present regulations to future climatic conditions and to estimate possible future changes in the heating EC of building under study in the cited regions. To this end, it has been necessary the estimation of the thermal zones for building, as well as the heating EC in different climate change scenarios through high spatial resolution meteorological data, energy simulation and specific methodology for the evaluation of future changes.

3.2. Materials and methods

This section presents the tools, study area, national building regulations and methodologies used in this study.

3.2.1. Computational tools used

This section describes the software used, its main functions and licensing:

- **3D modeling of structural and architectural components**. The Building Information Modeling (BIM) methodology was used, through the Revit software of the Autodesk® version 2018, licensed by the *Universidad Austral de Chile*. Revit allows the possibility to make a 3D model of the house and convert it into a gbXML file to later perform an energy analysis using an energy simulation tool.
- **Energy simulation.** The Green Building Studio (GBS), version 2018.99.46.101 (DOE-2.2-48r) (Autodesk®) associated with the Revit license was used. The results of GBS energy modelling were compared with results of other energy simulation tools (Abanda & Byers, 2016; Aljundi, Pinto, & Rodrigues, 2016; Jamnický, 2014; S. Kim & Woo, 2011; Mostafavi, Farzinmoghadam, & Hoque, 2015; Reeves, Olbina, & Issa, 2012, 2015; Yezioro, Dong, & Leite, 2008) and were used in various scientific works (Abhinaya, Prasath Kumar, & Krishnaraj, 2017; Ajayi, Oyedele, Ceranic, Gallanagh, & Kadiri, 2015; Ajayi, Oyedele, & Ilori, 2019; Alwisy, Barkokebas, Hamdan, Gül, & Al-Hussein, 2018; Kamel & Memari, 2019; H. Kim, Stumpf, & Kim, 2011; Najjar, Figueiredo, Palumbo, & Haddad, 2017; P. Singh & Sadhu, 2019; Thakur, Prasath Kumar, & Balasubramanian, 2018). In the general case for the EC analysis of a dwelling, more detailed and accurate modelling BIM tools can be used (Bahar, Pere, Landrieu, & Nicolle, 2013). GBS energy simulation is based on data from the Mesoscale Meteorological Model ver.5 (MM5) data from 2006, with a 12.7 km spatial resolution (Grell, Dudhia, & Stauffer, 1994). MM5 data contains hourly values of dry-bulb temperature, dew point temperature, atmospheric pressure, relative humidity, wind speed, wind direction, total sky cover, and components of solar radiation. In our investigation, due to the studied area´s extension, using GBS is correct for EC modelling because it is necessary to have high spatial resolution EC simulation results and cover a fairly large geographical area.
- **Mapping.** ArcGIS 10.5 (ESRI, 2019). Licensed by the *Pontificia Universidad Católica de Chile*.
- **Statistical analysis.** The IBM SPSS Statistics software ver. 22.0 licensed by the *Pontificia Universidad Católica de Chile* was used.

3.2.2. Study area

The study area comprising three regions in southern Chile, framed between latitudes 37.5°S and 44.1°S: La Araucanía region, Los Ríos region and Los Lagos region. In Fig. 12 the map of the study area with the location of geographic points for the energetic simulation are presented.

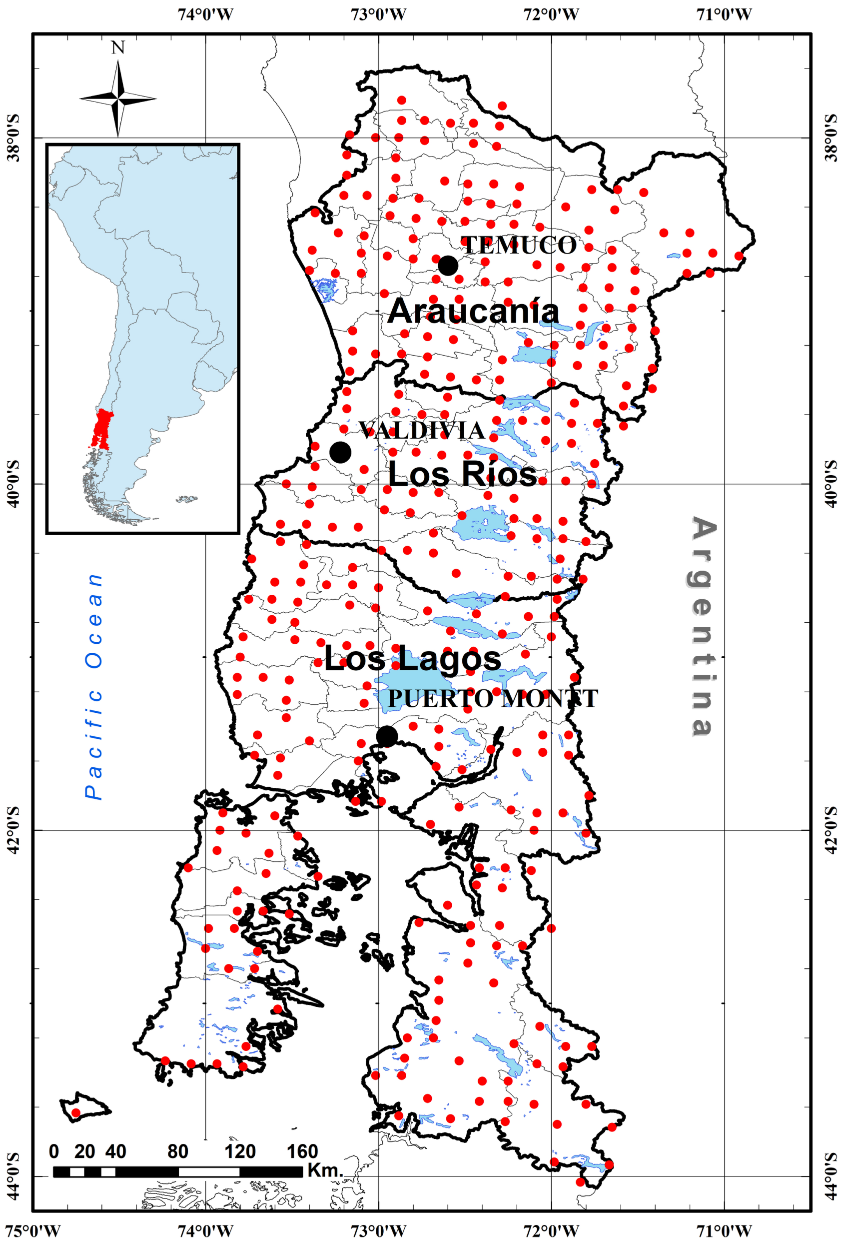


Fig. 12 Map of general location of study area with geographical locations for energy simulation (red dots).

3.2.3. *Study of the evolution of thermal zones*

3.2.3.1. Thermal zones of RT OGUC

To determine the spatial distribution of RT OGUC thermal zones based on meteorological data from MM5 in 360 geographical locations (Fig. 12), the annual value of HDD15°C was calculated using the following equation (ASHRAE, 2013):

$$HDD = \sum_{i=1}^{365}\left[T_b - \left(\frac{T_i^{max.}+T_i^{min.}}{2}\right)\right]^+, \qquad (Eq.\ 1)$$

where HDD is calculated as the difference between the base temperature (T_b; in this case it is 15 °C) and average daily temperature, which is calculated as half of the sum between the maximum daily temperature ($T_i^{max.}$) and the minimum daily temperature ($T_i^{min.}$); the sign (+) means that it is only necessary to calculate positive differences. To determine the boundaries of the thermal zones, the intervals for the HDD15°C were used, presented in the Table 7.

3.2.3.2. Data validation, scenarios and periods considered and modification of baseline climate data

Since it was decided to use the meteorological data from the 2006 MM5 model, it was necessary to show the correspondence of these model data with the data of meteorological observations. For validating meteorological data, 16 stations were selected with temperature measurements in 2006 (Fig. 13a) (Chile, 2019b), with more than 350 days of measurements.

A correlation was obtained between the annual values of the HDD15°C according to the data from meteorological stations and according to MM5 data interpolated into the coordinates of the geographical location of each station (Fig. 13b and Table 9). With a good level of correlation, generally, MM5 data are overestimated compared to data from meteorological stations. This is a logical result and is because the MM5 model data is calculated using 12.7 km grid nodes, which, because of the complexity of the relief, can be located in colder area than meteorological stations. Also, meteorological stations can be located in the influence area of urban heat islands. Comparison of MM5 data and meteorological stations data has already been carried out for the two regions of Chile (Verichev et al., 2019b) and for Nicaragua (Walsh et al., 2018).

Table 9 Annual average HDD15°C values from meteorological stations and MM5 (2006).

Lat.	Lon.	Name of Met. st.	Alt.,m	HDD15°C Met. st.	MM5
-37.7794	-72.6372	Angol (DGA)	113	872	1375
-38.0442	-72.4611	Ercilla (DGA)	262	1107	1482
-38.2156	-71.8106	Laguna Malleco (DGA)	894	2165	2362
-38.6517	-71.0919	Liucura (DGA)	1043	2351	3196
-38.4536	-71.3742	Lonquimay (DGA)	931	2248	3022
-38.4703	-71.5753	Malalcahuello (DGA)	950	2205	2958
-38.7700	-72.6369	Maquehue Temuco (DMC)	92	1253	1327
-38.7886	-73.3936	Puerto Saavedra (DGA)	5	861	1028
-39.0278	-73.0781	Teodoro Schmitd (DGA)	13	1303	1223
-38.2561	-72.6536	Traiguen (DGA)	234	1272	1452
-39.6506	-73.0808	Pichoy (DMC)	21	1325	1368
-39.8103	-73.2517	U. Austral (DGA)	10	1081	1389
-40.5883	-73.1069	Adolfo Matthei (DGA)	55	1386	1619
-40.6050	-73.0608	Canal Bajo (DMC)	61	1459	1650
-42.9303	-72.7008	Chaiten (DMC)	10	1794	2116
-41.4350	-73.0978	El Tepual (DMC)	16	1628	1486

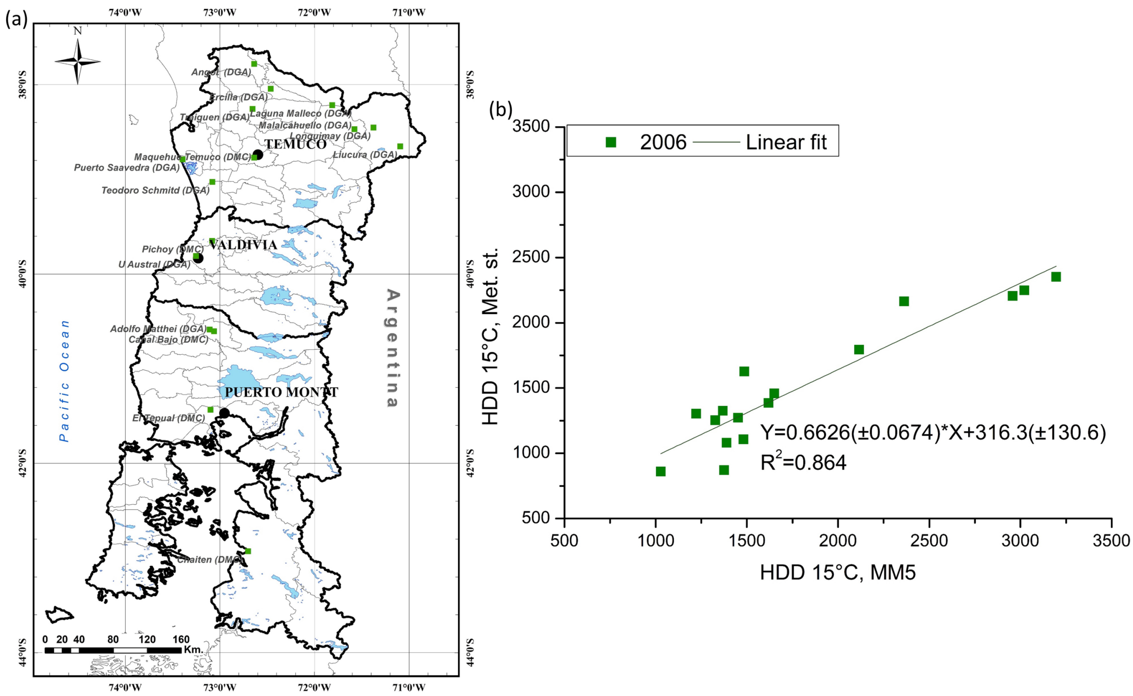


Fig. 13 Map of geographical location of meteorological stations (a) and correlation of annual values of HDD15°C from the meteorological stations and HDD15°C from the MM5 (slope and intercept of the regression line with standard errors) (b).

Subsequently, based on MM5 data (Grell et al., 1994) in 360 geographical locations of the study area (Fig. 12), the spatial distribution of HDD15°C was analysed and the boundaries of the thermal zones were determined in accordance with the criteria of the RT OGUC (Table 7). The MM5 meteorological data were used as baseline climate data for future calculations.

For the projections of the temperature change in the study area, data from the Center for Climate and Resilience Research (CCRR) were used (Chile, 2019b). For modification of the HDD15°C values of MM5, the differences in monthly average minimum and maximum temperatures between three periods in the future and baseline climate period were used: (i) near future 2020–2035; (ii) intermediate future 2035–2050 and (iii) far future 2050–2065. In all cases, the climate change scenarios RCP2.6 and RCP8.5 available in CCRR were considered.

The differences in monthly average minimum/maximum temperatures data (Table 10), in the case of the RCP2.6 scenario, were based on the average simulation results of 22 global models, 4 regional models and 2 local models. The RCP8.5 scenario has been based on the average simulation results of 35 global models of the Coupled Model Intercomparison Project (CMIP5) (WCRP, 2019), 7 regional climate models and 2 local models (Chile, 2019b).

In addition, it is necessary to analyse the projections of changing temperatures in the research area. In Fig. 14, the intra-annual variability of the expected differences in monthly average minimum/maximum temperatures for the entire study area can be observed.

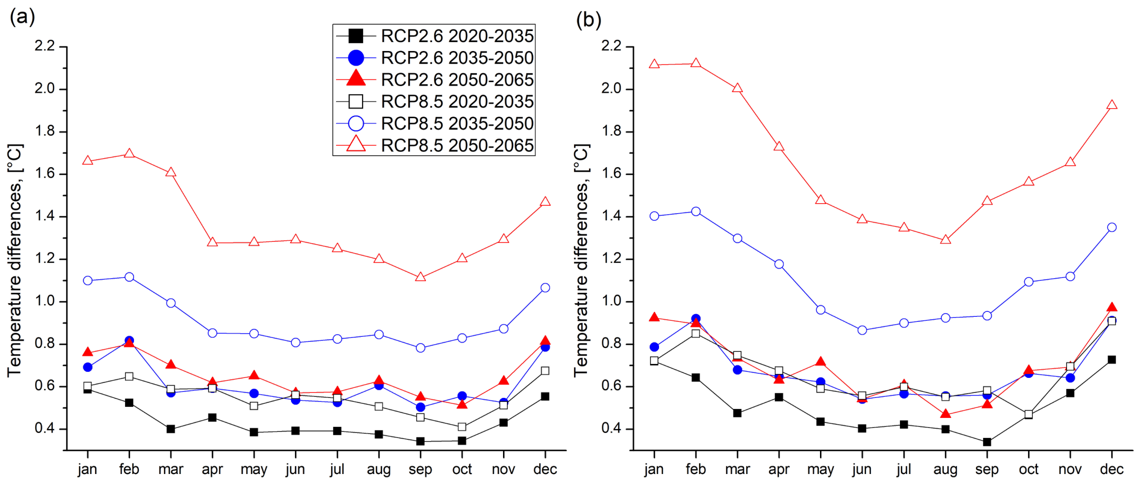


Fig. 14 Monthly values of differences in monthly average minimum (a) and maximum(b) temperatures between future periods and baseline climate.

It can be seen that, for both temperatures, there is a variability of expected temperature changes with maximum in the summer months and minimum in the winter months. This variability is clear in all future periods and for both scenarios. On the other hand, for the monthly average maximum expected temperature, the changes are higher (Fig. 14b) than for the monthly average minimum temperature (Fig. 14a). This phenomenon can be connected with the maximum temperature being a more sensitive meteorological parameter and reflects changes in the synoptic regime and changes in daytime radiative balance in the future.

Table 10 List of climatic models used in the research.

Model	Modelling group (or centre)	Type	RCP2.6	RCP8.5
ACCESS1-0	Commonwealth Scientific and Industrial Research Organisation/Bureau of Meteorology, Australia	global		+
ACCESS1-3	Commonwealth Scientific and Industrial Research Organisation/Bureau of Meteorology, Australia	global		+
bcc-csm1-1	Beijing Climate Center Climate System Model	global	+	+
bcc-csm1-1-m	Beijing Climate Center Climate System Model	global	+	+
BNU-ESM	Beijing Normal University, China	global	+	+
CanESM2	Canadian Centre for Climate Modelling and Analysis, Canada	global	+	+
CCSM4	National Center for Atmospheric Research, USA	global	+	+
CESM1-BGC	National Science Foundation, Department of Energy, National Center for Atmospheric Research, USA	global		+
CESM1-CAM5	National Science Foundation, Department of Energy, National Center for Atmospheric Research, USA	global	+	+
CESM1-CAM5-1-FV2	National Science Foundation, Department of Energy, National Center for Atmospheric Research, USA	global		+
CMCC-CESM	Centro Euro-Mediterraneo per I Cambiamenti Climatici, Italy	global		+
CMCC-CM	Centro Euro-Mediterraneo per I Cambiamenti Climatici, Italy	global		+
CMCC-CMS	Centro Euro-Mediterraneo per I Cambiamenti Climatici, Italy	global		+
CNRM-CM5	Centre National de Recherches Météorologiques, Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique, France	global	+	+
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organisation/Queensland Climate Change Centre of Excellence, Australia	global	+	+
DMC-WRF@MIROC5	Forecasts WRF from Chile DMC: Dirección Meteorológica de Chile	local	+	+
FGOALS-g2	State Key Laboratory Numerical Modeling for atmospheric Science and geophysical Fluid Dynamics, China	global	+	+
FIO-ESM	The First Institute of Oceanography, SOA, China	global	+	+
GISS-E2-H	NASA/GISS (Goddard Institute for Space Studies), USA	global	+	+
GISS-E2-H-CC	NASA/GISS (Goddard Institute for Space Studies), USA	global		+
GISS-E2-R	NASA/GISS (Goddard Institute for Space Studies), USA	global	+	+
GISS-E2-R-CC	NASA/GISS (Goddard Institute for Space Studies), USA	global		+
HadGEM2-AO	Met Office Hadley Centre, UK	global	+	+
HadGEM2-CC	Met Office Hadley Centre, UK	global		+
HadGEM2-ES	Met Office Hadley Centre, UK	global	+	+
inmcm4	Russian Academy of Sciences, Institute of Numerical Mathematics, Russian Federation	global		+
IPSL-CM5A-MR	Institut Pierre Simon Laplace, France	global	+	+
IPSL-CM5B-LR	Institut Pierre Simon Laplace, France	global		+
MIROC4h	Atmosphere and Ocean Research Institute, National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology, Japan	global		+
MIROC5	Atmosphere and Ocean Research Institute, National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology, Japan	global	+	+
MIROC-ESM	Atmosphere and Ocean Research Institute, National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology, Japan	global	+	+
MIROC-ESM-CHEM	Atmosphere and Ocean Research Institute, National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology, Japan	global	+	+
MPI-ESM-LR	Max Planck Institute for Meteorology, Germany	global	+	+
MPI-ESM-MR	Max Planck Institute for Meteorology, Germany	global	+	+
MRI-CGCM3	Meteorological Research Institute, Japan	global	+	+
MRI-ESM1	Meteorological Research Institute, Japan	global		+
NorESM1-M	Bjerknes Centre for Climate Research, Norwegian Meteorological Institute, Norway	global	+	+
RegCM4@MPI-M-MPI-ESM-MR	National Center for Atmospheric Research, USA	local	+	+
SMHI-RCA4@CCCma-CanESM2	Swedish Meteorological and Hydrological Institute	regional		+
SMHI-RCA4@IPSL-IPSL-CM5A-MR	Swedish Meteorological and Hydrological Institute	regional		+
SMHI-RCA4@MIROC-MIROC5	Swedish Meteorological and Hydrological Institute	regional	+	+
SMHI-RCA4@MOHC-HadGEM2-ES	Swedish Meteorological and Hydrological Institute	regional	+	+
SMHI-RCA4@MPI-M-MPI-ESM-LR	Swedish Meteorological and Hydrological Institute	regional	+	+
SMHI-RCA4@NCC-NorESM1-M	Swedish Meteorological and Hydrological Institute	regional	+	+
SMHI-RCA4@NOAA-GFDL-GFDL-ESM2M	Swedish Meteorological and Hydrological Institute	regional		+

A similar conclusion can be traced from an analysis of Fig. 15, which presents box-plots of the variability of the expected differences in annual average minimum (Fig. 15a) and maximum (Fig. 15b) temperatures in the 360 geographical locations of the study area. Also, it can be seen that for the RCP2.6 scenario, a stabilisation of change is observed after the 2035–2050 period in both temperatures, so the variability of the expected temperature change is quite similar in the periods 2050–2065 and 2035–2050, which is consistent with the main geophysical idea of the RCP2.6 scenario.

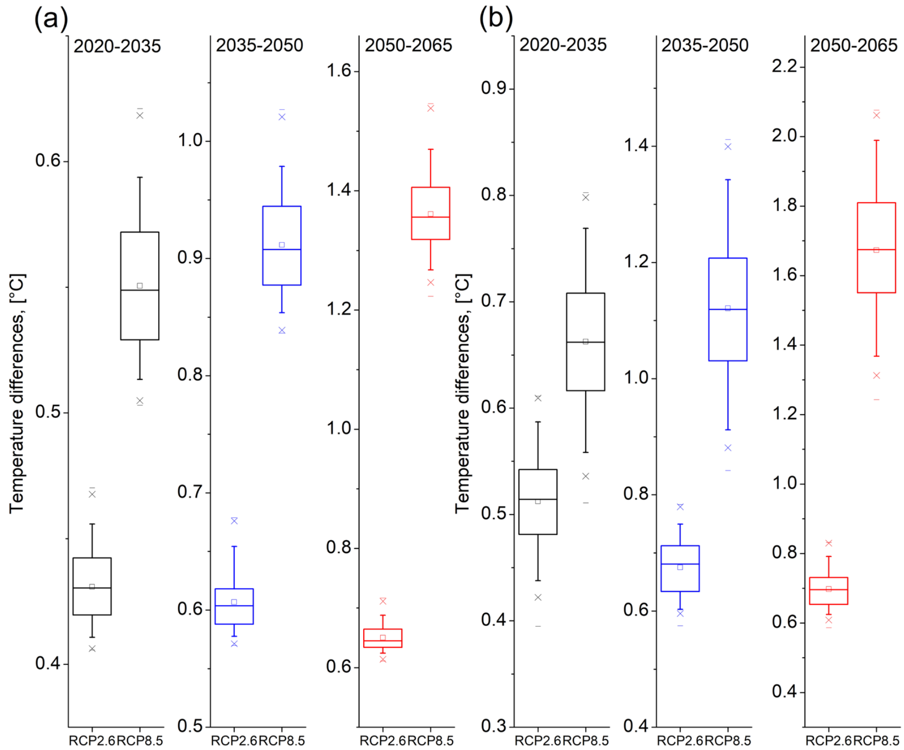


Fig. 15 Box-plots of variability of the values of expected changes in annual average minimum (a) and maximum (b) temperatures compared to the baseline climate for the study area. Box range – 25-75%, whisker range – 5-95%, asterisk range – 1-99% and min-max.

Additionally, in Fig. 16, the spatial distribution maps of the differences in annual average temperature (average between maximum and minimum temperature and between the two scenarios RCP2.6 and RCP 8.5) are presented for three periods in the future as compared to the baseline climate. It can be seen that the average annual temperature change for the entire study area is generally positive for the three periods, however, it is not spatially homogeneous. The maximum temperature rise is expected in the mountainous area of the northeast. A minimum temperature increase, for all periods in the future, is observed for the coast south of the city of Valdivia. For the period 2020–2035, an annual average temperature increase between +0.45 to +0.65 °C is expected; for the period 2035–2050 this interval is between +0.65 to +0.95 °C and for the period 2050–

2065 the temperature increase will range between +0.95 to +1.25 °C as compared to baseline climate.

Intra-annual and spatial heterogeneity of the expected changes in the minimum and maximum temperature in the study area observed was based on data from a large number of climatic models. Therefore, these data can be applied to change baseline climate data and analyse changes in future thermal zone scenarios.

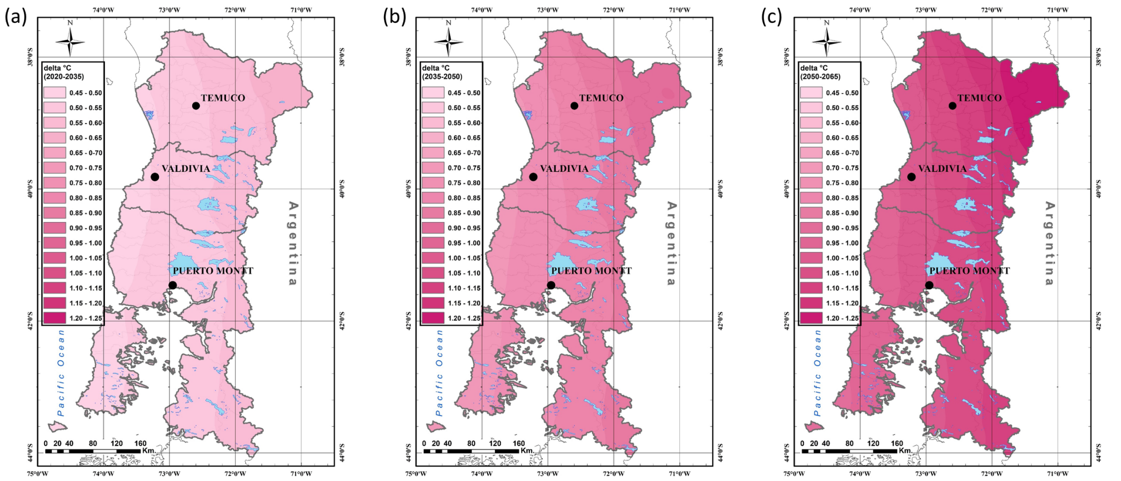


Fig. 16 Change in the annual average temperature in future periods (a) 2020–2035, (b) 2035–2050 and (c) 2050–2065, as compared to baseline climate (average of the RCP2.6 and RCP8.5 scenarios).

The modification of daily temperature data of MM5 will be carried out in accordance with methodologies already presented in other scientific works (Belcher, Hacker, & Powell, 2005; A. L. S. Chan, 2011; A. Jiang, Zhu, Elsafty, & Tumeo, 2018). Based on Belcher *et al.* and Jiang *et al.* (Belcher et al., 2005; A. Jiang et al., 2018), it is possible to apply “a shift” algorithm to modify the baseline climate data to edit the daily values of maximum and minimum baseline climate temperatures by adding the projected monthly average difference for future periods. This methodology has uncertainties that should be noted:

– first, the quality of data in future periods depends primarily on the quality of data in the baseline climate period. The reliability level of the MM5 data was noted previously.

– second, the quality of data in the future depends on the quality of climate modelling for future climate change scenarios. Therefore, data on the average results of the ensemble of climate models were used in this work to reduce inaccuracies in reproducing the future temperature of some climate models in the study area.

Based on this, the calculation of HDD15°C values in the future will be done by applying the following equation:

$$HDD\ 15°C_f = \sum_{j=1}^{12} \sum_{i=1}^{k} \left[\left(T_b - \left(\frac{(T_i^{max.} + \Delta_j^{max.}) + (T_i^{min.} + \Delta_j^{min.})}{2} \right) \right) \right]^+ , \qquad (Eq.\ 2)$$

where T_b – base temperature (15°C); $T_i^{max.}$ – maximum daily temperature of MM5 in baseline climate period; $T_i^{min.}$ – minimum daily temperature of MM5 in baseline climate period; $\Delta_j^{max.}/\Delta_j^{min.}$ – differences in monthly average maximum/minimum temperatures between future periods (2020–2035; 2035–2050; 2050–2065) and the baseline climate; k – number days in each month and the sign (+) means that it is only necessary to calculate positive differences. Values of $\Delta_j^{max.}$ and $\Delta_j^{min.}$ were taken from the website of CCRR (Chile, 2019b). For scenarios RCP2.6 and RCP 8.5, $\Delta_j^{max.}$ and $\Delta_j^{min.}$ are average values of 28 and 44 climate models, respectively (Table 10). Therefore, to modify the daily data on the maximum and minimum temperatures of the baseline climate in each geographical location (Fig. 12), a data set was created with 36 values of $\Delta_j^{max.}$and 36 of values $\Delta_j^{min.}$ for each geographical point and for each scenario of climate change. The Kriging interpolation method is used to restore the spatial distribution of all parameters (Oliver & Webster, 1990).

3.2.4. *Simulation of heating energy consumption*

3.2.4.1. Description of dwelling type

To carry out the energy simulation, a dwelling of the real estate type was used, with a 76.20 m^2 constructed area and a 66.37 m^{2}useful area. This is a typical type of house in the southern part of Chile. This is an existing house with two inhabitants, and it is in the city of Valdivia. Geographic coordinates of the area where the house is located are -39°47´58´´S 73°12´30´´W. Architectural plans and a three-dimensional view are shown in Fig. 17. The housing stock in Chile is 6.5 million dwellings. The number of houses and apartments represent 79.9% and 17.5% of the existing residential building stock, respectively (López-Ochoa, Verichev, Las-Heras-Casas, & Carpio, 2019; Molina, Kent, Hall, & Jones, 2020). According to Molina *et al.* (Molina et al., 2020), the average floor area for dwellings in Chile is 66 m^2 and two-story houses with a 64–79 m^2 area represent 14.4% of the total housing stock of the country.

Table 11 shows the thermal transmittance of the different construction elements of a house used for 3-D modelling and energy simulation. The dwelling roof and walls meet the standards for Thermal zone 6, other construction elements comply with the regulations for the colder thermal zone, zone 7.

Table 11 Thermal transmittance of dwelling structural elements and compliance with standards for thermal zones of RT OGUC.

	Modelling	Compliance RT OGUC
Roofing – U [W/m²·K]	0.3290	Zone 6
Walls – U [W/m²·K]	0.6294	Zone 6
Floors – U [W/m²·K]	0.2662	Zone 7
Doors – U [W/m²·K]	1.06	—
Hermetically double-glazed windows – U [W/m²·K]	3.16	Zone 7
Maximum glazed surface with respect to vertical thermal envelope [%]	16%	Zone 7

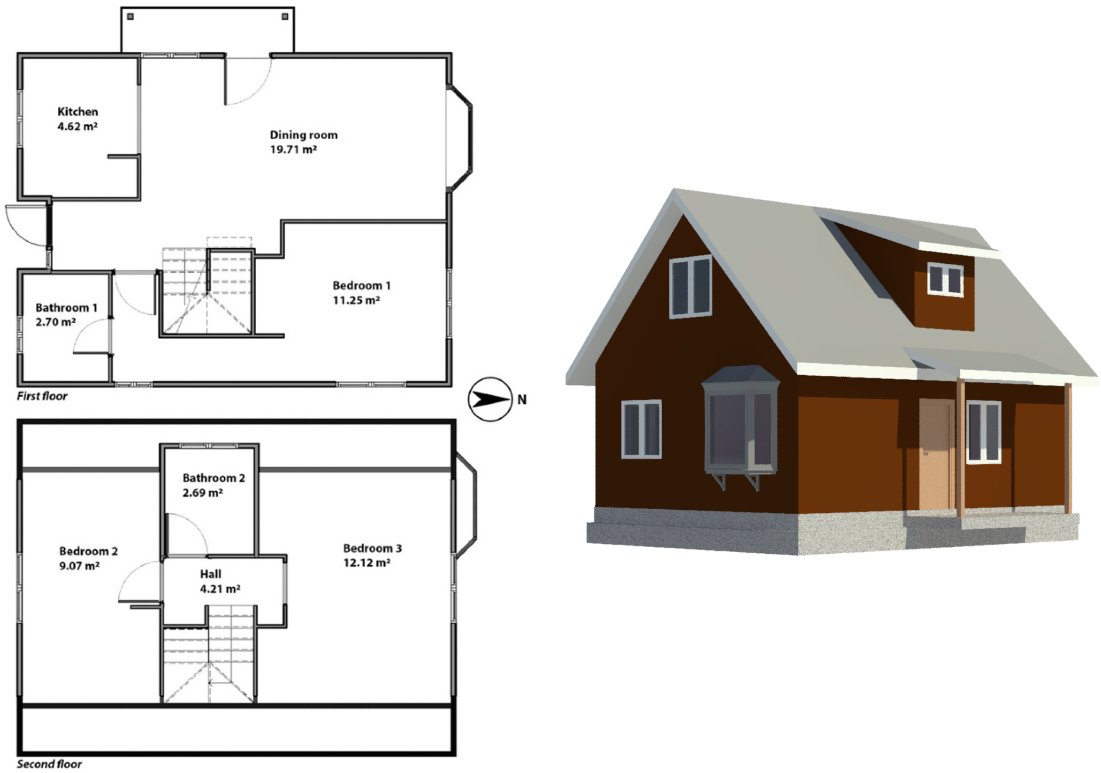


Fig. 17 Type of simulated dwelling.

To simulate heating EC HVAC system "Residential 14 SEER/8.3 HSPF Split/Packaged Heat Pump" from the Revit standard library was used. This system was an efficient < 5.5-ton split/packaged heat pump system with 8.3 Heating Seasonal Performance Factor and 14 Seasonal Energy Efficiency Ratio for cooling. According to references (S. M. Levy, 2012; B. Purushothama, 2009), the seasonal COP value for heating of this system is 2.43, and seasonal COP for cooling is 4.10. This HVAC system includes other elements: (i) Residential constant volume cycling fan; (ii) 2.0 inch of water gauge (498 pascals) static pressure constant volume duct system; (iii) Integrated differential dry-bulb temperature economizer (Autodesk, 2019). The heating part of this system is electrical, and values of the EC are presented in kWh.

EC simulation was carried out for 8760 hours over a calendar year in 360 geographical locations of the study area (Fig. 12). In all areas of the house, heating was simulated to 20°C. According to the ECS (Chile, 2018c), from the minimum values for the intervals of internal thermal comfort in the thermal zones of the country—where heating is necessary—20°C is the maximum value accepted.

Occupation by two persons was considered for the simulation. Currently, in European countries such as Denmark and the United Kingdom, the average household size is 2.1 (Olaya, Vásquez, & Müller, 2017) and 2.48 (Molina et al., 2020) people per house, respectively. In South America, in Chile and in Colombia, the average household size is 3.64 (Molina et al., 2020) and 3.9 (Olaya et al., 2017) people per house, respectively. However, according to forecasts, by 2100 in Colombia, the average household size will decrease to 2.09–2.85 people per house, depending on the forecast of the country's economic development (Olaya et al., 2017). Based on these projections, it was decided to leave the occupation of the house with two people for simulation. Subsequently, the results of an EC simulation will be projected into the future.

Additional simulation parameters, such as sensible heat gains per person – 73.27 W and latent heat gains per person – 45.43 W, were taken from the standard Revit library for residential dwellings. These values are close to the values presented in other studies. So, for example, in the work of Martin *et al.* (Martin, Wong, Hii, & Ignatius, 2017), to simulate the EC of a residential dwelling, the authors used – 70 W for the value of sensible heat gains per person and – 50 W for latent heat gains per person. In Moreno *et al.* (Moreno, Riverola, & Chemisana, 2018), the authors used – 80 W for the value of sensible heat gains per person and 40 W for latent heat gains per person. The method used to calculate outdoor airflow to space depends on dwellers and useful surface area. Outdoor air per person was 2.36 L/s and outdoor air per area was 0.30 L/s·m^2. Fig. 18 shows the occupancy schedule settings applied in the energy simulation. These settings are from the Revit standard library for residential buildings. For hourly simulations, parameters that affect EC of a dwelling and are dependent on the people present will be multiplied by a factor shown in Fig. 18.

Only the results of heating EC simulation were considered, and according to them, the regions under study are characterized by a high-level of wood use for heating dwellings. Government programs are aimed at reducing heating EC and also at reducing the environmental and epidemiological consequences for the population of these regions (Verichev & Carpio, 2018). Therefore, results obtained will help to detail geographical areas with a high level of heating EC and evaluate the natural potential of reducing heating EC in the context of climate change. Currently, in the study area, there is no problem related to the cooling EC of dwellings. But in the future, it will also be important to evaluate changes in cooling EC.

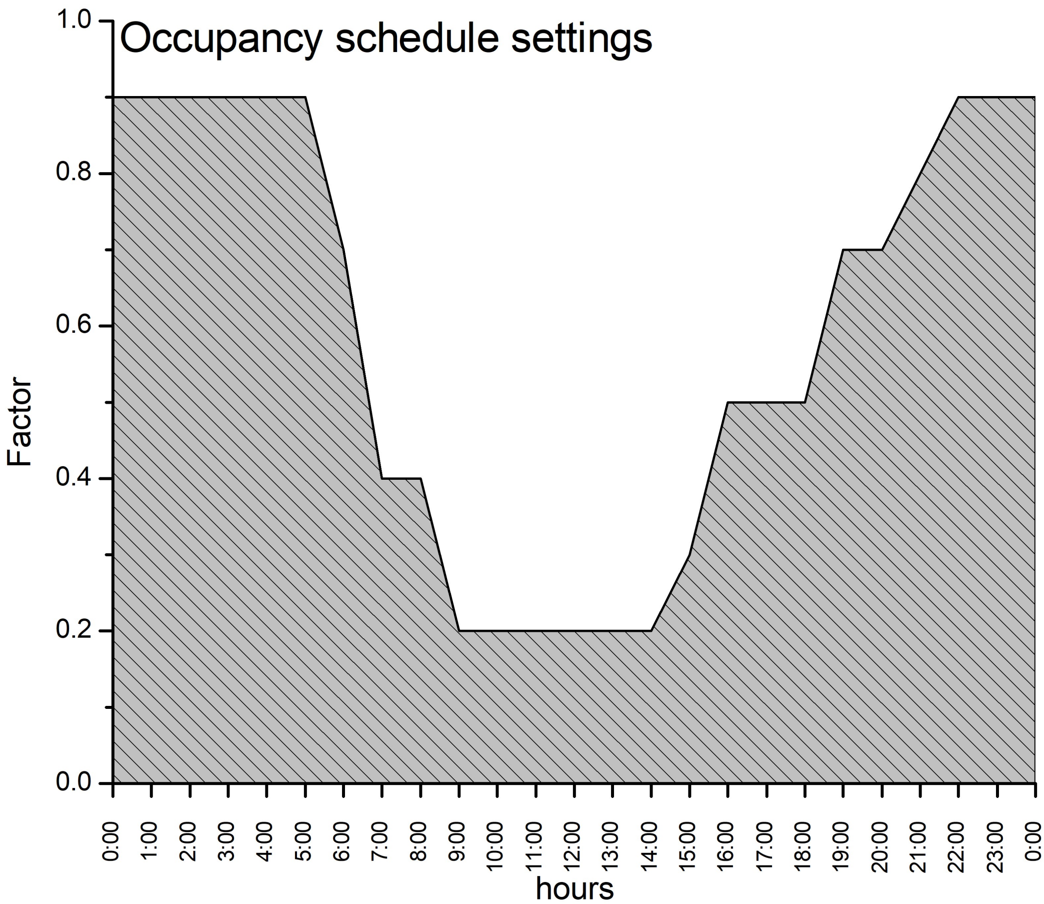


Fig. 18 Dwelling occupancy schedule settings for energy simulation.

3.2.4.2. Estimation of heating energy consumption in the future

For the estimation of heating EC for the future, the quotient between heating EC and HDD15°C of baseline climate will be used, which demonstrates the amount of energy for heating (kWh/m^2/year) corresponding to a degree-day of heating with a base of 15 °C in each geographical location. This will reveal geographic regions with the same annual value of HDD15°C, but with different EC values. Thus, assuming that the quotient between heating EC and HDD15°C will be maintained in different geographical areas in the future, the future heating EC can be calculated in a first approximation, which will depend only on temperature changes in conditions of global climate change expected in the study area. The heating EC value expected in the future (EC_f) will be calculated with the equation:

$$EC_f = \frac{EC_a}{HDD15°C} \cdot HDD15°C_f, \qquad \text{(Eq. 3)}$$

where EC_a— heating EC according to the simulation results in GBS, $HDD15°C$ – value obtained from Eq. 1 of baseline climate; $HDD15°C_f$ – HDD15°C value in future period, calculated according to Eq. 2. Currently, in the scientific literature there have been no studies that consider a similar methodology and that have used the quotient between heating EC and HDD as a parameter that can be implemented to estimate changes EC and climate zoning for building in a fairly large geographical area.

3.3. Results and discussion

In order to know the effects that climate change will have on heating EC in the study area, the situation of the thermal zones distribution in the baseline climate period was analysed first, as well as the foreseeable changes; subsequently, the EC in the baseline climate period will be simulated and finally estimated for the future.

3.3.1. Thermal zones distribution

3.3.1.1. Thermal zones in baseline climate period

In accordance with the provisions of the official RT OGUC document for the study area, four thermal zones are presented (4, 5, 6 and 7). In Fig. 11 and in Table 12 (column "Of. Doc. RT OGUC 1999"), these zones are represented and the results of thermal zones of the official document for each principality of the communes are collected. It can be seen that most of the cities belong to Thermal zones 5 and 6; specifically, out of the 74 cities listed in Table 12, 37 are in zone 5 and 31 in zone 6. And six cities located in small areas in the northwest and southeast belong to Thermal zone 4 (four cities) and Thermal zone 7 (two cities), respectively.

Table 12 Summary table of thermals zones in the principal cities of communes according to the RT OGUC.

Principal city of communes	Of. Doc. RT OGUC	MM5 baseline climate	RCP2.6			RCP8.5		
year	1999***	2006**	2020-2035*	2035-2050*	2050-2065*	2020-2035*	2035-2050*	2050-2065*
	Fig. 11	Fig. 19b	Fig. 20a	Fig. 20c	Fig. 20e	Fig. 20b	Fig. 20d	Fig. 20f
La Araucanía								
Angol	4	5-1387	5-1257(-9%)	4-1214(-12%)	4-1203(-13%)	4-1220(-12%)	4-1110(-20%)	3-987(-29%)
Carahue	5	5-1252	4-1129(-10%)	4-1084(-13%)	4-1075(-14%)	4-1094(-13%)	3-992(-21%)	3-871(-30%)
Cholchol	5	5-1307	4-1182(-10%)	4-1139(-13%)	4-1129(-14%)	4-1147(-12%)	4-1045(-20%)	3-923(-29%)
Collipulli	5	5-1423	5-1291(-9%)	5-1250(-12%)	4-1239(-13%)	5-1254(-12%)	4-1145(-20%)	4-1018(-28%)
Cunco	5	6-1932	6-1779(-8%)	6-1730(-10%)	6-1717(-11%)	6-1732(-10%)	6-1600(-17%)	5-1447(-25%)
Curacautín	5	7-2066	6-1913(-7%)	6-1864(-10%)	6-1851(-10%)	6-1865(-10%)	6-1727(-16%)	6-1567(-24%)
Curarrehue	6	7-2733	7-2565(-6%)	7-2510(-8%)	7-2495(-9%)	7-2509(-8%)	7-2357(-14%)	7-2182(-20%)
Ercilla	5	6-1509	5-1374(-9%)	5-1330(-12%)	5-1320(-13%)	5-1334(-12%)	4-1221(-19%)	4-1089(-28%)
Freire	5	5-1328	4-1203(-9%)	4-1162(-13%)	4-1151(-13%)	4-1166(-12%)	4-1063(-20%)	3-941(-29%)
Galvarino	5	5-1377	5-1251(-9%)	4-1208(-12%)	4-1198(-13%)	4-1215(-12%)	4-1111(-19%)	3-985(-28%)
Gorbea	5	5-1385	5-1259(-9%)	4-1217(-12%)	4-1206(-13%)	4-1221(-12%)	4-1116(-19%)	3-991(-28%)
Lautaro	5	5-1452	5-1321(-9%)	5-1279(-12%)	5-1268(-13%)	5-1282(-12%)	4-1171(-19%)	4-1040(-28%)
Loncoche	5	6-1598	5-1464(-8%)	5-1418(-11%)	5-1407(-12%)	5-1422(-11%)	5-1310(-18%)	4-1175(-26%)
Lonquimay	6	7-3021	7-2849(-6%)	7-2793(-8%)	7-2777(-8%)	7-2791(-8%)	7-2632(-13%)	7-2449(-19%)
Los Sauces	4	5-1443	5-1307(-9%)	5-1263(-12%)	5-1251(-13%)	5-1271(-12%)	4-1157(-20%)	4-1026(-29%)
Lumaco	5	5-1403	5-1273(-9%)	4-1229(-12%)	4-1217(-13%)	4-1237(-12%)	4-1128(-20%)	4-1001(-29%)
Melipeuco	6	7-2719	7-2551(-6%)	7-2498(-8%)	7-2482(-9%)	7-2497(-8%)	7-2344(-14%)	7-2165(-20%)
Nueva Imperial	5	5-1260	4-1135(-10%)	4-1092(-13%)	4-1082(-14%)	4-1100(-13%)	3-999(-21%)	3-879(-30%)
Padre Las Casas	5	5-1346	4-1219(-9%)	4-1177(-13%)	4-1167(-13%)	4-1182(-12%)	4-1077(-20%)	3-954(-29%)
Perquenco	5	5-1479	5-1346(-9%)	5-1303(-12%)	5-1292(-13%)	5-1306(-12%)	4-1195(-19%)	4-1062(-28%)
Pitrufquén	5	5-1333	4-1209(-9%)	4-1167(-12%)	4-1157(-13%)	4-1172(-12%)	4-1068(-20%)	3-947(-29%)
Pucón	6	7-2113	6-1955(-7%)	6-1904(-10%)	6-1891(-11%)	6-1905(-10%)	6-1767(-16%)	6-1607(-24%)
Purén	4	5-1461	5-1326(-9%)	5-1280(-12%)	5-1268(-13%)	5-1290(-12%)	4-1176(-20%)	4-1041(-29%)
Renaico	4	5-1390	5-1288(-7%)	4-1245(-10%)	4-1232(-11%)	4-1248(-10%)	4-1140(-18%)	4-1016(-27%)
Saavedra	5	4-1025	3-909(-11%)	3-865(-16%)	3-858(-16%)	3-876(-15%)	3-782(-24%)	2-675(-34%)
Temuco	5	5-1355	4-1228(-9%)	4-1186(-12%)	4-1175(-13%)	4-1190(-12%)	4-1084(-20%)	3-960(-29%)
Teodoro Schmidt	5	4-1208	4-1087(-10%)	4-1043(-14%)	4-1034(-14%)	4-1051(-13%)	3-953(-21%)	3-838(-31%)
Toltén	5	4-1219	4-1097(-10%)	4-1052(-14%)	4-1043(-14%)	4-1061(-13%)	3-962(-21%)	3-847(-31%)
Traiguén	5	5-1444	5-1314(-9%)	5-1270(-12%)	5-1260(-13%)	5-1277(-12%)	4-1169(-19%)	4-1040(-28%)
Victoria	5	6-1538	5-1402(-9%)	5-1358(-12%)	5-1346(-12%)	5-1361(-12%)	4-1246(-19%)	4-1112(-28%)
Vilcún	5	6-1546	5-1409(-9%)	5-1365(-12%)	5-1354(-12%)	5-1367(-12%)	5-1250(-19%)	4-1113(-28%)
Villarrica	5	6-1560	5-1421(-9%)	5-1377(-12%)	5-1366(-12%)	5-1379(-12%)	5-1261(-19%)	4-1124(-28%)
Los Ríos								
Corral	5	5-1395	5-1266(-9%)	4-1220(-13%)	4-1210(-13%)	4-1230(-12%)	4-1126(-19%)	4-1003(-28%)
Futrono	5	7-2019	6-1864(-8%)	6-1812(-10%)	6-1801(-11%)	6-1817(-10%)	6-1688(-16%)	6-1533(-24%)
La Unión	5	6-1571	5-1437(-9%)	5-1390(-12%)	5-1380(-12%)	5-1398(-11%)	5-1289(-18%)	4-1160(-26%)
Lago Ranco	6	6-1920	6-1769(-8%)	6-1718(-11%)	6-1707(-11%)	6-1723(-10%)	6-1600(-17%)	5-1450(-24%)
Lanco	5	6-1538	5-1404(-9%)	5-1358(-12%)	5-1347(-12%)	5-1363(-11%)	5-1252(-19%)	4-1120(-27%)
Los Lagos	5	6-1620	5-1485(-8%)	5-1438(-11%)	5-1427(-12%)	5-1444(-11%)	5-1333(-18%)	4-1199(-26%)
Máfil	5	5-1421	5-1291(-9%)	4-1246(-12%)	4-1236(-13%)	5-1253(-12%)	4-1148(-19%)	4-1024(-28%)
S.J. de la Mariquina	5	5-1399	5-1270(-9%)	4-1226(-12%)	4-1215(-13%)	4-1232(-12%)	4-1128(-19%)	4-1004(-28%)
Paillaco	5	6-1682	6-1543(-8%)	5-1495(-11%)	5-1484(-12%)	6-1501(-11%)	5-1387(-18%)	5-1252(-26%)
Panguipulli	5	6-1928	6-1781(-8%)	6-1731(-10%)	6-1720(-11%)	6-1735(-10%)	6-1608(-17%)	5-1455(-25%)
Rio Bueno	5	6-1602	5-1466(-8%)	5-1418(-11%)	5-1409(-12%)	5-1425(-11%)	5-1315(-18%)	4-1184(-26%)
Valdivia	5	5-1405	5-1276(-9%)	4-1231(-12%)	4-1220(-13%)	4-1239(-12%)	4-1136(-19%)	4-1013(-28%)
Los Lagos								
Ancud	6	5-1286	4-1157(-10%)	4-1108(-14%)	4-1100(-14%)	4-1124(-13%)	4-1027(-20%)	3-913(-29%)
Calbuco	6	4-1249	4-1106(-11%)	4-1056(-15%)	4-1048(-16%)	4-1071(-14%)	3-967(-23%)	3-847(-32%)
Castro	6	5-1442	5-1306(-9%)	5-1253(-13%)	4-1244(-14%)	5-1272(-12%)	4-1169(-19%)	4-1052(-27%)
Chaitén	6	7-2096	6-1930(-8%)	6-1866(-11%)	6-1859(-11%)	6-1887(-10%)	6-1755(-16%)	6-1601(-24%)
Chonchi	6	5-1373	4-1242(-10%)	4-1190(-13%)	4-1183(-14%)	4-1209(-12%)	4-1110(-19%)	3-997(-27%)
Cochamó	6	7-2572	7-2407(-6%)	7-2347(-9%)	7-2337(-9%)	7-2358(-8%)	7-2219(-14%)	7-2051(-20%)
Curaco de Vélez	6	5-1251	4-1118(-11%)	4-1067(-15%)	4-1059(-15%)	4-1084(-13%)	3-984(-21%)	3-870(-30%)
Dalcahue	6	5-1307	4-1175(-10%)	4-1124(-14%)	4-1116(-15%)	4-1141(-13%)	4-1041(-20%)	3-926(-29%)
Fresia	6	6-1818	6-1674(-8%)	6-1620(-11%)	6-1610(-11%)	6-1635(-10%)	6-1519(-16%)	5-1380(-24%)
Frutillar	6	6-1677	6-1536(-8%)	5-1485(-11%)	5-1475(-12%)	5-1496(-11%)	5-1383(-18%)	4-1248(-26%)
Futaleufú	7	7-3940	7-3758(-5%)	7-3685(-6%)	7-3678(-7%)	7-3705(-6%)	7-3553(-10%)	7-3372(-14%)
Hualaihué	6	6-1633	5-1471(-10%)	5-1414(-13%)	5-1407(-14%)	5-1431(-12%)	5-1311(-20%)	4-1171(-28%)
Llanquihue	6	6-1621	5-1480(-9%)	5-1428(-12%)	5-1419(-12%)	5-1440(-11%)	5-1329(-18%)	4-1195(-26%)
Los Muermos	6	6-1662	6-1520(-9%)	5-1466(-12%)	5-1457(-12%)	5-1481(-11%)	5-1369(-18%)	4-1235(-26%)
Maullín	6	5-1300	4-1170(-10%)	4-1119(-14%)	4-1111(-15%)	4-1134(-13%)	4-1033(-21%)	3-916(-30%)
Osorno	5	6-1599	5-1465(-8%)	5-1416(-11%)	5-1406(-12%)	5-1424(-11%)	5-1317(-18%)	4-1189(-26%)
Palena	7	7-3503	7-3320(-5%)	7-3247(-7%)	7-3239(-8%)	7-3267(-7%)	7-3115(-11%)	7-2937(-16%)
Puerto Montt	6	5-1489	5-1346(-10%)	5-1295(-13%)	5-1287(-14%)	5-1308(-12%)	4-1201(-19%)	4-1072(-28%)
Puerto Octay	6	6-1687	6-1546(-8%)	5-1495(-11%)	5-1485(-12%)	6-1505(-11%)	5-1393(-17%)	5-1257(-25%)
Puerto Varas	6	6-1595	5-1453(-9%)	5-1401(-12%)	5-1392(-13%)	5-1414(-11%)	5-1303(-18%)	4-1171(-27%)
Puqueldón	6	5-1290	4-1160(-10%)	4-1109(-14%)	4-1102(-15%)	4-1126(-13%)	4-1029(-20%)	3-918(-29%)
Purranque	6	6-1763	6-1621(-8%)	6-1569(-11%)	6-1558(-12%)	6-1579(-10%)	5-1464(-17%)	5-1328(-25%)
Puyehue (Entre Lagos)	6	7-2039	6-1886(-8%)	6-1833(-10%)	6-1821(-11%)	6-1840(-10%)	6-1714(-16%)	6-1560(-23%)
Queilén	6	5-1291	4-1159(-10%)	4-1106(-14%)	4-1100(-15%)	4-1126(-13%)	4-1025(-21%)	3-912(-29%)
Quellón	6	5-1308	4-1177(-10%)	4-1124(-14%)	4-1118(-15%)	4-1145(-12%)	4-1046(-20%)	3-936(-28%)
Quemchi	6	4-1187	4-1057(-11%)	4-1008(-15%)	4-1000(-16%)	4-1023(-14%)	3-925(-22%)	3-811(-32%)
Quínchao	6	4-1220	4-1084(-11%)	4-1031(-15%)	4-1024(-16%)	4-1049(-14%)	3-947(-22%)	3-831(-32%)
Rio Negro	6	6-1715	6-1574(-8%)	6-1523(-11%)	6-1512(-12%)	6-1533(-11%)	5-1421(-17%)	5-1288(-25%)
San Juan de la Costa (Puaucho)	6	6-1654	6-1517(-8%)	5-1468(-11%)	5-1457(-12%)	5-1478(-11%)	5-1368(-17%)	4-1235(-25%)
San Pablo	5	6-1581	5-1446(-9%)	5-1398(-12%)	5-1389(-12%)	5-1405(-11%)	5-1296(-18%)	4-1167(-26%)

*Green = no change (thermal zone same as period of baseline climate), yellow = change of 1 thermal zone, orange = change of 2 thermal zones. Column information structure: *thermal zone number – HDD15°C value – % of change of HDD15°C in comparison with baseline climate; ** thermal zone number – HDD15°C value; *** thermal zone number.*

If the spatial distribution of HDD15°C of the MM5 data for the year 2006 is analysed (Fig. 19a), it is observed that its annual values range between 1000 and 4000, with maximum values in the southeast part in mountainous areas, and minimum values west of Temuco city and along the shore of the inner bay, located south of Puerto Montt city. Based on these values, and with the thermal zoning recommendations of RT OGUC (Table 7), the baseline climate thermal zones presented in Fig. 19b have been restored. If a comparison is made with the distribution of the thermal zones of the official RT OGUC document (Fig. 11), a notable difference is observed; for example, the entire area of mountains on the east is characterised by belonging to Thermal zone 7 as compared to zone 6 which is specified in the current RT OGUC document.

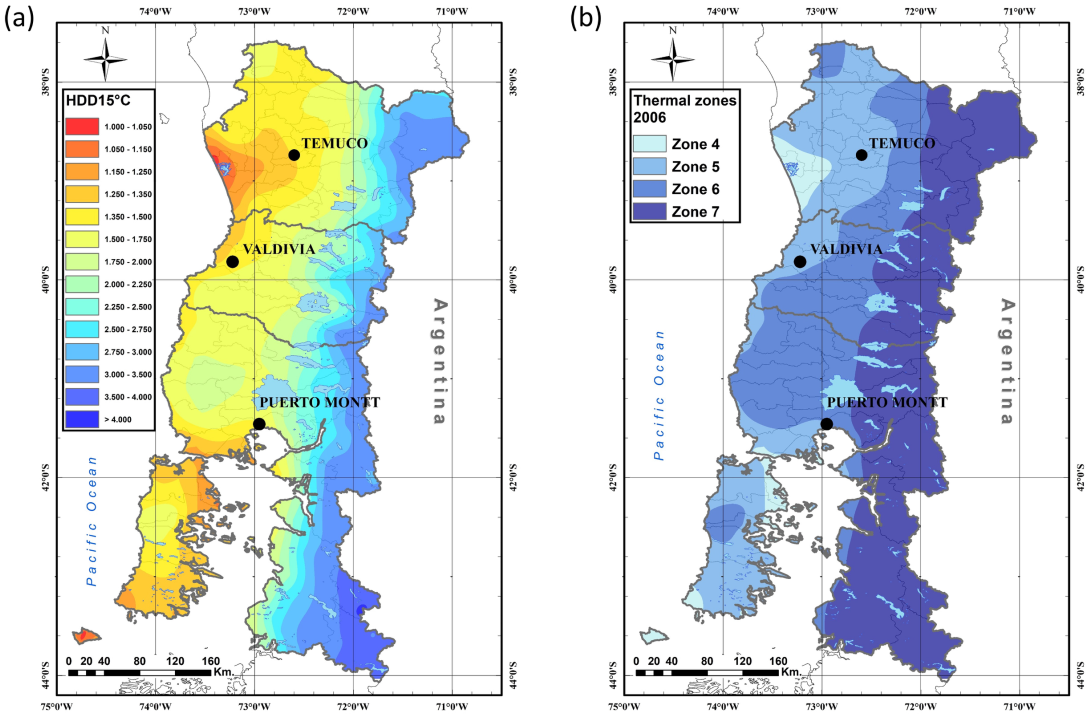


Fig. 19 Map of HDD15°C (a) and thermal zones of the RT OGUC (b) by MM5 data in baseline climate period (2006).

Also, the area within Thermal zone 4 is smaller as compared with RT OGUC. Table 12 (column "MM5 baseline climate 2006") shows the thermal zones for each city with annual values of HHD15°C. Cities like Valdivia and Temuco are located in Thermal zone 5, while Puerto Montt is located between Thermal zones 5 and 6. In comparison, according to the official document of RT OGUC, Puerto Montt city is located in Thermal zone 6. Another notable difference is that 11 cities are located in Thermal zone 7. It should be noted that the official RT OGUC document defines a warmer thermal zone in cities where a colder thermal zone is observed by MM5 data. This difference is noticed thanks to the high spatial resolution of MM5 data, which reflects more meso- and microclimatic specifications in the study area.

The differences found are explained because the thermal zones of the official RT OGUC document are based on administrative boundaries, so they do not reflect the meso- and microclimatic diversity of the region under study, which is why this standard has already been criticised (Vasco, Muñoz-Mejías, Pino-Sepúlveda, Ortega-Aguilera, & García-Herrera, 2017; Verichev, Salimova, & Carpio, 2018); nevertheless, they have not been updated in a long period (Verichev & Carpio, 2018).

In the research (Verichev & Carpio, 2018) also determined the boundaries of thermal zones for a similar geographical area. However, the data was only from 35 meteorological stations over the past decade. The methodology for determining the thermal zones boundaries was manual-cartographic. The border refinement was based on bioclimatic maps and the official RT OGUC map. Therefore, for example, in the Andes region on the border with Argentina, it was not possible to clearly establish the boundaries of Thermal zone 7, which was performed in present chapter. In addition, not all meteorological stations had a sufficient set of meteorological data, which are necessary to simulate EC. Additionally, MM5 data is from 2006, but with their detailed spatial resolution, this data reflects the meso- and microclimatic features of the studied area. Therefore, the boundaries of the zones obtained in the present chapter do not coincide with the previous work. MM5 data makes it possible to carry out multiple simulations, mapping and analysis of the spatial distribution of EC (Verichev et al., 2019b). Also, MM5 data can potentially be used to modify meteorological data files used for simulation in other tools, for example, in Energy Plus (Walsh et al., 2018).

3.3.1.2. Forecast evolution of the thermal zones

In Fig. 20, the RT OGUC thermal zone maps are recalculated based on baseline climate data and taking into account thermal effects (temperature changes only) of climate change in the study area. In Table 12, numbers of RT OGUC thermal zones and HDD15°C values of baseline climate for principal cities are presented for three future periods, 2020–2035, 2035–2050 and 2050–2065, and for the two scenarios of climate change: RCP2.6 and RCP8.5. As has happened in other studies, a change in climatic zones to warmer ones can be observed (Z. J. Zhai & Helman, 2019). For the baseline climate period in cities in the Araucanía region, the HDD15°C values are in the range 1025–3021;

in the Los Ríos region 1395–1864 and in the Los Lagos region 1187–3940. The average decrease in these values for the 2050–2065 period in the entire study area will be 12% and 27% for the RCP2.6 and RCP8.5 scenarios, respectively, that is, the changes will be more drastic in the case of the second scenario.

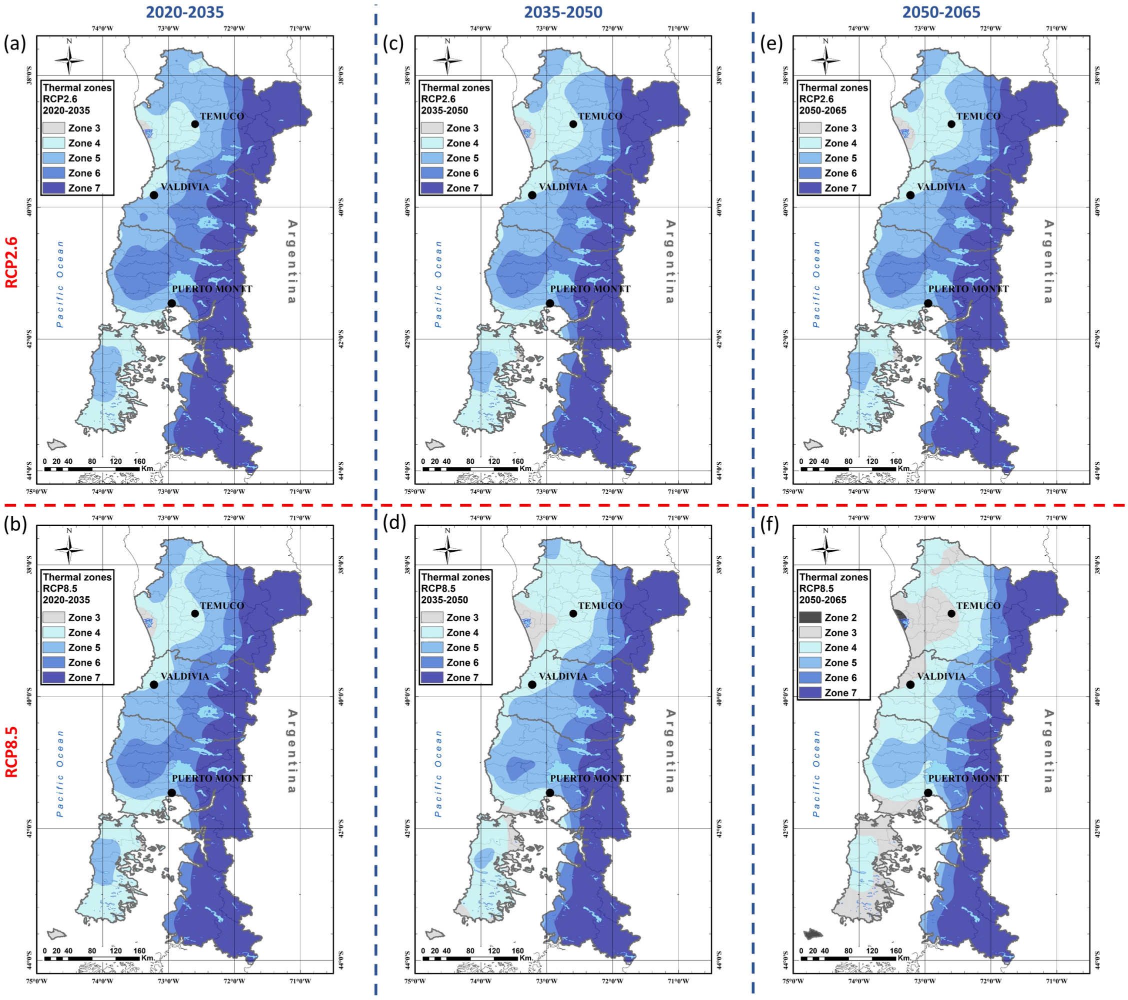


Fig. 20 RT OGUC thermal zones in future periods (a, b) 2020–2035; (c, d) 2035–2050; (e, f) 2050–2065) for scenarios RCP2.6 and RCP8.5, respectively.

In the case of scenario RCP2.6 (Fig. 20c,e), the main changes in thermal zones will happen until the period 2035–2050. Because this climate change scenario predicts that the climate will stabilise and decelerate in subsequent periods (Van Vuuren et al., 2011). As a consequence of climate change, in the northwest part of the study area, in the period 2020–2035 (Fig. 20a) Thermal zone 3 begins to form, specifically to the west of Temuco city. On the other hand, the borders of Thermal zone 7 will not vary much. For the period 2050–2065 and scenario RCP2.6, six cities will be located in Thermal zone 7; 11 cities will be located in Thermal zone 6; 25 cities in Thermal zone 5; 31 cities in Thermal zone 4 and one city will be located in Thermal zone 3. In total 50 out of 74 cities in the 2050–

2065 period will experience changes in thermal zones from baseline climate to a warmer zone (Table 12).

More drastic changes are observed for scenario RCP8.5, especially in the period 2050–2065 in which Thermal zone 2 in the northwest part (Fig. 20f), specifically in the city of Puerto Saavedra (Table 12) and in the part of Chiloé Island (southwest Fig. 20d) will change as Thermal zone 3 begins to form in the period 2035–2050 (Table 12, Curaco de Vélez city). For the period 2050–2065 and scenario RCP8.5, six cities will be located in Thermal zone 7; 5 cities will be located in Thermal zone 6; 8 cities in Thermal zone 5; 31 cities in Thermal zone 4; 23 cities in Thermal zone 3 and 1 city will be located in Thermal zone 2 (Table 12). For 37 cities, the baseline climate thermal zones will change by two thermal zones and 31 cities will change their zones for one warmer, 6 cities will remain unchanged; this will happen in cities located in mountainous areas with Thermal zone 7.

After comparison of predicted thermal zones with baseline climate thermal zones, we proceeded to analyse the application of current RT OGUC standards to the future and comparison of the thermal zones presented in the RT OGUC with the predicted thermal zones. It can be seen (Table 13) that, in 2020–2035, thermal zones are preserved by 47% (RCP2.6) and in 38% (RCP8.5) of cities. Warmer thermal zones will be observed in 35% (RCP2.6) and 47% (RCP8.5) of cities. For the next period (2035–2050), the number of cities with preserved thermal zones will decrease to 36.5% (RCP2.6) and 28% (RCP8.5). In parallel, the number of cities where thermal zones will change to warmer will increase up to 50% (RCP2.6) and up to 61% (RCP8.5). In the period 2050–2065, only 35% and 15% of the cities will maintain their thermal zone with respect to scenarios RCP2.6 and RCP8.5, respectively. In 13.5% (RCP2.6) and 8% (RCP8.5) of the cities under study, it is necessary to improve the housing insulation regulations, since in those cities, a colder climate is actually observed compared to the information proposed by the official RT OGUC document. For other cities, 51.5% (RCP2.6) and 77% (RCP8.5) need to adapt the current RT OGUC regulations to climate change in order to optimise the housing construction and operating costs for future warmer weather conditions. In any situation, with a scenario of stabilisation of climate change (RCP2.6) and a scenario of drastic climate change (RCP8.5), considerable changes in thermal zones are observed. For this reason, the current RT OGUC construction regulations must be updated, improved and adapted to future climatic changes in the study area.

Table 13 Summary of changes of expected thermal zones in cities compared to thermal zones of the official RT OGUC document (Fig. 11).

		2020-2035				2035-2050				2050-2065			
		RCP2.6		RCP8.5		RCP2.6		RCP8.5		RCP2.6		RCP8.5	
		Nº of cities	Change of zones (Nº of cities)	No. of cities	Change of zones (Nº of cities)	Nº of cities	Change of zones (Nº of cities)	Nº of cities	Change of zones (Nº of cities)	Nº of cities	Change of zones (Nº of cities)	Nº of cities	Change of zones (Nº of cities)
Change to colder zone	Change of 1 thermal zone	13 (18%)	4⇒5(4) 5⇒6(5) 6⇒7(4)	11 (15%)	4⇒5(2) 5⇒6(5) 6⇒7(4)	10 (13.5%)	4⇒5(2) 5⇒6(4) 6⇒7(4)	8 (11%)	5⇒6(4) 6⇒7(4)	10 (13.5%)	4⇒5(2) 5⇒6(4) 6⇒7(4)	6 (8%)	5⇒6(2) 6⇒7(4)
No change of zone		35 (47%)	5(22) 6(11) 7(2)	28 (38%)	4(2) 5(16) 6(8) 7(2)	27 (36.5%)	4(2) 5(16) 6(7) 7(2)	21 (28%)	4(4) 5(10) 6(5) 7(2)	26 (35%)	4(2) 5(15) 6(7) 7(2)	11 (15%)	4(3) 5(3) 6(3) 7(2)
Change to warmer thermal zone	Change of 1 thermal zone	14 (19%)	5⇒4(9) 6⇒5(5)	23 (31%)	5⇒4(15) 6⇒5(8)	25 (34%)	5⇒4(16) 6⇒5(9)	27 (36.5%)	5⇒4(18) 6⇒5(9)	25 (34%)	5⇒4(17) 6⇒5(8)	26 (35%)	4⇒3(1) 5⇒4(20) 6⇒5(5)
	Change of 2 thermal zone	12 (16%)	5⇒3(1) 6⇒4(11)	12 (16%)	5⇒3(1) 6⇒4(11)	12 (16%)	5⇒3(1) 6⇒4(11)	14 (19%)	5⇒3(5) 6⇒4(9)	13 (17.5%)	5⇒3(1) 6⇒4(12)	19 (26%)	5⇒3(11) 6⇒4(8)
	Change of 3 thermal zone							4 (5.5%)	6⇒3(4)			12 (16%)	5⇒2(1) 6⇒3(11)

3.3.2. Heating energy consumption

3.3.2.1. Heating energy consumption in baseline climate period

The heating EC has been simulated in the baseline climate period, which allowed us to obtain the results shown in Fig. 21, in which the structure of the heating EC isolines is similar to the HDD15°C isolines shown in Fig. 19a.

The variability of heating EC and HDD15°C is in a range of 60–300 kWh/m^2/year and 1000–4000, respectively. This is a consequence of the MM5 meteorological data used for energy simulation. The average value of heating EC observed for all cities is 106 kWh/m^2/year (σ = 37 kWh/m^2/year) with a maximum in the case of dwellings located in the mountainous part, generally in the southeast part of the study area (250–300 kWh/m^2/year), and a minimum value that is reached on the northwest oceanic coast (60 kWh/m^2/year). Specifically in Table 14, results of simulation of heating EC in the cities are presented, in which Futaleufú, a city in the southeast of the study area, has the highest heating EC value of 286 kWh/m^2/year, while the minimum of 65 kWh/m^2/y was observed in Puerto Saavedra, located in the northwestern part.

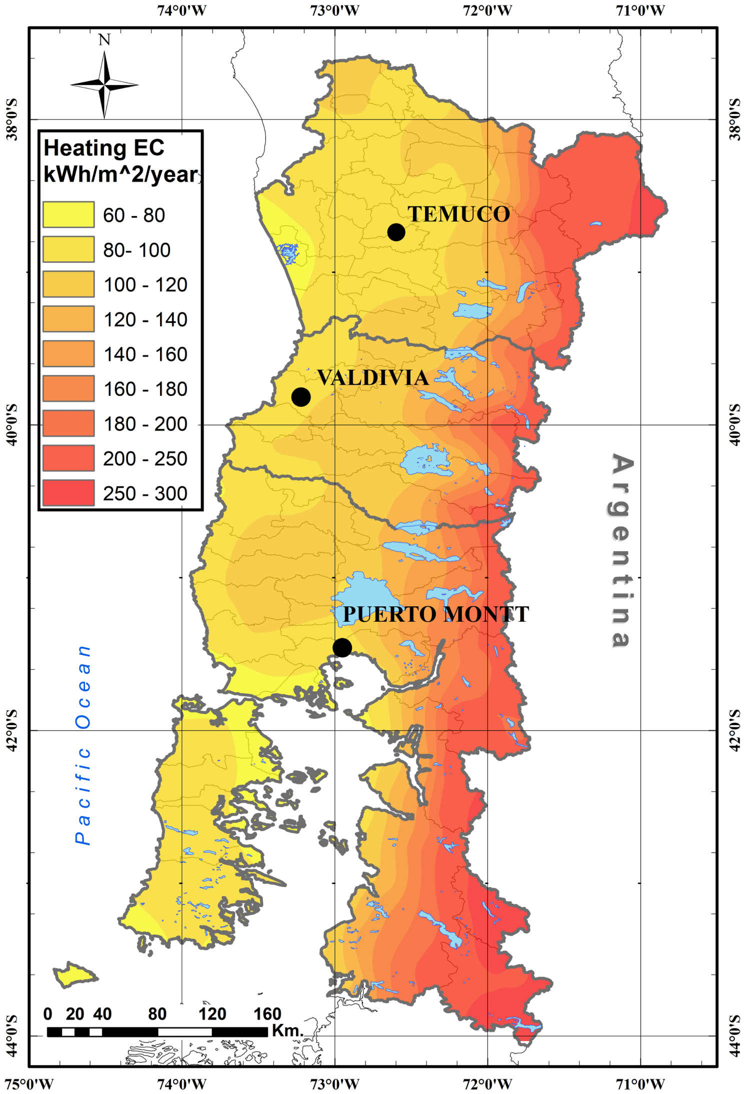


Fig. 21 Results of heating EC simulation in the baseline climate period.

If the heating EC is related to the annual HDD15°C values in all the energy simulation points of the study area (Fig. 22), a linear correlation between these two parameters can be observed, similar to the work of Conradie *et al.* (Conradie, van Reenen, & Bole, 2018). On the other hand, there is also a sufficient data difference; thus, for the value of HDD15°C equal to 3000, it can be seen that the heating EC can range between 175 kWh/m^2/year and 225 kWh/m^2/year. This means that different geographical locations with the same annual HDD15°C value will have different heating EC values, and this difference can be explained by the fact that the energy simulation is carried out on the basis of different hourly meteorological parameters in every geographic place (Verichev et al., 2019b), and the HDD15°C values were calculated by the maximum and minimum daily temperatures.

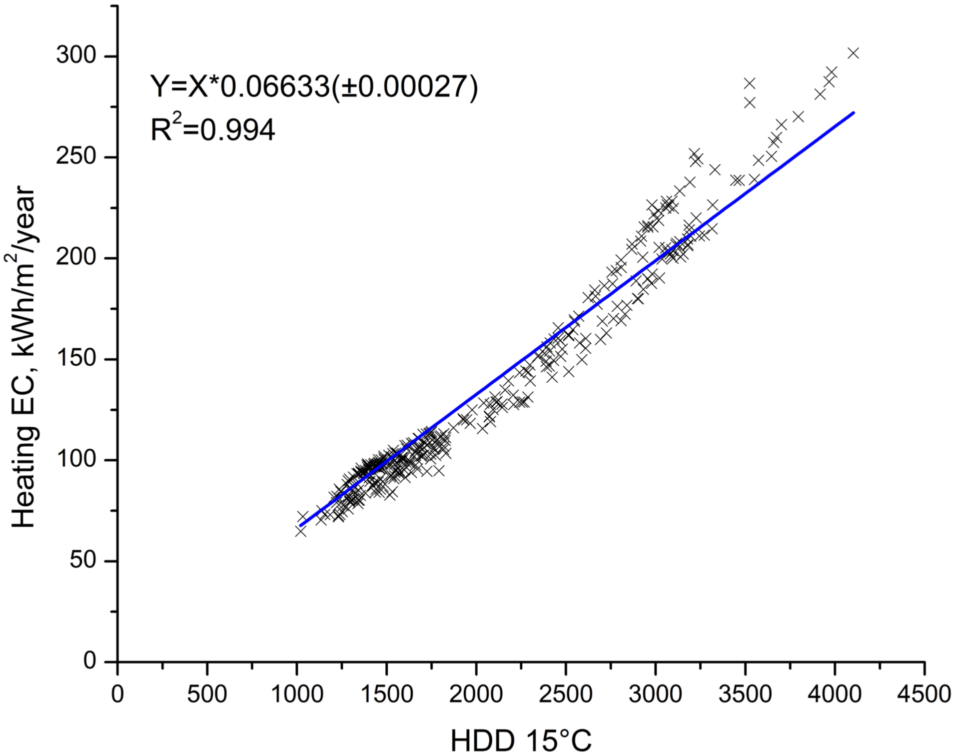


Fig. 22 Correlation between heating EC and annual value of HDD15°C in 360 geographical locations in baseline climate period (slope of the regression line with standard error).

Due to this correlation, it can be established that in each geographical location there is a conversion coefficient between HDD15°C and heating EC, so for each geographical point of energy simulation it has been possible to calculate the quotient between heating EC and HDD15°C for the baseline climate period. In Fig. 23, the spatial distribution map of the quotient between heating EC and HDD15°C for 2006 is shown.

It can be seen, that in high-altitude mountain areas, a quotient greater than 0.070 kWh/m^2/year per HDD15°C is observed, while, in the southern part, near Puerto Montt, this quotient is at the threshold of 0.050–0.055 kWh/m^2/year per HDD15°C. Similarly, near large lakes, there are areas with a minimum quotient between heating EC and HDD15°C. Thus, Mourshed M. (Mourshed, 2011) describes the coefficient between HDD and heating EC as dependent on the overall seasonal heating system efficiency and the overall building heat loss coefficient. Therefore, for a single house with the same operating conditions, the same heating system, the same orientation with respect to north and other similar characteristics, variability of heating EC in two different geographical locations with the same value of HDD15°C, will generally depend on heat loss. Which will, in turn, depend on other meteorological parameters, mainly wind (speed and direction will affect infiltration of air) and solar radiation (will affect external heat gain).

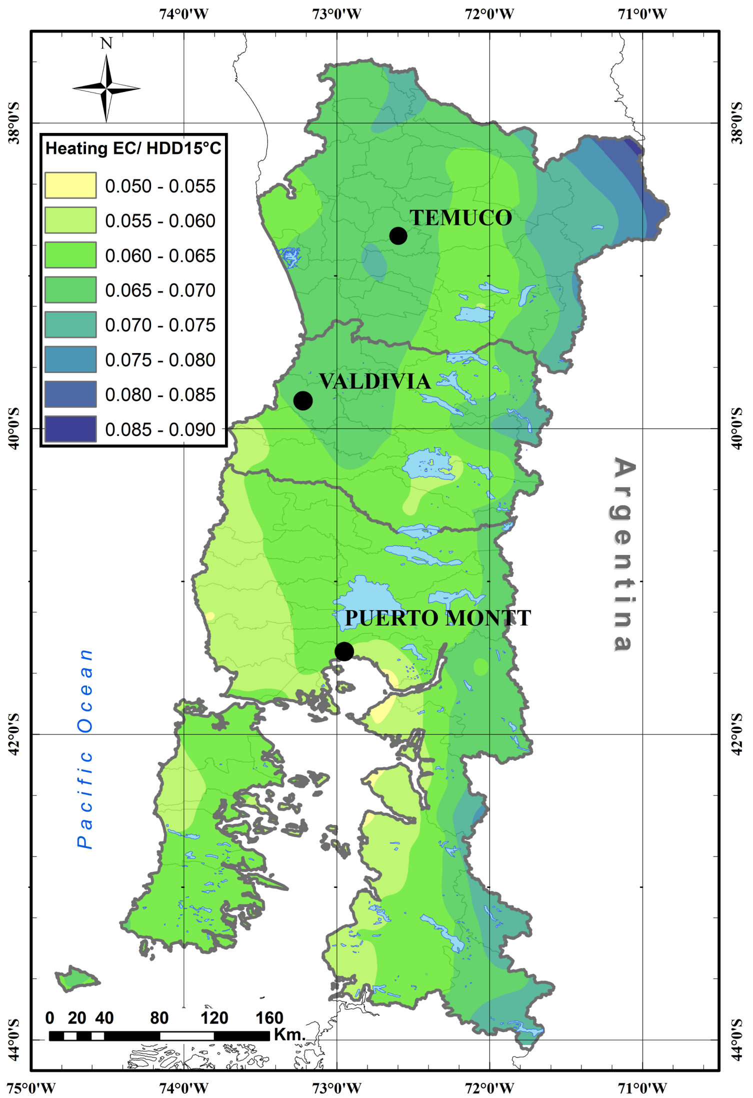


Fig. 23 Spatial distribution of the quotient between heating EC and HDD15°C [kWh/m²/year/HDD15°C] in the baseline climate period.

It can therefore be concluded that the quotient between heating EC and HDD15°C can be used as a quantitative characteristic of some areas with similar climatic conditions, where a linear relationship between heating EC and HDD15°C is observed. Of course, each house, with its own characteristics of architecture, construction and other individual parameters, will have different absolute values of the quotient between heating EC and HDD15°C; but the spatial distribution of this quotient with its zones of maximum and minimum will be maintained. For all this, the use of the energy simulation results together with HDD data will help with climatic zoning for building in areas with cold climates.

3.3.2.2. Forecast change of heating energy consumption

Finally, heating EC of the dwelling under study has been estimated for the future, taking into account the two climate change scenarios and the three periods considered. The results are presented in Fig. 24. Since the estimation of heating EC has been based solely on HDD changes for the study area, it can be said that this heating EC takes into account only future temperature changes.

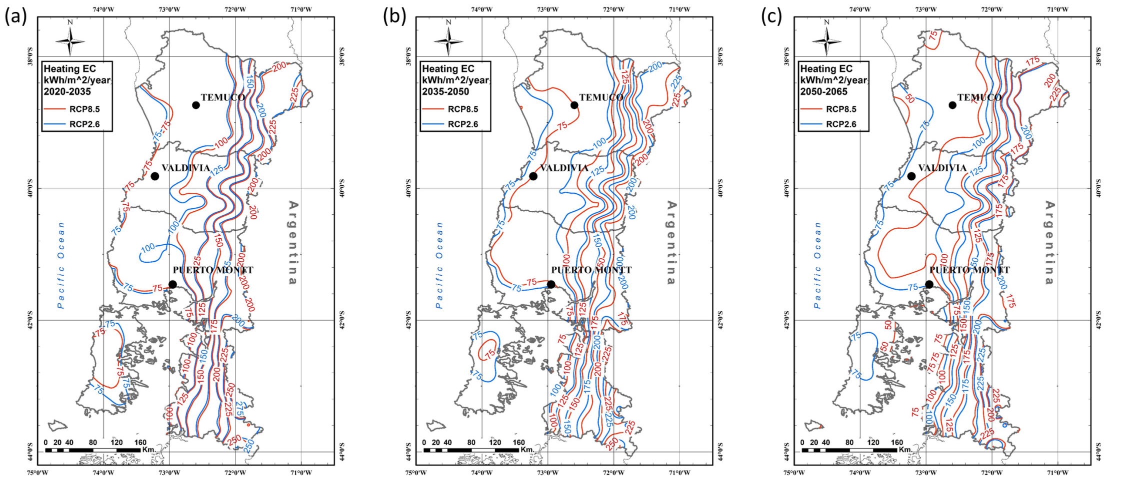


Fig. 24 Estimated heating EC in the dwelling under study in future periods (a) 2020–2035, (b) 2035–2050 and (c) 2050–2065).

If Fig. 24 is compared with Fig. 21, it is observed that the isolines shape and spatial distribution of EC for heating are similar. Thus, in the period 2020–2035, the EC for heating will decrease (on average between the two scenarios RCP2.6 and RCP8.5) between 5 kWh/m^2/year and 20 kWh/m^2/year. In the period 2050–2065 the reduction will be greater, estimated between 10 kWh/m^2/year and 25 kWh/m^2/year; and finally, in period 2050–2065, it will reach values between 12 kWh/m^2/year and up to 45 kWh/m^2/year.

Table 14 shows the estimating heating EC of the dwelling under study in principal cities in the southern part of Chile for the period 2050–2065. It can be seen that the heating EC values will have a decreasing trend in all cities and for the two scenarios analysed. However, this does not mean that a decrease in heating EC is a positive effect for reduce of total EC, because can increase part of the consumption for cooling and ventilation of the houses (Berger et al., 2014).

Table 14 Heating EC [kWh/m²/year] in cities for baseline climate period and in the future 2050–2065.

Cap. city of comm.	EC baseline climate 2006 (Fig. 21)	EC 2050-2065 RCP2.6/RCP8.5 (Fig. 24c)	ΔEC RCP2.6/RCP 8.5	Cap. city of comm.	EC baseline climate 2006 (Fig. 21)	EC 2050-2065 RCP2.6/RCP8.5 (Fig. 24c)	ΔEC RCP2.6/RCP 8.5
Angol	96	84/69	-13%/-29%	Los Lagos	108	95/80	-12%/-26%
Carahue	82	71/57	-14%/-30%	Máfil	98	85/71	-13%/-28%
Cholchol	91	79/64	-14%/-29%	S.J. de la Mariquina	95	83/68	-13%/-28%
Collipulli	99	86/71	-13%/-28%	Paillaco	112	99/83	-12%/-26%
Cunco	120	107/90	-11%/-25%	Panguipulli	121	108/91	-11%/-25%
Curacautín	130	116/98	-10%/-24%	Rio Bueno	103	91/76	-12%/-26%
Curarrehue	190	174/152	-9%/-20%	Valdivia	93	81/67	-13%/-28%
Ercilla	102	89/73	-13%/-28%	Ancud	79	67/56	-14%/-29%
Freire	92	80/65	-13%/-29%	Calbuco	74	62/50	-16%/-32%
Galvarino	95	83/68	-13%/-28%	Castro	88	76/64	-14%/-27%
Gorbea	96	84/69	-13%/-28%	Chaitén	120	106/91	-11%/-24%
Lautaro	98	85/70	-13%/-28%	Chonchi	85	73/62	-14%/-27%
Loncoche	106	94/78	-12%/-26%	Cochamó	167	152/133	-9%/-20%
Lonquimay	223	205/181	-8%/-19%	Curaco de Vélez	75	64/52	-15%/-30%
Los Sauces	99	86/71	-13%/-29%	Dalcahue	79	68/56	-15%/-29%
Lumaco	97	84/69	-13%/-29%	Fresia	108	95/82	-11%/-24%
Melipeuco	189	173/151	-9%/-20%	Frutillar	104	91/77	-12%/-26%
Nueva Imperial	87	75/61	-14%/-30%	Futaleufú	286	267/245	-7%/-14%
Padre Las Casas	93	80/66	-13%/-29%	Hualaihué	90	78/65	-14%/-28%
Perquenco	98	86/71	-13%/-28%	Llanquihue	99	87/73	-12%/-26%
Pitrufquén	93	81/66	-13%/-29%	Los Muermos	97	85/72	-12%/-26%
Pucón	130	116/99	-11%/-24%	Maullín	77	66/55	-15%/-30%
Purén	98	85/70	-13%/-29%	Osorno	101	89/75	-12%/-26%
Renaico	97	86/71	-11%/-27%	Palena	243	225/204	-8%/-16%
Saavedra	65	55/43	-16%/-34%	Puerto Montt	89	77/64	-14%/-28%
Temuco	93	81/66	-13%/-29%	Puerto Octay	104	92/78	-12%/-26%
Teodoro Schmidt	82	71/57	-14%/-31%	Puerto Varas	97	85/71	-13%/-27%
Toltén	83	71/57	-14%/-31%	Puqueldón	80	68/57	-15%/-29%
Traiguén	98	85/70	-13%/-28%	Purranque	109	97/82	-12%/-25%
Victoria	101	88/73	-12%/-28%	Puyehue	124	111/95	-11%/-23%
Vilcún	99	86/71	-12%/-28%	Queilén	80	68/56	-15%/-29%
Villarrica	100	88/72	-12%/-28%	Quellón	83	71/59	-15%/-28%
Corral	87	76/63	-13%/-28%	Quemchi	73	62/50	-16%/-32%
Futrono	123	110/94	-11%/-24%	Quínchao	72	60/49	-16%/-32%
La Unión	100	88/74	-12%/-26%	Rio Negro	107	94/80	-12%/-25%
Lago Ranco	115	102/87	-11%/-24%	San Juan de la Costa	100	88/75	-12%/-25%
Lanco	103	91/75	-12%/-27%	San Pablo	101	89/75	-12%/-26%

The decreases calculated between 2006 and 2050–2065 for scenario RCP2.6 are 13%, with an average value of heating EC of 94 kWh/m²/year (σ = 36 kWh/m²/year). In the case of the most extreme RCP8.5 scenario, this decrease would be 27% with an average heating EC value of 79 kWh/m²/year (σ = 34 kWh/m²/year).

Similar results have been observed in cities of the southern hemisphere. For example, Wang *et al.* (X. Wang et al., 2010) estimated for the city of Hobart, located at the southern tip of Tasmania Island (42.9°S), that the heating EC of residential dwellings will decrease of 25% (42%) and 28% (58%) in the year 2050 (2100), under the A1B and A1FI scenarios, respectively. Flores-Larsen *et al.* (Flores-Larsen et al., 2019) analysed the change in EC in four cities in Argentina located between latitudes 23°S–37°S under the SRES A2 scenario, concluding that, by the year 2080 in an isolated single-family home, the heating EC will decrease in the range of 23–59%. The minor changes in the heating EC observed in our research, for scenario RCP2.6, are due to the fact that this climate change mitigation scenario is the most positive for the world with minimisation of anthropogenic effects to climate system.

Finally, differences are observed between mountain and coastal areas. Thus, for the period 2050–2065 and RCP8.5, in Lonquimay city, the decrease in heating EC of 42 kWh/m^2/year is observed in absolute values (corresponding to only 19% of the consumption in 2006). On the other hand, the coastal city of Dalcahue, on Chiloe Island, shows a decrease in heating EC for 23 kWh/m^2/year in absolute values (corresponding to 29% of consumption in 2006), not being as significant as in the mountainous area.

3.4. Conclusions

In this chapter it has shown that, from the point of view of the current situation and taking into account the results obtained for the “baseline climate”, the inconsistency the official document RT OGUC with the climatological reality in La Araucanía, Los Ríos and Los Lagos regions was confirmed, because it establishes the thermal zones as a function of administrative boundaries, not climatic ones. This means that today its application would imply a building design that does not agree with the real climatic conditions in which it is located. Besides, the inconsistent detected will get worse in most cities of the studied area in the future; in fact, as for the expected temperature changes, these are positive throughout the study area and provide trends of decrease of HDD°15 in the entire investigated zone.

Due to the diversity of meso- and microclimatic zones within La Araucanía, Los Ríos and Los Lagos regions, a methodology has been developed for estimating heating EC for the future, taking into account the effect of temperature change in the future and the quotient between heating EC and HDD of baseline climate year. The application of this methodology has demonstrated, that, as a consequence of the insufficiency of the current climate zoning, the simulate results of the heating EC in regions studied, in the case of a single-family house for the baseline climate period, results have shown five-fold variability, between 60 kWh/m^2/year and 300 kWh/m^2/year. Besides, as a consequence of the variation of the meteorological conditions, we expected a decrease of the heating EC of 5–15%, 6–24%, 7–34% (under the two scenarios RCP 2.6 and RCP 8.5) for future periods 2020–2035, 2035–2050 and 2050–2065, respectively. Given that the changes in total EC depend not only on the consumption for heating but also on the need for cooling and ventilation of the house, among others parameters, the need to extend this study in their determination is evident. It is also worth noting that in the future, the importance of taking into account CDD and the effects of direct solar radiation in the process of climatic zoning for the area under study will increase.

Then, it is possible conclude that the method of energy simulation in numerous geographical locations with different types of dwellings, the matching of energy results with weather parameters and adaptation and mitigation methods for climate change are priority for the development of the correct climatic zone determination for building in the future in different regions of the world.

CHAPTER 4.- ASSESSING THE APPLICABILITY OF VARIOUS CLIMATIC ZONING METHODS FOR BUILDING CONSTRUCTION: A CASE STUDY FROM THE EXTREME SOUTH PART OF CHILE[3]

[3] The results shown in this chapter were presented in: **Verichev, K.**, Zamorano, M., Carpio, M., **Assessing the applicability of various climatic zoning methods for building construction: Case study from the extreme southern part of Chile** (2019) *Building and Environment* 160 V., 106165.

4.1. Introduction

According to RT OGUC, the territory of the two regions with the highest consumption of heating energy in the residential sector of the country, Aysén and Magallanes, and located in extreme south of the country, are considered in Thermal zone 7, with an average annual value of more than 2000 HDD15°C (Table 7 and Fig. 11). As a result, RT proposes the same norms for thermal transmittance values of building elements for the third part of the country (Chile, 2006a), which is characterised by many different climates (see Chapter 2). The same consideration is observed in the case of ECS regulations that includes both regions under study in the same climatic zone – Thermal zone I – Fig. 11 (Chile, 2008). Compared to the three northern regions of the study area, the two southern regions differ significantly in climatic conditions and building codes, which are the most stringent in terms of buildings' energy efficiency. The complete absence of any meso- and microclimatic features in the current thermic zoning for buildings is also clearly traced. Therefore, the methodology of energy simulation at multiple locations will be used to demonstrate the inconsistency of current thermal zoning and verify climatic zoning methods that are hypothetically capable of improving climatic zoning for building in the meso- and microclimatic aspects in Aysén and Magallanes regions.

The previous chapter has demonstrated the importance of considering meso- and microclimatic and climate change characteristics in climate zoning for building in La Araucanía, Los Ríos and Los Lagos regions characterised by the lack of recognition of these parameters in the current climate zoning for building.

For this purpose, the results obtained in the previous chapter have been considered, as well as other studies developed in Nicaragua (Walsh et al., 2018) and in China (Xiong et al., 2019), which use multiple EC simulations for climate zoning of buildings to validate the accuracy of the determination of climate zones. Specifically, it was decided to apply the method of using the results of heating energy simulation to assess the applicability of climatic/thermal zoning in a fairly cold climate condition of the extreme south part of Chile. Using the same building standard that in the other regions, in the whole study area in the process of performing computational energy simulations, the result will show variations in EC which will depend on the diversity of real climatic conditions, so the use data of meteorological models with higher spatial resolution in the respective simulations will be necessary. Finally, and based on the results of the simulation of heating EC, the possibility of using other climate zoning methods to improve zoning for building in the studied area will be analysed. In this case, the Köppen bioclimatic zoning method and cluster zoning method based on various meteorological parameters will be considered, according to several scientific works (Walsh et al., 2017a, 2017b; Wan, Li, Yang, & Lam, 2010).

Taking into account the above considerations, the goal of the present chapter on the basis of simulated EC of dwelling, has been the assessment of the applicability of existing different climatic/thermal zoning for building and identify key parameters that could be used to propose a new climate zoning for building in the extreme south part of Chile. The following stages were performed to achieve that goal: (i) Analysis of the current thermal zoning for building in the study area; (ii) Modelling of the level of heating EC in a single-family house, and assessment of the zoning system based on the simulation of EC of the dwellings; (iii) Analysis of the values of heating EC of the dwelling under study, and values of HDD in different bioclimatic zones; and (iv) Analysis of the use of cluster method based on meteorological variables for climatic zoning for building.

4.2. Material and methods

4.2.1. Working methodology

Fig. 25 illustrates the general scheme of the present chapter. First, the official thermal zones of the RT OGUC standard have been compared with the thermal zones based on MM5 in 680 geographical locations (Fig. 25) (1) to detect possible inconsistencies of the thermal zones established by the official document of the RT OGUC, and the thermal zones of meteorological data that are used for energy simulation in the study area. (2) - Cluster analysis zones based on various metrological data and values of HDD15°C from MM5 were created. (3) - Simulation of heating EC in GBS was realized. After modelling the EC of a single-family house, a correlation between HDD15°C and heating EC in different zones of bioclimatic zoning (4) and cluster zoning (5) was compared.

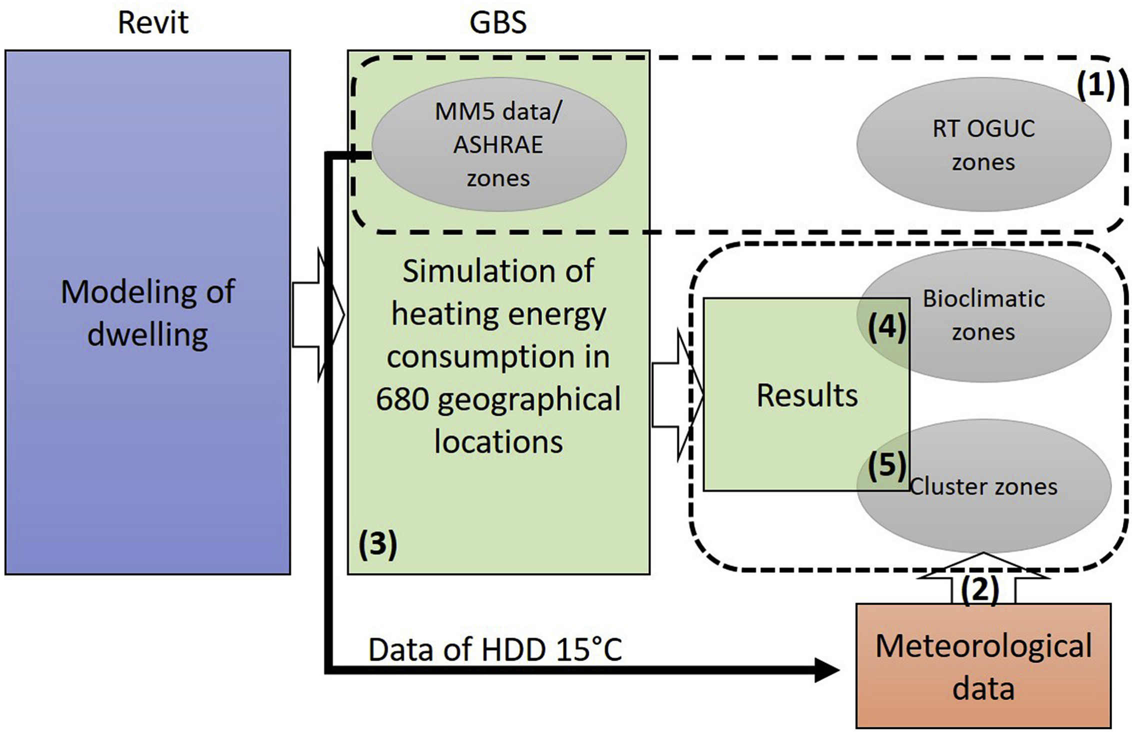


Fig. 25 Structure of the Chapter 4.

4.2.2. Computational tools used

The software used in the present chapter for 3D modelling of structural and architectural components of the dwelling under study, for energy simulation and for mapping are described in Chapter 3. Statistical analysis and cluster analysis performed using the IBM SPSS Statistics version 22.0 software, with a license from the *Pontificia Universidad Católica de Chile*.

4.2.3. Study area

Two southern regions in Chile, Aysén and Magallanes have been included in this chapter. A detailed geographical description of the studied regions is presented in the Section 2.2. Fig. 26 shows the general situation of the study area in South America and 680 geographical locations (red dots) where the energy simulations will be performed.

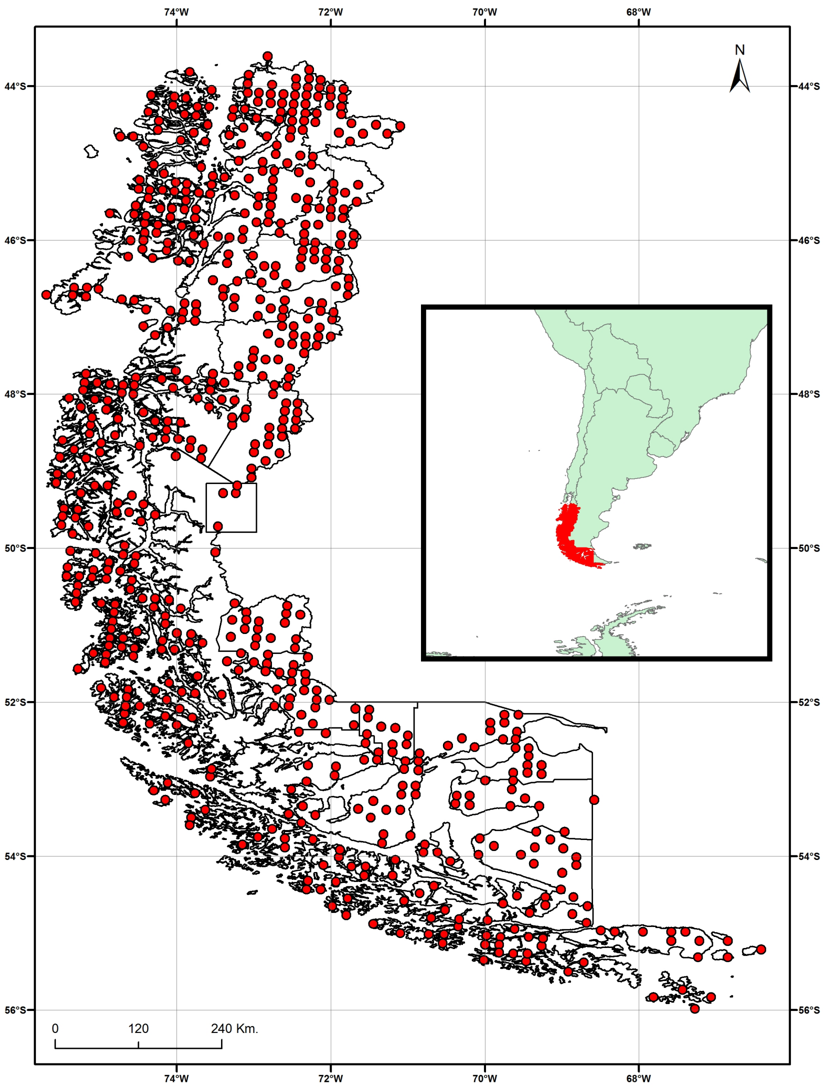


Fig. 26 Map of the study area and the 680 geographical locations for energy simulations.

4.2.4. Methods applied to determine climatic/thermal zones in the studied area

According to the working methodology, three different methods have been applied to study climatic/thermal zones in Aysén and Magallanes regions. Thermal zones from of the RT OGUC will be restored based on the meteorological data of GBS for energy simulation. Cluster zones will be defined based on different meteorological data. And the possibility of applicability of cluster and bioclimatic zones for more detailed zoning of the studied area will be assessed on the basis of the heating EC simulation results.

4.2.4.1. Climatic zones of ASHRAE and Thermal zones of RT OGUC based on GBS data

The meteorological data provide by GBS for energy simulation is based on a combination of meteorological measurement data and modelling data – MM5 (Grell et al., 1994). In GBS, climatic zones are based on the climatic zoning method of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (ASHRAE, 2013). The ASHRAE climatic zones map is presented in Fig. 27, based on the names of ASHRAE climatic zones for each of the 680 locations assessed from GBS.

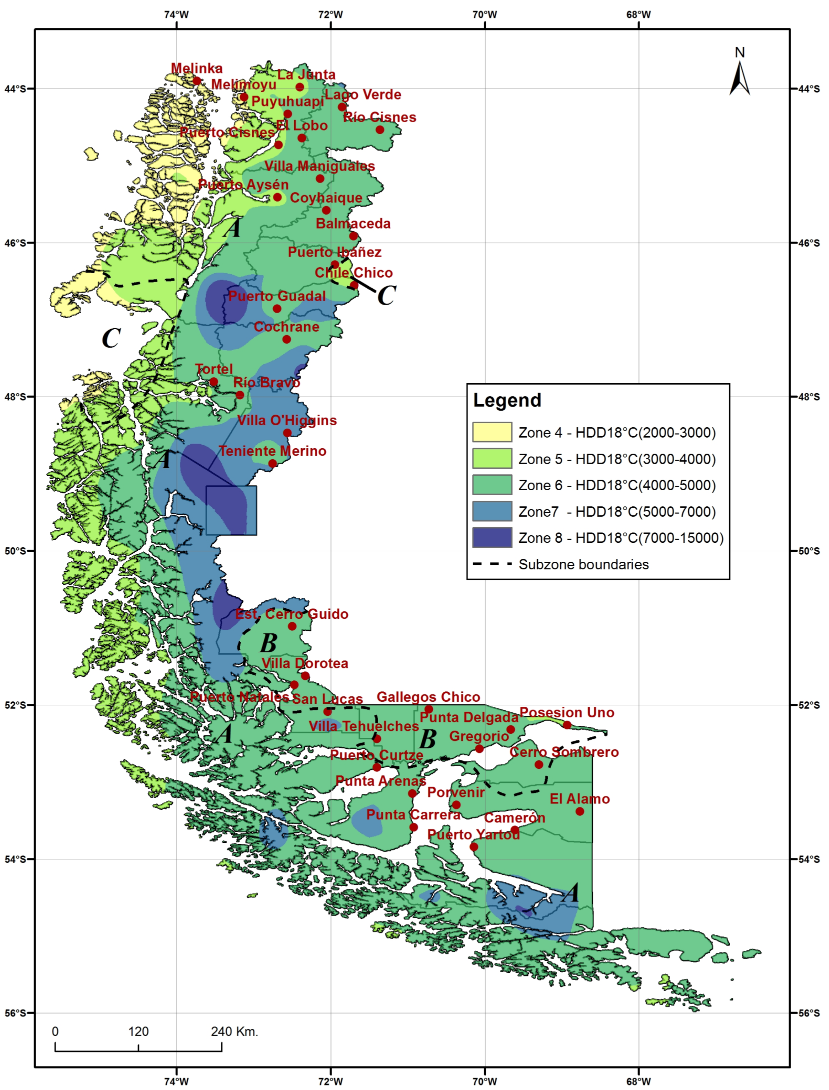


Fig. 27 ASHRAE climatic zoning (GBS).

There are eight ASHRAE climatic zones in the study area (4A, 4C, 5A, 5C, 6A, 6B, 7, and 8). Each zone depends on HDD18°C, CDD with a base temperature of 10 °C (CDD10°C), and annual precipitation (ASHRAE, 2013).

The ASHRAE method is used to calculate the HDD (Eq. 1) and CDD:

$$CDD = \sum_{i=1}^{365}\left[\left(\frac{T_i^{max.}+T_i^{min.}}{2}\right)-T_b\right]^{+}, \qquad (Eq.\ 4)$$

where CDD is calculated as the difference between the base temperature (T_b; in this case it is 10 °C) and average daily temperature, which is calculated as half of the sum between the maximum daily temperature ($T_i^{max.}$) and the minimum daily temperature ($T_i^{min.}$); the sign (+) means that it is only necessary to calculate positive differences.

The criteria for the ASHRAE climate classification are shown in Table 15. For determining the primary zones, the marine zone was determined first, then the dry zone, and the remaining region was classified as the humid zone.

Table 15 ASHRAE climate zone definition.

Climate zone	Zoning criterion
0	6000 < CDD10°C
1	5000 < CDD10°C ≤ 6000
2	3500 < CDD10°C ≤ 5000
3	CDD10°C < 3500 and HDD18°C ≤ 2000
4	CDD10°C < 3500 and 2000 < HDD18°C ≤ 3000
5	CDD10°C < 3500 and 3000 < HDD18°C ≤ 4000
6	4000 < HDD18°C ≤ 5000
7	5000 < HDD18°C ≤ 7000
8	7000 < HDD18°C

Marine (C) Zone Definition:

a. Mean temperature of coldest month between −3 °C and 18 °C;

b. Warmest month mean < 22 °C;

c. At least four months with mean temperatures over 10 °C;

d. Dry season in summer. The month with the heaviest precipitation in the cold season has at least three times as much precipitation as the month with the least precipitation in the rest of the year. The cold season is October-March in the Northern Hemisphere and April-September in the Southern Hemisphere.

Dry (B) Zone Definition:

a. Not Marine;

b. If 70% or more of the precipitation, P, occurs during the high sun period, then the dry/humid threshold is: P<20×(T+14)

c. If between 30% and 70% of the precipitation, P, occurs during the high sun period, then the dry/humid threshold is: $P<20\times(T+7)$

d. If 30% or less of the precipitation, P, occurs during the high sun period, then the dry/humid threshold is: $P<20\times T$

where P – annual precipitation [mm.]; T – annual mean temperature [°C]; Summer or high sun period – April-September in the Northern Hemisphere and October-March in the Southern Hemisphere; Winter or cold season – October-March in the Northern Hemisphere and April-September in the Southern Hemisphere.

Humid (A) Zone Definition:

Locations that are not Marine (C) and not Dry (B).

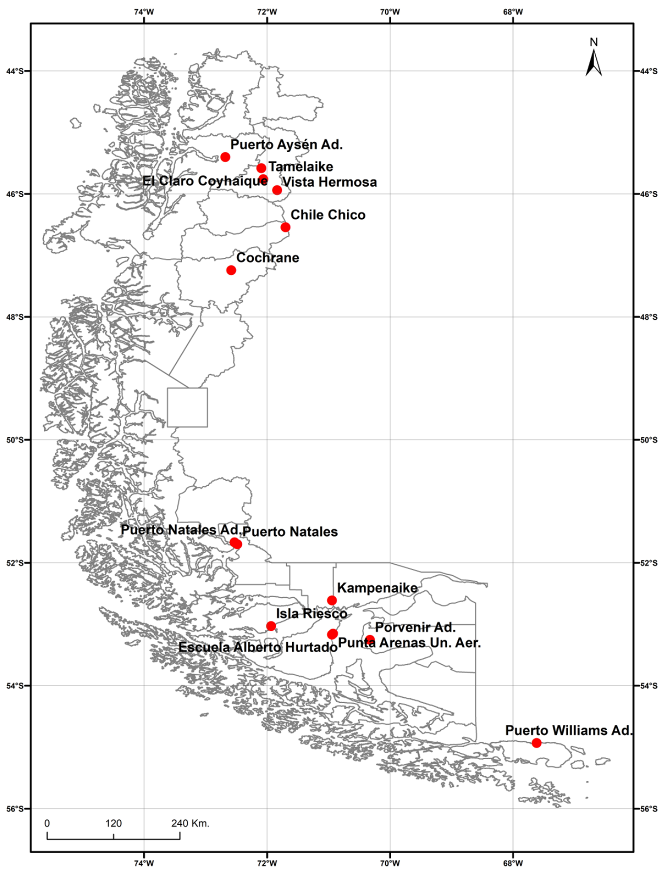


Fig. 28 Meteorological stations used to validate MM5 data.

The calculation of the values of HDD15°C was carried out on the basis of the ASHRAE method – Eq. 1. The values of HDD15°C by MM5 were compared with the values of HDD15°C by local meteorological stations. The map of Fig. 28 shows the geographical location of 14 meteorological stations used in this comparison, as well as stations belonging to the Chilean Meteorological Office (Chile, 2019c) and agrometeorological monitoring network (Chile, 2017).

To restore thermal zones of RT OGUC with meteorological data from the MM5, values of HDD15°C are used with the Kriging interpolation method (Oliver & Webster, 1990). This procedure is necessary to compare the thermal zones proposed by the official RT OGUC document with the thermal zones established by GBS for the analysis of EC in the study area. Thermal zones were determined by the intervals of annual values of HDD15°C, presented in Table 7.

4.2.4.2. Climatic zones based on cluster analysis

The cluster analysis method has being used for many decades in climatology (Mohammad, 2016) and in climatic zoning for buildings (Walsh et al., 2017a). In the present chapter, five climatic parameters have been used, namely: (1) HDD15°C of MM5 for 2006 (Grell et al., 1994; Malkin, 2008); (2) Average daily value of total solar radiation (ExSol, 2017); (3) Annual precipitation (2007-2017) (Chen et al., 2008; NOAA, 2018; Xie et al., 2007); (4) Relative humidity (2007-2017); and (5) Wind speed (2007-2017) (Berrisford et al., 2009; ECMWF, 2018).

Fig. 29 shows the data processing scheme for cluster analysis. First, by means of the Kriging interpolation method (Kumar, Maroju, & Bhat, 2007; Oliver & Webster, 1990), the spatial distribution of the climatologic parameters (2-5) was restored and determined their values in the 680 geographical locations assessed using the ArcGIS 10.5 software (ESRI, 2019). Therefore, the cluster analysis was based on the five meteorological parameters in the 680 geographical locations and the k-means algorithm. The goal of the k-means algorithm is to find the optimum 'partition' for dividing a number of objects into k clusters. This procedure will move objects from cluster to cluster with the goal of minimising the within-cluster variance and maximising the between-cluster variance (Park & Jun, 2009).

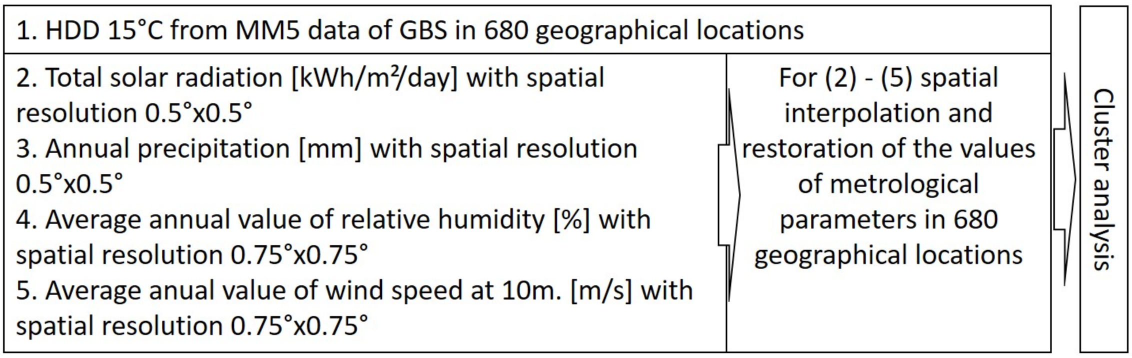


Fig. 29 Scheme of data processing for cluster analysis.

Meteorological values from various sources with different spatial resolutions were used to perform this analysis. Consequently, it is possible to have relatively independent parameters. The use of data from different sources can provide a climate zoning system based on a more precise cluster analysis.

4.2.4.3. Bioclimatic zoning

The bioclimatic zoning (Fig. 30) is based on the results of the study (Sarricolea et al., 2017). This paper presents updated Köppen–Geiger climate classification for continental Chile for 2016. On the first time in the last 45 years, work on the determination of bioclimatic zones based on data from 200 meteorological stations was realized. The shape file (.shp) format describing bioclimatic zones for Chile is an open access database.

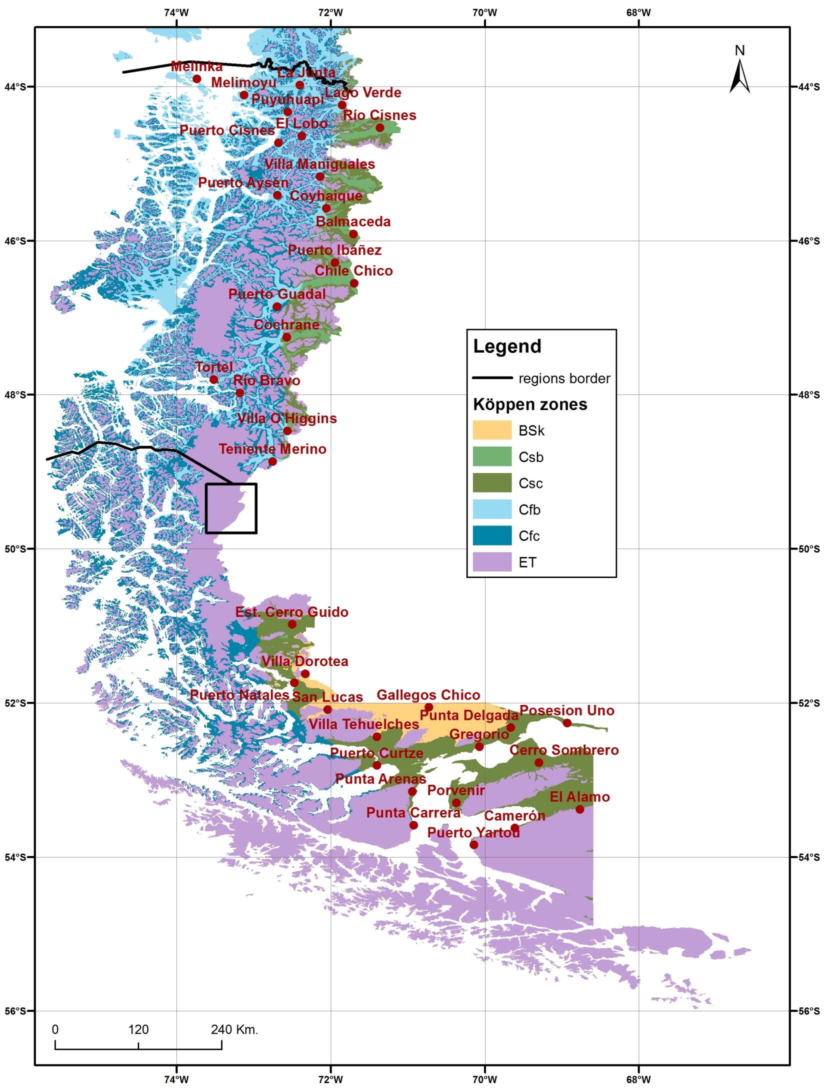


Fig. 30 Bioclimatic zones according to (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006).

Fig. 30 illustrates the map of bioclimatic zones, based on the modified Köppen-Geiger system (Kottek et al., 2006), where BSk – Cold semi-arid climate; Csb – Mediterranean climate with warm summer; Csc – Mediterranean climate with mild summer; Cfb – Marine west coast climate with warm summer; Cfc – Marine west coast climate with mild summer; and ET – Tundra climate.

4.2.5. Energy consumption

Finally, to carry out the study of EC, a residential dwelling with the same parameters in the 680 locations has been modelled. The main goal was to determine the level of heating EC in the geographical locations due to is the parameter that directly depends on climatic conditions. This dwelling would have different EC values under different climatic conditions.

In the present chapter, it was assessed a detached, single-family one-story house, with a total useful surface area of 83 m^2, in Fig. 31 shows the plans of the dwelling, location relative to the north and a general view of 3D modelling. These house for five dwellers, with a 24/7 function.

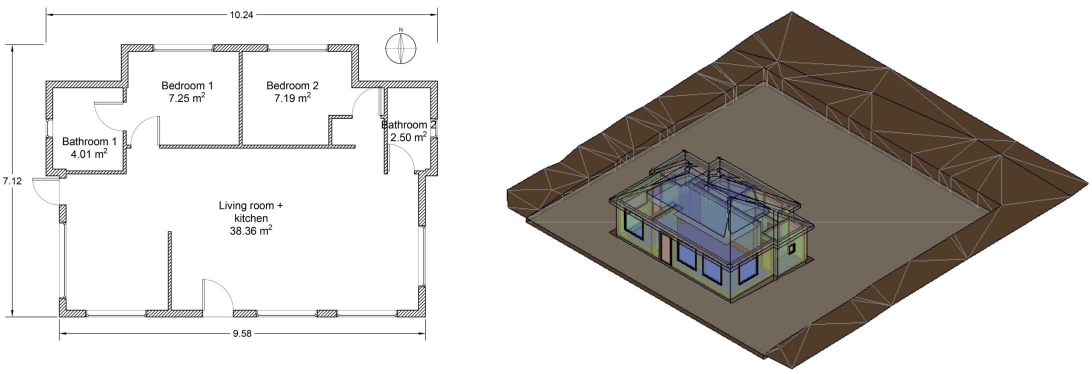


Fig. 31 Plans of the dwelling, energy simulation, and 3D view of the energy model.

For simulation of heating EC used the HVAC system, called *"Central VAV, Electric Resistance Heat, Chiller 5.96 COP"* by the standard library of Revit. Heating part of this HVAC system consists of: static pressure variable air volume duct system with electric resistance reheat boxes and integrated differential dry-bulb temperature economizer. This system was chosen due to it has a part of heating that is totally electric. To demonstrate relative variables in heating EC any other HVAC system from standard library Revit could has being used. Therefore, between two geographical locations, the existing difference in heating EC is doubled, this quotient will be conserved using any other type of HVAC. For heating, the indoor comfort reference temperature of 21 °C was used.

Additional simulation parameters such as sensible heat gains per person – 73.27 W, latent heat gains per person – 45.43 W, lighting load density – 11.95 W/m^2 and equipment power load density – 5.81 W/m^2 were taken from the standard Revit library for residential dwellings. Fig. 32 shows the schedule settings of occupancy, use equipment, and lighting, applied in the energy simulation. The used method to calculate outdoor airflow to space depends on dwellers and useful surface area. Outdoor air per person is 2.36 L/s and outdoor air per area is 0.30 L/s·m^2.

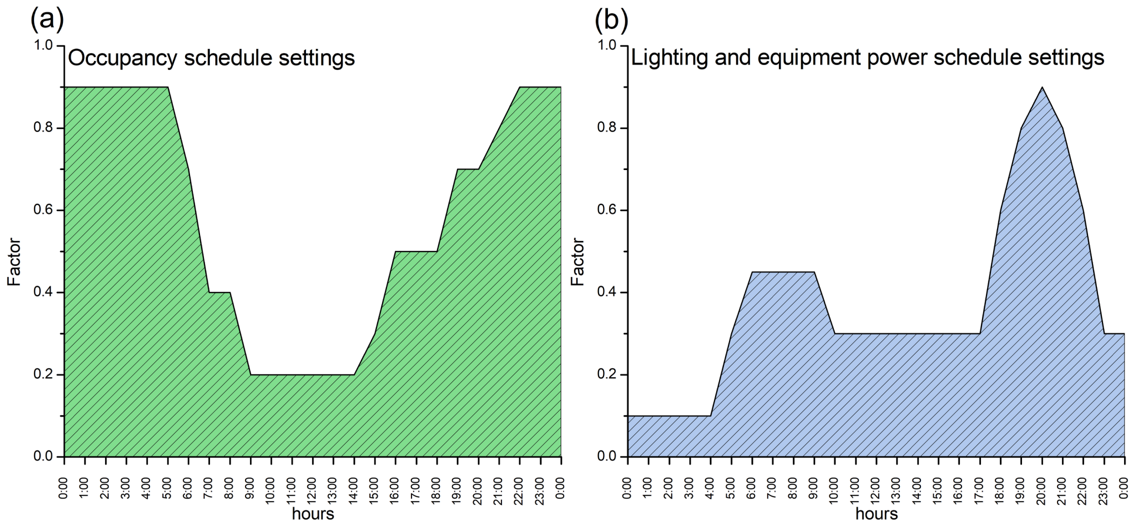


Fig. 32 Schedule: occupancy settings, and lighting and equipment power settings.

Table 16 shows the maximum U-values recommendations for the building elements, according to RT OGUC for Thermal zone 7, and the U-values used for the modelled dwelling. The RT OGUC norm contains recommendations on the maximum allowable U-value of structural elements of the dwelling for the seven thermal zones defined depending on the annual value of HDD15°C. Structural elements of a dwelling that are presented in this norm are roofs, walls, floors, and windows. The RT OGUC does not provide information about U-values for doors and about infiltration rates. As can be seen in Table 16, the dwelling modelled meeting all RT OGUC requirements for zone 7.

Table 16 RT OGUC dwelling envelope recommendations for Thermal zone 7 and envelope properties of the dwelling model of the study.

	RT OGUC maximum U-value	Modelling
Roofing – U [W/m²·K]	0.25	0.10
Walls – U [W/m²·K]	0.60	0.59
Floors – U [W/m²·K]	0.32	0.28
Doors – U [W/m²·K]	-	1.06
Hermetically double-glazed windows – U [W/m²·K]	3.6 ≥ U >2.4	3.16
Maximum glazed surface with respect to vertical thermal envelope	28%	28% *Double Clear* *SHGC=0.69; VLT=0.78* *3 – south-faces; 6 – non-south*

4.3. Result and discussion

4.3.1. Thermal zoning

The correlation between the data of the HDD15°C from the MM5 and the HDD15°C from the meteorological stations was analysed. Table 17 shows the values of HDD15°C from the MM5 interpolated to the geographic location of meteorological stations.

Table 17 Data of annual average values of HDD15°C from meteorological stations and MM5.

Name of station	Lat.	Lon.	Period	Met. Agency	HDD15°C met. st.	HDD15°C MM5	Delta
Puerto Aysén Ad.	-45.3994444	-72.6772222	12/2015-09/2017	Ch. met. of.	2056	2686	23%
El Claro Coyhaique	-45.5812	-72.092267	07/2012-09/2017	Agro.	2484	3042	18%
Tamelaike	-45.759114	-72.061843	09/2009-09/2017	Agro.	2911	3031	4%
Vista Hermosa	-45.936818	-71.835342	04/2010-09/2017	Agro.	3102	3241	4%
Chile Chico	-46.5432423	-71.6992977	09/2009-09/2017	Agro.	1944	2540	23%
Cochrane	-47.2417333	-72.5822028	12/2009-09/2017	Agro.	2670	3518	24%
Puerto Natales Ad.	-51.6672222	-72.5288889	12/2014-09/2017	Ch. met. of.	3023	3345	10%
Puerto Natales	-51.698367	-72.483082	05/2010-09/2017	Agro.	2843	3305	14%
Kampenaike	-52.6120484	-70.9432231	09/2012-06/2017	Agro.	3002	3091	3%
Isla Riesco	-53.030495	-71.933637	12/2012-04/2017	Agro.	3180	3682	14%
Punta Arenas Un. Aer.	-53.1527778	-70.9263889	08/2014-09/2017	Ch. met. of.	2987	3140	5%
Escuela Alberto Hurtado	-53.1669444	-70.9452778	08/2015-09/2017	Ch. met. of.	3018	3168	5%
Porvenir Ad.	-53.2536111	-70.3261111	12/2014-09/2017	Ch. met. of.	3070	3103	1%
Puerto Williams Ad.	-54.9316667	-67.6155556	12/2014-09/2017	Ch. met. of.	3279	3376	3%

Differences between annual values of HDD15°C from the MM5 and from the meteorological stations in the Aysén region are in the range of 4-24%. In the Magallanes, these differences range from 1-14%. The Aysén region is characterized by a heterogeneous relief, with significant differences in absolute altitudes. Therefore, the nodes of the model grid of the MM5 can be located around the meteorological station in high-mountainous areas. In the process of interpolating of HDD15°C data between model grid nodes located in high-mountainous areas, it is possible to obtain an overestimated value of HDD15°C from the MM5 for the geographical location of the meteorological station. For comparison, meteorological stations in the Magallanes region are mostly located in lowland areas. The graph in Fig. 33 demonstrates the correlation between HDD15°C from MM5 and HDD15°C from all meteorological stations. Considering the spatial resolution of the MM5 data, and the fact that the MM5 data from 2006 and meteorological stations data from 2010 to 2017, fairly good correlation was obtained between the data. Climate logic is also noted that in the last decade in conditions of global climate warming, HDD15°C data from meteorological stations is slightly less than HDD15°C from MM5 data.

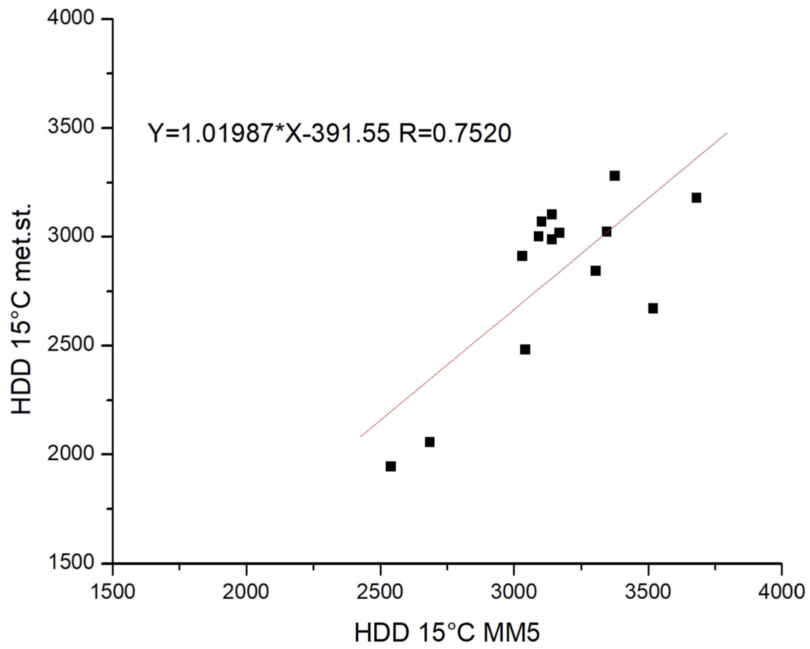


Fig. 33 Correlation of annual values of HDD15°C from the meteorological stations and HDD15°C from the MM5.

RT OGUC defines the entire area of the study as Thermal zone 7. The data obtained with HDD15°C of MM5 in the 680 locations were used to restore the thermal zones of RT OGUC that uses GBS to make energy simulation. The result shown in the map of (Fig. 34), that the northeast region had Thermal zones 4, 5, and 6, with annual value of the HDD15°C less than 2000.

On the other hand, the rest of the territory was characterised as Thermal zone 7. Therefore, for the process of energy simulation with RT OGUC standards, the correct use of GBS for energy simulation and proper interpretation of the results is recommended for the northeast region of the study area. Additionally, in zone 7, as shown in Fig. 35a, the HDD15°C oscillated between 2000 and 7500, which caused a low precision on the proper use of the unique building recommendations for this entire thermal zone. As shown in

Table 7, the RT OGUC defines each new thermal zone with a change in the value of the thresholds of HDD15°C to 250 up to zone 5, and 500 for zone 6.

EC of the studied dwelling that it complied with the stricter building recommendations for Thermal zone 7, provided by the RT OGUC was modelled for the analysis of all zoning methods.

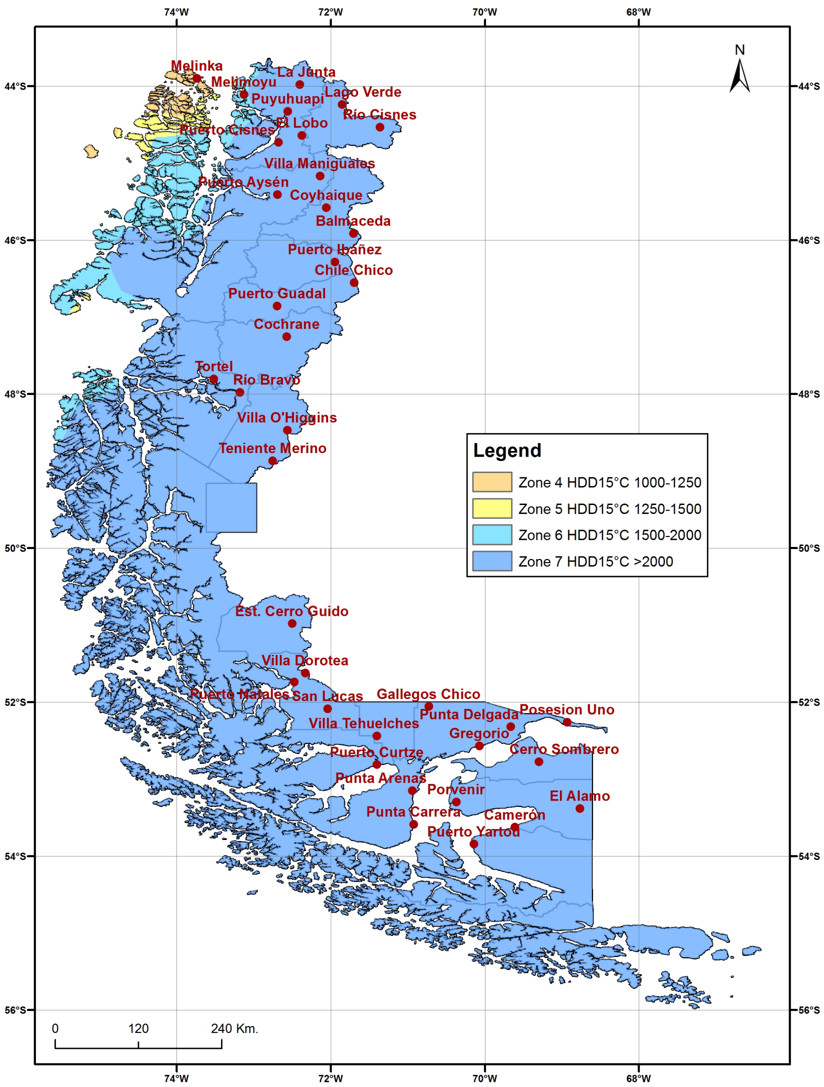


Fig. 34 Thermal zoning according to RT OGUC meteorological data from MM5/GBS.

4.3.2. Climatic zones based on cluster analysis

Fig. 35(a-e) shows the maps of the spatial distribution of the five input meteorological parameters for the cluster analysis, i.e., HDD15°C, total solar radiation, relative humidity, annual precipitation, and wind speed. These data for the cluster analysis was used, with a division between three and six clusters. However, results with correct climatology logic in the division with four clusters (Fig. 35f) were found.

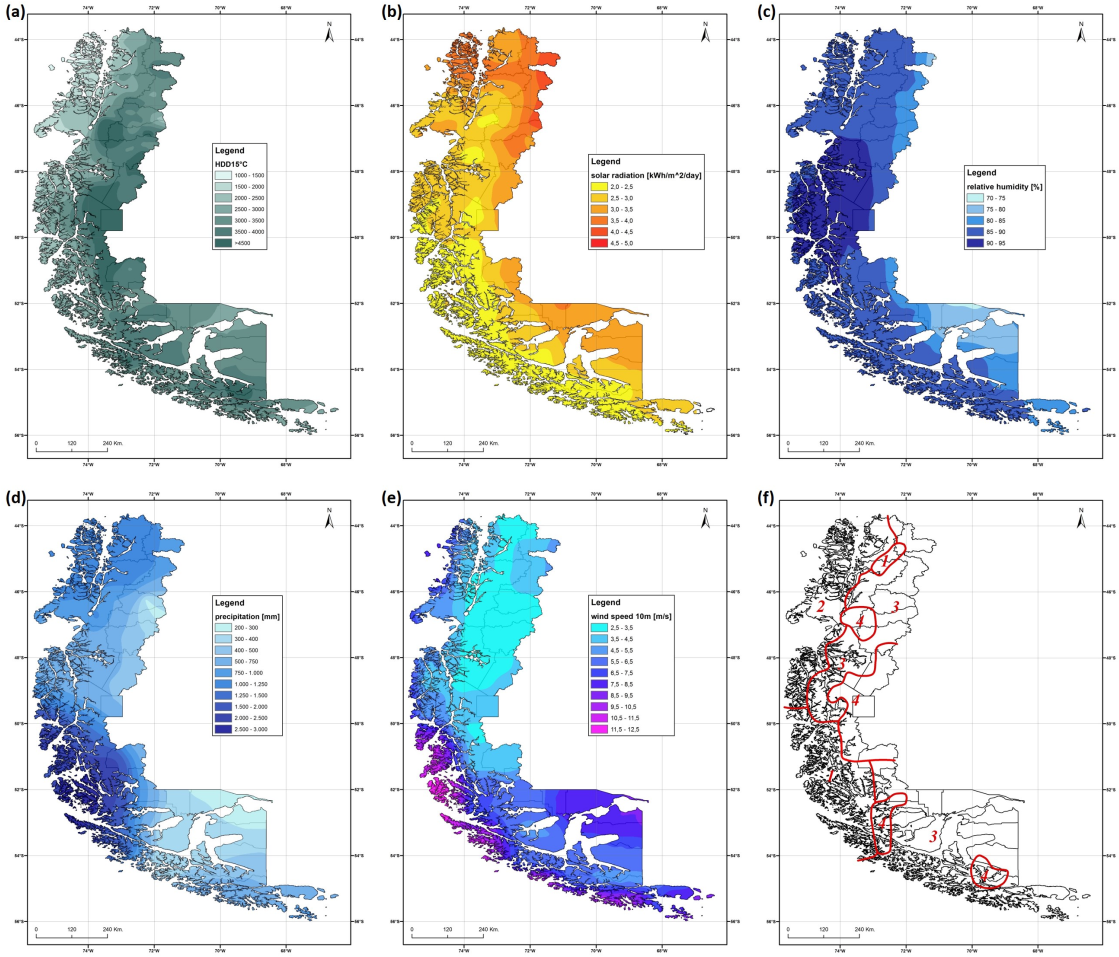


Fig. 35 Spatial distribution of the meteorological parameters used for cluster analysis (a) - (e) and climatic zones of the cluster analysis (4 clusters (f)).

Table 18 illustrates the results in the climatic zones of four clusters, with their quantitative characteristics of each meteorological parameter. Cluster 2 was characterised by milder climatic conditions, covering the entire northeast coast of the study area, with a minimum annual value of HDD15°C, a maximum value of total solar radiation, and moderate annual precipitation. Another coastal Cluster 1 was characterised by unfavourable climatic conditions, i.e.: maximum annual precipitation, maximum wind speed, and minimum of total solar radiation. In contrast, Clusters 3 and 4 were characterised by continental climatic conditions. Cluster 4 covered mountainous areas with maximum HDD15°C.

Fig. 35f shows four detached areas of Cluster 4, which were characterised by thermal effect of altitude. Cluster 3 covered the largest area and was characterised by a relatively continental climate, covering territories far from the Pacific coast in the north and in the south of the study area, including southern islands, which were characterised by another regime of precipitation compare with islands in Cluster 1 (Fig. 35d).

Before turning to the possibility of applying of bioclimatic zones and zones based on cluster analysis for more detailed zoning of the studied area, the results of EC simulation will be considered.

Table 18 Average values of meteorological parameters (with standard deviation-σ).

	Cluster 1	Cluster 2	Cluster 3	Cluster 4
HDD15 °C	2874 (451)	1811 (453)	3218 (314)	4252 (465)
Solar radiation [kWh/m^2/day]	2.4 (0.3)	3.2 (0.4)	3.0 (0.6)	2.8 (0.4)
Wind speed [m/s]	8.6 (2.8)	5.3 (1.9)	6.3 (2.3)	4.1 (1.3)
Relative Humidity [%]	89 (1)	89 (1)	84 (5)	88 (4)
Annual precipitation [mm]	2245 (370)	1018 (210)	563 (273)	769 (354)

4.3.3. Heating energy consumption

As shown in Fig. 36, the data obtained from the modelling of heating EC in the dwelling of the study were used to create the map of heating EC. As noted above, it is a priority for this region to have buildings with minimum heating EC due to the climatic conditions of the area. The results indicated that the consumption oscillated between 75 and 300 kWh/m^2/year. This way, it can be affirmed that heating EC in the Thermal zone 7 of the RT OGUC could have a difference of up to 300%.

Given that the studied regions were extended and presents depopulated areas, it can be affirmed that heating EC could vary from 75 to 150 kWh/m^2/year where the population was concentrated, thus, doubling the demand. This difference in heating EC of the same dwelling—with the same architectural, construction, and operation parameters—was significant in the boundaries of the single thermal zone (Fig. 11). Asdrubali *et al.* (Asdrubali et al., 2008) presented results of the simulation of EC in individual single-family dwellings located in three climatic zones of Spain, and four climatic zones of Italy. The variability of total EC in Spain was within the range 157-296 kWh/m^2/year, whereas in Italy it was 137-254 kWh/m^2/year. It is worth noting that, in the present study area, the variability of heating EC in one thermal zone far exceeded the total EC in the three zones of Spain and four of Italy. The isolines of heating EC resemble the shape of the HDD isolines (Fig. 36 and Fig. 35a). This result indicates the existence of a clear relationship between these two parameters.

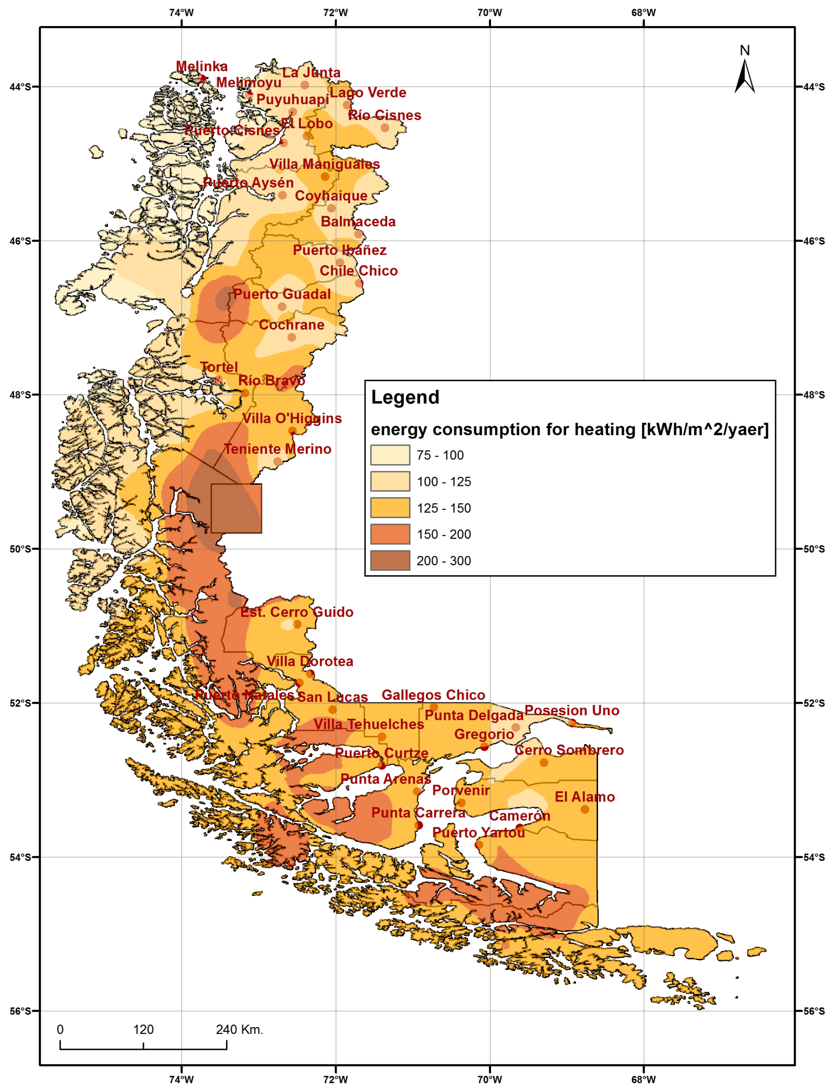


Fig. 36 Heating energy consumption of the modelled dwelling.

4.3.4. Analysis of bioclimatic zoning

In this phase of present chapter, the Köppen's bioclimatic zones were assessed, which were established based on the geographical differences of thermal regimes and precipitation. With generally homogeneous meteorological parameters, any bioclimatic zone should be characterised by a relatively linear relationship between HDD values and data on modelling of heating EC.

Fig. 37 shows the correlation between heating EC and HDD15°C in all bioclimatic zones of the study area. Geographical points located in the boundaries of the bioclimatic zones were excluded. The maximum correlation between these two parameters was observed in bioclimatic zones Cfc and Cfb (R = 0.93 and 0.96), and the minimum correlation was observed in the south of the Csc zone (R = 0.75). Zones Csc, Cfc, and ET (Fig. 30) were divided into two regions, i.e., northern (north of longitude 49°S) and southern (south of longitude 49°S), because only this division allowed observing the linear correlation between heating EC and HDD15°C.

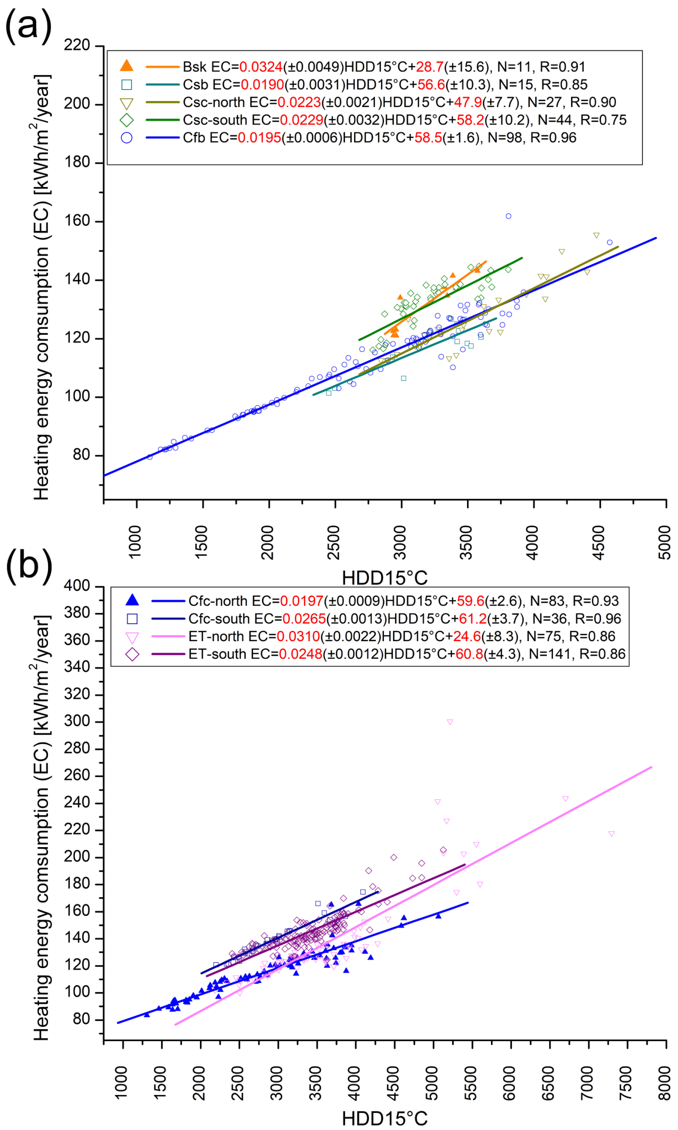


Fig. 37 Correlation between heating energy consumption and HDD15°C in bioclimatic zones according to Fig. 30, slope and intercept of the regression line with standard errors.

It can be seen that with 3000 HDD15°C in the north of the Csc zone (Fig. 37b), the heating EC of the modelled dwelling was 115 ± 14 kWh/m^2/year; whereas in the south of the Csc zone the heating EC was 127 ± 19 kWh/m^2/year. This difference was significant in the bioclimatic zone Cfc, where the heating EC in the north was 119 ± 5 kWh/m^2/year and in the south was 141 ± 8 kWh/m^2/year. The bioclimatic zone Cfc was characterised by the most humid climate and high level of annual precipitation (Fig. 35d). On the other hand, the southern region of this zone was characterised by the highest annual precipitation value in the study area, with high frequency of cloudy days and the minimum value of direct solar radiation.

4.3.5. Analysis of zones based on cluster analysis

The correlation between heating EC in clusters was assessed (Fig. 38). Geographical points located in the boundaries of the clusters zones were excluded.

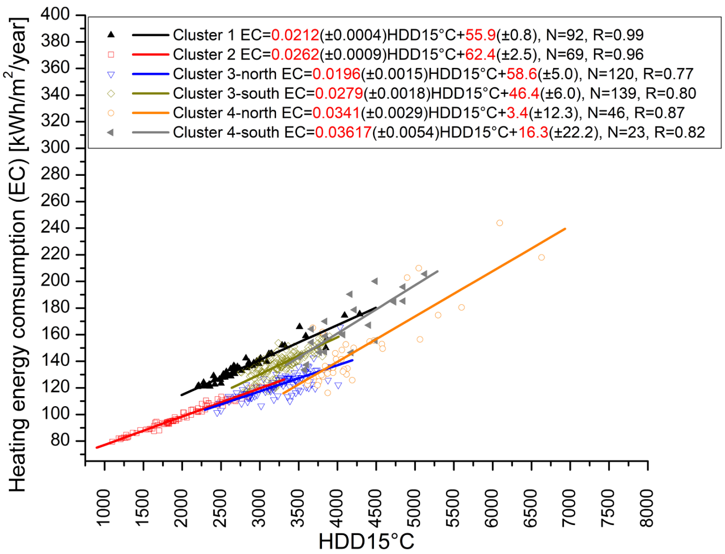


Fig. 38 Correlation between heating energy consumption and HDD15 °C in clusters (Fig. 35f), slope and intercept of the regression line with standard errors.

It can be observed that, in the same way as with the bioclimatic zoning, Clusters 3 and 4 were divided into northern and southern. This procedure allowed obtaining precise correlations between heating EC and HDD15°C. With the same value of HDD15°C, the heating EC in the southern part was higher than in the northern part for both clusters. As shown in Table 18, the mean value of the total solar radiation for Cluster 3 is 3.0 kWh/m^2/day. But, if consider the map of the spatial distribution of total solar radiation (Fig. 35b), it can be noted that in the northern part of the Cluster 3 values of total solar radiation vary in the interval of 2.0 to 4.5 kWh/m^2/day, whereas for the southern part this interval of 2.0 to 3.5 kWh/m^2/day. With the same value of HDD15°C, solar heat gains are higher in the northern part of the cluster, which affects the reduction of heating EC. The same situation is typical for Cluster 4.

Finally, Cluster 1 was characterised by maximum EC for the same value of HDD15°C. It can be observed that Cluster 1 generally repeated the bioclimatic zone Cfc-south. This zone of the study area was characterised by the maximum value of heating EC in comparison to the other zones.

4.3.6. Discussion of results

Primary the discrepancy between the official thermal zones of RT OGUC and thermal zones on the basis of MM5 data, which the simulation of EC in the GBS is realized was shown. The inconsistency of the zones leads to an inadequate interpretation of the results of the simulation. If in fact, in some geographical area, there is a Thermal zone 4 or 5, there is no need to use excess building materials to meet the recommendations for the Thermal zone 7. On the other hand, highland areas have rather severe climatic conditions, so the use of building recommendations for the Thermal zone 7 is not acceptable in these areas. It was also shown that the MM5 data of HDD15°C are overestimated in comparison with the data of meteorological stations in some geographic areas. Therefore, a more realistic and detailed spatial distribution of thermal zones should be investigated further.

The importance of using the results of multiple simulations of heating EC to assess climate zoning in cold climates was demonstrated. Was shown that, bioclimatic and cluster zoning (four cluster division) based on 5 meteorological parameters is not quite suitable for building in this region. Of course, this methodology needs further improvement, such as using more accurate software, modelling various types of buildings.

Methodology for climatic zoning validation based on multiple simulations of total EC of different types of dwellings was applied for Nicaragua (Walsh et al., 2018). Methodology for climatic zoning validation based on simulations of heating and cooling EC of dwelling was applied in China (Xiong et al., 2019). Results of multiple energy simulations of various types of dwellings can be used to validate climatic zones or can be used in the development of climatic zones like in Spain (de la Flor et al., 2006).

Results of energy simulation can also be used to detail climate zoning. Detailed climatic zoning of building can be based on homogeneous zones with a linear relationship between heating EC and HDD. In these areas, the dependence of heating EC from other meteorological parameters is reduced. The temperature is the main factor that determines the level of heating EC. This idea needs further methodological development and analysis.

In addition, an important variably of all energy simulations is solar radiation and its components. Many studies used total solar radiation for climate zoning (Walsh et al., 2017a), for detailing climate zoning (Xiong et al., 2019), and for assessing potential renewable energy in various climatic zones (López-Ochoa, Las-Heras-Casas, López-González, & Olasolo-Alonso, 2019). Total solar radiation is composing by two main parts, i.e., direct and diffuse radiation. The study only uses total solar radiation in the analysis of the clusters, without dividing it into the two components. Therefore, for correlation analysis between HDD15°C and heating EC, the zones of the clusters were artificially divided into northern and southern, as it was made with bioclimatic zones.

Changes in a linear correlation between HDD15°C and heating EC in southern and northern parts of the clusters and bioclimatic zones could be related with different levels of total solar radiation and changes in the proportion of the components of total solar radiation, which subsequently affects to solar heat gains of dwelling. Also, while maintaining the same value of total solar radiation, different percentages of direct and diffuse radiation can change the contribution of direct solar radiation to the thermal balance of the dwellings.

Therefore, on the basis of homogeneous zones of strict linear dependence (between HDD and heating EC) and climatic zones of direct solar radiation, it is quite possible to perform new detailed climatic zoning for building. As, climate zoning for building in Spain, which is based on indexes, which reflect the relative level of EC of dwellings and depend on HDD, cooling degree-days and the sunshine duration (Spain, 2006a).

The development of a new detailed climatic zoning for building needs further study, modelling and zoning methodology should be published in a scientific journal with the possibility of further improvement and strengthen.

4.4. Conclusions

This chapter has worked based on simulated EC of dwelling to assess the applicability of existing different climatic and thermal zoning for building with the objective of proposing a new climate zoning for building in Aysén and Magallanes, the most extreme southern regions of Chile.

As in the regions of La Araucanía, Los Ríos and Los Lagos, the results obtained have shown that current building standards cannot guarantee the construction of energy-efficient housing in the two extreme regions of Chile. In fact, the meteorological data with high spatial resolution obtained in the regions assessed by simulations of EC indicated that the annual HDD15°C value ranged from 1000 to 7500; this will result in a single-family dwelling in 680 different geographical locations, allowed to determine that the heating EC values varied from 75 kWh/m^2/year to 300 kWh/m^2/year.

Zoning based on clusters analysis and bioclimatic zoning were analyzed using the results obtained from the modelling of heating EC. It was found that each bioclimatic or cluster area had a good linear correlation between EC values and HDD15°C. However, the oscillation of the annual value of HDD15°C in the boundaries of a cluster or a bioclimatic zone could exceed 3000. Also, it was demonstrated that the two types of zoning did not sufficiently consider the effects of direct solar radiation.

On the other hand, the determination of climatic zones for building through the cluster method and the use of bioclimatic zones for building additionally requires the development of recommendations for the thermal transmittance of the building elements of dwellings. However, the existence of large HDD15°C ranges in the zones significantly complicates finding the energetically optimal U-values for building recommendations. It can therefore be concluded that a suitable alternative might be the use of building recommendations for ASHRAE climate zones (Fig. 37), which reflect the meso- and microclimatic complexity of the study region more accurately.

Part III. Solutions to improve the energy efficiency of buildings in southern Chile

As shown in the previous chapters of this dissertation, climate zoning is an important tool in energy policy and regulation. More detailed and homogeneous climate zones, in conjunction with appropriate building standards, can help to make energy policy in the building area more sustainable.

As shown in Chapters 3 and 4, in Chile, the RT OGUC, whose climatic zoning is based more on administrative boundaries than on the diversity of existing meso-microclimatic zones, is unable to ensure energy-efficient housing design in the southern regions of the country today, due to its inability to adapt to changes, the inconsistent detected will get worse in most cities of the studied area in the future because of the climate change effects. Likewise, the ECS thermal zones do not reflect the real climatic diversity of the Aysén and Magallanes regions. At the same time, it was shown in Chapter 4 that bioclimatic zones, as well as zones determined based on clustering of climatic parameters, are not suitable for improving climatic zoning for building in the named regions.

Based on the findings of the previous chapters of this dissertation, finally, this part of the dissertation presents chapters with two solutions to improve the energy efficiency of dwellings in the South of Chile - one on the proposal of a new climate zoning for building in the study area and another on a methodology that allows taking into account future climate change and carry out the adaptation and mitigation of building recommendations in energy and environmental aspects.

For this, the main parameters and aspects to be considered when developing new climate zones for construction in the research area are HDD to reflect the climatic characteristics of the cold period, CDD to reflect the climatic characteristics of the warm period and solar radiation data. At the same time, to reflect meso- and micrometeorological diversity, the data must have a high spatial resolution, and the methodology for determining zones must be reproducible for both current and future climate conditions.

All these aspects will be used to propose a new climatic zones classification in regions at South of Chile, to address future climate change and implement adaptation and mitigation of building recommendations in terms of energy and environmental aspects. For this purpose, climate zoning methodologies and building standards already developed in other countries will be applied, which can help establish of new climate zones for building and standards in the study area.

In the case of the regions of La Araucanía, Los Ríos, and Los Lagos, the climate zones derived from the climate severity index method and the Spanish CTE building standards could be applicable. The use of CTE climatic zones for these three regions is due to the similarity of the observed climatic conditions in these regions and in Spain.

In the case of two regions in the extreme south of Chile (Aysen and Magallanes), the climate zoning methodology in ASHRAE-Standard 169-2013, "Climatic Data for Building Design Standards", could be used (ASHRAE, 2013) with construction standards stated in ANSI/ASHRAE/IES Standard 90.2-2018 "Energy-Efficient Design of Low-Rise Residential Buildings" (ASHARE, 2018); This is due to its ability to define climate zones under climate change conditions, to include a constant update and improvement of the US building standards, as well as to include the cooler ASHRAE climate zones. In the context of future climate warming, this zoning will be relevant for application for a long time to come as, over the years, climate zones will simply change to warmer zones.

CHAPTER 5.-

PROPOSAL ON A NEW CLIMATIC ZONING[4]

[4] The results shown in this chapter were presented in: **Verichev, K.**, Carpio, M., **Climatic zoning for building construction in a temperate climate of Chile** (2018) Sustainable Cities and Society, 40 V., Pages 352-364

5.1. Introduction

For building climatic zoning for La Araucanía, Los Ríos and Los Lagos regions, the climate severity index method (Markus, 1982) will be considered in the present chapter. This method reflects the relationship between the energy requirement of a building and climatic features based on ´severity´ of the climate. It is calculated based on the simulation of EC of building types, common in a region in the whole range of constructive and architectural scenarios in average climatic conditions (Makhmalbaf, Srivastava, & Wang, 2013), and differentiates between climate severity index for the winter climate severity index (WCS) and summer climate severity index (SCS), which allow for the analysis of EC of buildings for heating and cooling. The main advantage of this method is the possibility of comparing the EC of certain buildings in different climatic zones relative to the reference point (Markus, 1982; Salmerón, Álvarez, Molina, Ruiz, & Sánchez, 2013). This method additionally helps to take into account the effects of solar radiation on buildings in climatic zoning.

For the first time, the official application of this methodology for climatic zoning for building in Spain was presented in the Basic Energy-Saving Document of the CTE06 (Spain, 2006a, 2006b). In 2013, this method of determining zones has undergone minor changes, but the equations for calculating the WCS and SCS indexes have not changed in CTE13 (Spain, 2013) and in February 2017, the Spanish Ministry of Public Works, Secretary of State for Infrastructures, Transport and Housing, General Office for Architecture, Housing and Land published the *"Documento descriptivo climas de referencia"* (Descriptive document on reference climates) (Spain, 2017) which presented new formulas relating some climatic parameters to WCS and SCS indexes, as well as the ranges of values used to define climatic zones of the Basic Document, HE Energy Saving. (CTE19) (Spain, 2019).

Good correlation between the WCS and SCS indexes and climatic parameters (degrees-days and solar radiation data) makes it possible to calculate the values of these indexes in other regions where simulation of EC of buildings was not carried out (de la Flor et al., 2006; Makhmalbaf et al., 2013). In this chapter, it was decided to consider both methodologies CTE06-13 and CTE19 to calculate the climate severity indexes and show the correspondence between the indexes calculated according to these two methodologies. Combinations of WCS and SCS indexes define climatic zones for building of Spain will be used to propose climate zones in La Araucanía, Los Ríos, and Los Lagos regions.

For the Aysén and Magallanes regions, due to the current climatic conditions, it is not possible to apply the Spanish CTE building climate zones, since the current climatic characteristics of these two regions are outside the climatic conditions of Spain, on which the methodology for the climate zoning of the CTE was developed. Therefore, to improve building zoning in these two regions, it was decided to use the ASHRAE climate zoning methodology.

Based on the above, it was decided to present a proposal for new climate zones for the study region – combined between the CTE zones for the La Araucanía, Los Ríos and Los Lagos regions and the ASHRAE zones for the Aysén and Magallanes regions. This proposal will represent accurately the meso- and microclimatic variations of the study area and will allow for stricter building requirements than the current national standards, with a clear and replicable methodology for the zone definition.

5.2. Materials and methods

5.2.1. Study area

The present chapter focused on five regions in southern Chile; a detailed socio-economic and climatological-geographical description of these regions are presented in Chapter 2. In this chapter, two CTE climatic zoning methods will be applied to the La Araucanía, Los Ríos and Los Lagos regions. And finally, a proposal of combined CTE19 and ASHRAE climate zones for five regions in southern Chile will be presented.

5.2.2. Method CTE for determining climatic zones

The CTE methods of Spain for determining climatic zones was used in this chapter. The climatic severity index methods by CTE06-13 and CTE19 was developed based on climatic values of air temperature and solar radiation in 50 cities of Spain. To begin a comparison of climatic parameters in Spain and in the study region will be implemented.

Climatic values of global solar radiation (for summer and winter periods) for 50 cities of Spain will be taken from "*Atlas de Radiación Solar en España"* and temperature data from *"SAF de Clima de EUMETSAT"* and data for 44 meteorological stations in

Chile will be taken from Solar Energy Explorer (ExSol, 2017; Sancho, Riesco, & Jiménez, 2012).

For the comparison of the thermal conditions in Spain and Chile climatological data of average maximum temperatures for summer period and average minimum temperatures for winter period will be used (AEMET, 2011; Castillo, 2001).

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 global solar radiation in two parts of the world (Fig. 39).

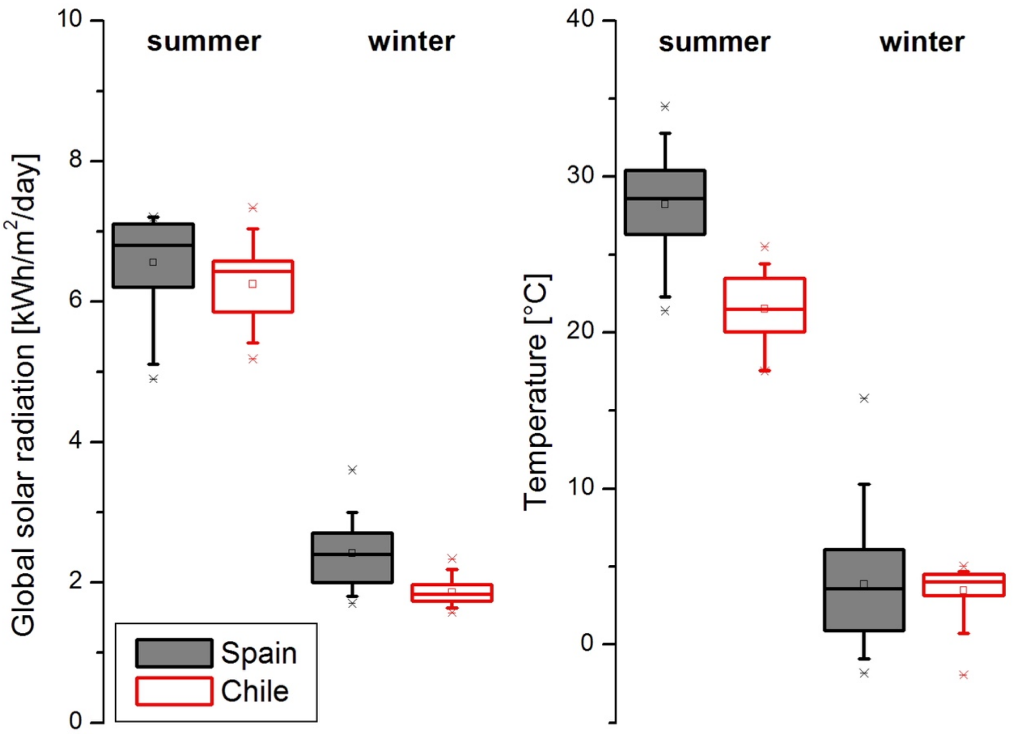


Fig. 39 Boxplots of climatic data of the global solar radiation and climatic data of the average maximum temperature for summer period and the average minimum temperature for winter period for 50 cities of Spain and for 44 meteorological stations in La Araucanía, Los Ríos and Los Lagos regions.

The Fig. 39 also 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 this area. In the case of calculation SCS index, errors can occur in the cold climates of study area. But, in any case, these areas are characterized by zero EC for cooling, and will be characterized by the coldest summer climate zone of CTE06-13 and CTE19.

5.2.2.1. Climate zoning of CTE06-13 for La Araucanía, Los Ríos and Los Lagos regions

Firstly, the methodology CTE06-13 of Spain to determine the climatic zones in the La Araucanía, Los Ríos and Los Lagos regions was used in present chapter. 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:

$$WCS = a \cdot R + b \cdot HDD_{jun-aug} + c \cdot R \cdot HDD_{jun-aug} + d \cdot (R)^2 + e \cdot HDD_{jun-aug}{}^2 + f, \quad \textit{(Eq. 5)}$$

where $HDD_{jun-aug}$ is the monthly average HDD with base temperature of 20°C for winter months (June, July, and August); R [kWh/m^2] is the monthly average accumulated global radiation incident upon a horizontal surface for the same months; the values of the coefficients a, b, c, d, e, f are presented in the Table 19.

$$SCS = a \cdot R + b \cdot CDD_{dec-mar} + c \cdot R \cdot CDD_{dec-mar} + d \cdot (R)^2 + e \cdot CDD_{dec-mar}{}^2 + f, \quad \textit{(Eq. 6)}$$

where $CDD_{dec-mar}$ is the monthly average CDD with base temperature of 20°C for summer months (December, January, February, and March); R [kWh/m^2] is the monthly average accumulated global radiation incident upon a horizontal surface for the same months; the values of the coefficients a, b, c, d, e, f are presented in the Table 19.

Table 19 Coefficients values to calculate WCS and SCS according to the CTE06-13.

	a	*b*	*c*	*d*	*e*	*f*
WCS	$-8.35\cdot10^{-3}$	$3.72\cdot10^{-3}$	$-8.62\cdot10^{-6}$	$4.88\cdot10^{-5}$	$7.15\cdot10^{-7}$	$-6.81\cdot10^{-2}$
SCS	$3.724\cdot10^{-3}$	$1.409\cdot10^{-2}$	$-1.869\cdot10^{-5}$	$-2.053\cdot10^{-6}$	$-1.389\cdot10^{-5}$	$-5.434\cdot10^{-1}$

Daily HDD and CDD are obtained by "hourly method" Eq. 7 and Eq. 8, respectively (Mourshed, 2012):

$$HDD_d = [\textstyle\sum_{i=1}^{24}(T_b - T_i)^+]\frac{1}{24}, \quad \textit{(Eq. 7)}$$

$$CDD_d = [\sum_{i=1}^{24}(T_i - T_b)^+]\frac{1}{24}, \qquad (Eq.\ 8)$$

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 values.

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 20, according to the corresponding intervals.

Table 20 Climatic zones according to the CTE06-13.

Intervals for winter climatic zones				
A	B	C	D	E
WCS ≤ 0.3	0.3 < WCS ≤ 0.6	0.6 < WCS ≤ 0.95	0.95 < WCS ≤ 1.3	WCS > 1. 3

Intervals for summer climatic zones			
1	2	3	4
SCS ≤ 0.6	0.6 < SCS ≤ 0.9	0.9 < SCS ≤ 1.25	SCS > 1.25

Combinations of values of the two indexes can characterise up to 20 climatic zones (Table 20). 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 cooling EC of 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 WCS (Carpio et al., 2015).

For calculation WCS and SCS by CTE06-13 method, open-access data of hourly temperature and global solar radiation from different sources of various agencies were used:

- **Data of hourly temperature** measured in period 2011-2017 by:(i) Directorate General of Civil Aviation, Meteorological Directorate of Chile (DGAC) (5 stations) (Chile, 2019c); (ii) MMA of Chile - National Air Quality Information System (4 stations) (SINCA, 2017); (iii) Ministry of Agriculture (Agromet) - National Agroclimatic Network (35 stations) (Chile, 2017);
- **Modelled global solar radiation data** by Solar Energy Explorer – programme of the School of Physical Sciences and Mathematics of the University of Chile (ExSol, 2017).

The map of Fig. 40 illustrates the spatial coverage of the meteorological stations used for calculation WCS and SCS by CTE06-13 method and in Table 21, the information about meteorological stations is presented.

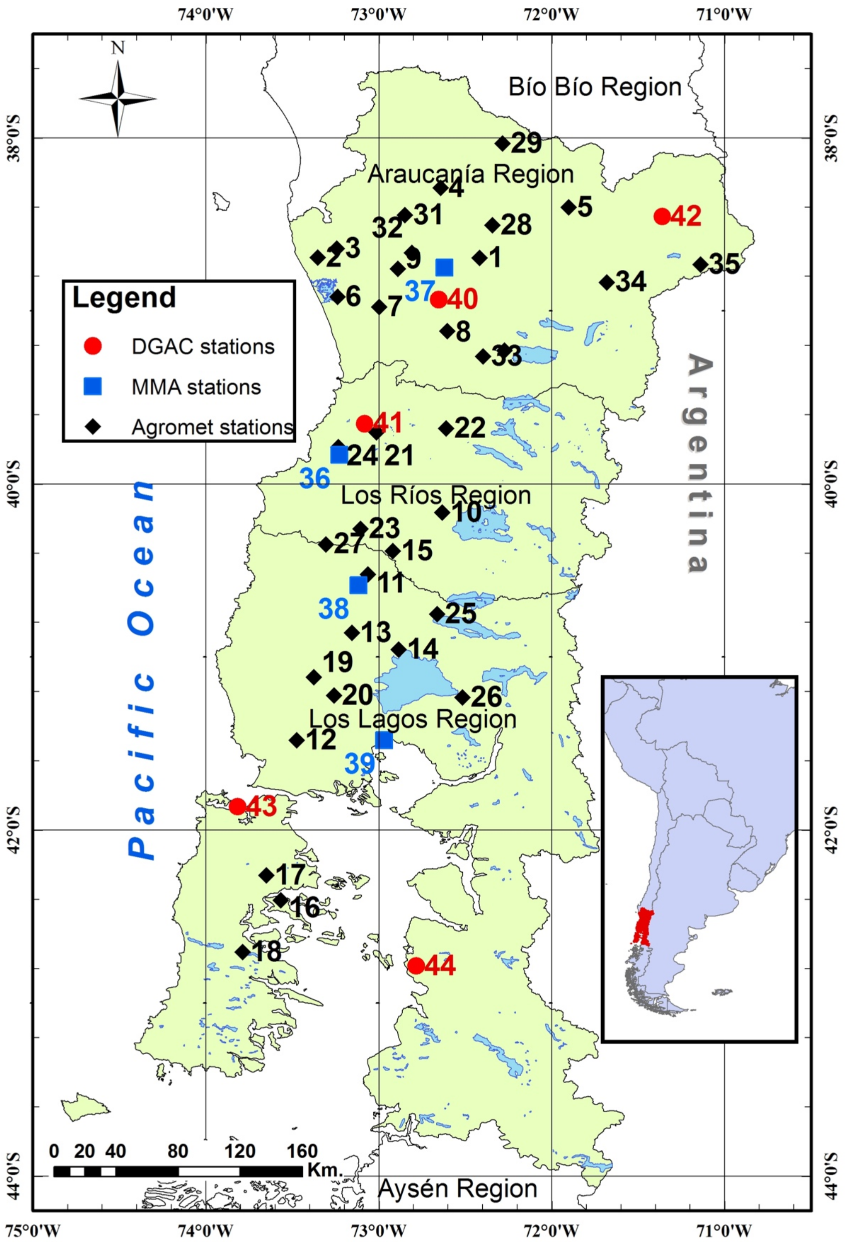


Fig. 40 Map of meteorological stations, the data of which were used to calculate the indexes WCS and SCS according to the CTE06-13.

Table 21 Meteorological stations whose data were used for the calculation of the WCS and SCS indexes according to the CTE06-13.

ID	Name of st.	Lat.	Long.	Alt.	ID	Name of st.	Lat.	Long.	Alt.
1	Carillanca	-38.69	-72.42	200	23	Palermo	-40.26	-73.11	78
2	Tranapuente	-38.69	-73.35	64	24	Est. Exp. Austral	-39.79	-73.23	15
3	Quiripio	-38.64	-73.24	332	25	Desague Rupanco	-40.75	-72.66	272
4	La Providencia	-38.29	-72.64	254	26	Ensenada	-41.23	-72.52	76
5	San Luis	-38.40	-71.90	549	27	Quilacahuin	-40.35	-73.31	17
6	Dominguez	-38.92	-73.24	93	28	Sta Ines	-38.50	-72.34	263
7	C.Llollinco	-38.98	-73.00	24	29	Surco y Semilla	-38.03	-72.29	379
8	Cuarta Faja	-39.12	-72.61	115	30	Las Palmas	-39.23	-72.27	388
9	Sta. Adela	-38.76	-72.89	50	31	San Fabian	-38.45	-72.85	197
10	Lago Verde	-40.17	-72.63	248	32	Perales	-38.66	-72.81	55
11	Remehue	-40.52	-73.06	73	33	Huiscapi	-39.26	-72.40	266
12	Los Canelos	-41.48	-73.47	105	34	El Membrillo	-38.83	-71.68	527
13	La Pampa	-40.86	-73.16	96	35	Marimenuco	-38.73	-71.14	1084
14	Octay	-40.96	-72.89	178	36	Valdivia MMA	-39.83	-73.23	8
15	El Cardal	-40.39	-72.92	80	37	Las Encias Temuco MMA	-38.75	-72.62	106
16	Huyar Alto	-42.40	-73.57	155	38	Osorno MMA	-40.58	-73.12	52
17	Butalcura	-42.26	-73.65	148	39	Pto. Montt MMA	-41.48	-72.97	104
18	Tara	-42.70	-73.79	145	40	La Araucanía	-38.93	-72.65	96
19	Polizones	-41.12	-73.38	137	41	Pichoy	-39.65	-73.08	21
20	Colegual	-41.22	-73.26	177	42	Lonquimay	-38.46	-71.36	912
21	Las Lomas	-39.70	-73.01	22	43	Ancud	-41.87	-73.82	31
22	Santa Carla	-39.68	-72.61	264	44	Nueva Chaiten	-42.79	-72.78	10

5.2.2.2. Climate zoning of CTE19 for La Araucanía, Los Ríos and Los Lagos regions

Secondly, the CTE19 methodology from Spain (Spain, 2017, 2019) and results from the work of Verichev & Carpio (Verichev & Carpio, 2018) were used for the definition of climate zones in the La Araucanía, Los Ríos and Los Lagos regions.

The winter climatic severity of the CTE19 method is obtained using the following expression:

$$WCS = a \cdot HDD20_{apr-nov} + b \cdot \frac{n}{N} + c \cdot HDD20_{apr-nov}{}^{2} + d \cdot \left(\frac{n}{N}\right)^{2} + e, (Eq.\ 9)$$

where $HDD20_{apr-nov}$ is the sum of the HDD with a base temperature of 20°C for the months from April to November (for the southern hemisphere), calculated using the hourly method (Eq. 7), n – sunshine duration hours from April to November, N – maximum of sunshine duration hours possible for the months from April to November, coefficients a, b, c, d and e are shown in Table 22.

The summer climatic severity of the CTE19 method is obtained using the following expression:

$$SCS = a \cdot CDD20_{dec-mar} + b \cdot CDD20_{dec-mar}{}^{2} + c, \qquad (Eq.\ 10)$$

where, $CDD20_{dec\text{-}mar}$ is the sum of the CDD with a base temperature of 20°C for the months from December to March (for the southern hemisphere), calculated using the hourly method (Eq. 8), coefficients a, b and c are shown in Table 22.

Table 22 Coefficients values to calculate WCS and SCS according to the CTE19.

	a	*b*	*c*	*d*	*e*
WCS	$3.546 \cdot 10^{-4}$	$-4.043 \cdot 10^{-1}$	$8.394 \cdot 10^{-8}$	$-7.325 \cdot 10^{-2}$	$-1.137 \cdot 10^{-1}$
SCS	$2.990 \cdot 10^{-3}$	$-1.1597 \cdot 10^{-7}$	$-1.713 \cdot 10^{-1}$	-	-

The summer climate zone is determined based on the SCS, with each summer climate zone of the CTE19 (1, 2, 3, 4) corresponding to the interval indicated in Table 23, being 4, the climatic zone with the warmest summer. Each winter climate zone of the CTE19 (α, A, B, C, D and E) corresponds to the WCS range indicated in Table 23, being α the climatic zone with the warmest winter.

Finally, with the combination of letter and number (Table 23), the building climate zone code (maximum 24) is obtained for any city or geographical location.

Table 23 Climatic zones according to the CTE19.

Intervals for winter climatic zones					
α	A	B	C	D	E
WCS ≤ 0	0 < WCS ≤ 0.23	0.23 < WCS ≤ 0.5	0.5 < WCS ≤ 0.93	0.94 < WCS ≤ 1.51	WCS > 1. 51
Intervals for summer climatic zones					
1	2	3	4		
SCS ≤ 0.5	0.5 < SCS ≤ 0.83	0.83 < SCS ≤ 1.38	SCS > 1.38		

In work by Verichev & Carpio (Verichev & Carpio, 2018) for the study area, SCS index values were calculated, and the entire study region was found to be located in the CTE19 Summer Climate Zone 1. Within the results of this research, it was observed that in all the meteorological stations of the study area, the value of the SCS index is less than 0.5.

Therefore, in the present chapter, it was decided to calculate only the WCS index, using Eq. 9, and determine the winter climate zones according to Table 23. Meteorological data from different sources were used to implement these calculations:

- **Hourly temperature measurement data** for a period of 8 years (2013-2020) from 80 meteorological stations. These stations are 2 from the DGAC, 5 from the MMA, and 73 from the Agromet (Table 24 and Fig. 41).

- **Synoptic monthly means of sunshine duration hours** from ERA Interim by European Centre for Medium-Range Weather Forecasts reanalysis project for the period 2013-2018, with a spatial resolution of 0.125x0.125 degrees longitude and latitude (ECMWF, 2018).
- **Maximum of sunshine duration hours.** These have been calculated using "NOAA solar calculations year"(NOAA ESRL GMD, 2019) by the NOAA Earth System Research Laboratory (ESRL) Global Monitoring Division (GMD).

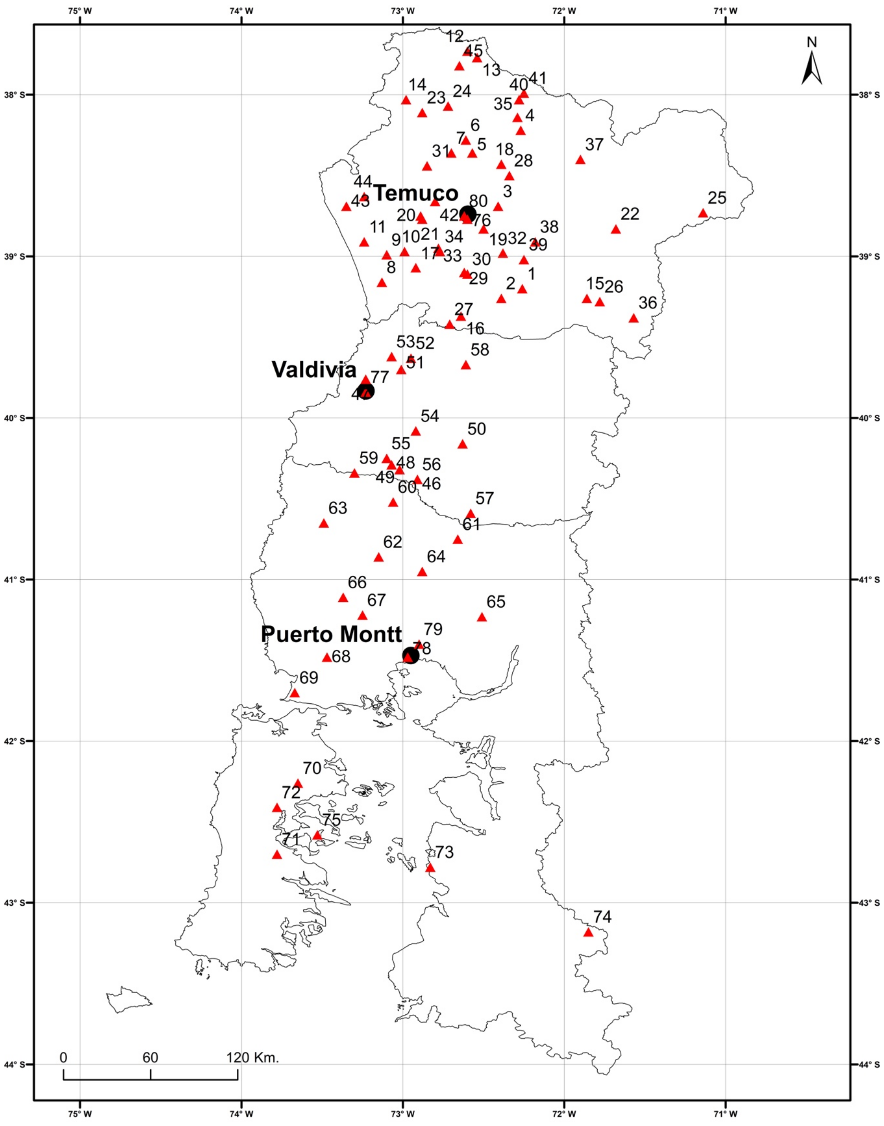


Fig. 41 Map of meteorological stations, the data of which were used to calculate the indexes WCS and SCS according to the CTE19.

Table 24 Meteorological stations whose data were used for the calculation of the WCS and SCS indexes according to the CTE19.

ID	Name	Lat.	Lon.	Alt.	ID	Name	Lat.	Lon.	Alt.
1	Vida Nueva	-39.2	-72.26	263	41	Collipulli	-37.99	-72.25	375
2	Huiscapi	-39.26	-72.39	266	42	Perales	-38.66	-72.8	55
3	Carillanca	-38.69	-72.41	200	43	Tranapuente	-38.69	-73.35	64
4	Las Palmas	-38.22	-72.27	388	44	Quiripio	-38.63	-73.24	322
5	Traiguén	-38.36	-72.57	253	45	El Vergel	-37.82	-72.65	81
6	La Providencia	-38.28	-72.61	254	46	El Cardal	-40.38	-72.91	80
7	Galvarino	-38.36	-72.7	230	47	Austral	-39.78	-73.23	15
8	Los Arrayanes	-39.16	-73.13	8	48	La Union Norte	-40.29	-73.07	29
9	Pocoyan	-38.99	-73.1	30	49	La Union	-40.32	-73.02	28
10	C. Llollinco	-38.97	-72.99	24	50	Lago Verde	-40.16	-72.63	248
11	Dominguez	-38.91	-73.24	93	51	Las Lomas	-39.7	-73.01	22
12	Renaico	-37.73	-72.6	88	52	Mafil	-39.63	-72.95	32
13	Manzanares	-37.77	-72.54	87	53	Mariquina	-39.62	-73.07	25
14	La Isla	-38.03	-72.98	76	54	Paillaco	-40.08	-72.92	110
15	San Enrique	-39.26	-71.86	279	55	Palermo	-40.25	-73.1	78
16	Loncoche	-39.37	-72.64	108	56	Río Bueno	-40.38	-72.91	80
17	Faja Maisan	-39.07	-72.92	56	57	Rucatayo	-40.59	-72.58	278
18	San Sebastián	-38.43	-72.39	299	58	Santa Carla	-39.67	-72.61	264
19	Taplon	-38.83	-72.5	130	59	Quilacahuin	-40.34	-73.3	17
20	Sta. Adela	-38.75	-72.89	50	60	Remehue	-40.52	-73.06	73
21	Nueva Imperial	-38.77	-72.88	49	61	Desagüe Rupanco	-40.75	-72.66	272
22	El Membrillo	-38.83	-71.68	527	62	La Pampa	-40.86	-73.15	96
23	Gaby-Ranquilco	-38.11	-72.88	76	63	Huacamapu	-40.65	-73.49	144
24	San Rafael	-38.07	-72.72	173	64	Octay	-40.95	-72.88	178
25	Marimenuco	-38.73	-71.14	1084	65	Ensenada	-41.23	-72.51	76
26	Pucon	-39.28	-71.78	430	66	Polizones	-41.11	-73.37	137
27	La Paz	-39.42	-72.71	86	67	Colegual	-41.22	-73.25	177
28	Sta. Inés	-38.5	-72.34	263	68	Los Canelos	-41.48	-73.47	105
29	Gorbea	-39.1	-72.62	113	69	Carelmapu	-41.7	-73.67	29
30	Cuarta Faja	-39.11	-72.6	115	70	Butalcura	-42.26	-73.65	148
31	San Fabián	-38.44	-72.85	198	71	Tara	-42.7	-73.78	145
32	Radal	-38.98	-72.38	168	72	Pid-Pid	-42.41	-73.78	81
33	Los Quilantos	-38.95	-72.78	85	73	Nueva Chaitén DMC	-42.78	-72.83	10
34	Freire	-38.97	-72.77	84	74	Futaleufu DMC	-43.18	-71.85	347
35	Pailahueque	-38.14	-72.29	379	75	Isla Chelin	-42.58	-73.53	33
36	Puala	-39.38	-71.57	393	76	Padre las Casas MMA	-38.77	-72.6	116
37	Curacautín-San Luis	-38.4	-71.9	549	77	Valdivia MMA	-39.83	-73.23	8
38	El Quincho	-38.91	-72.18	293	78	Puerto Montt MMA	-41.48	-72.97	104
39	Cunco	-39.02	-72.25	236	79	Alerce MMA	-41.4	-72.9	118
40	Surco y Semilla	-38.03	-72.28	379	80	Las Encias MMA	-38.75	-72.62	106

5.2.3. Proposed new combined zoning of CTE and ASHRAE climate zones

After defining climate zones for the La Araucanía, Los Ríos, Los Lagos regions with methods CTE06-13 and CTE19, a proposal for new combined building climate zones will be implemented for the study area identified for this thesis.

For the regions La Araucanía, Los Ríos and Los Lagos, the new climate zoning will be based on those corresponding to CTE19.

For the regions Aysén and Magallanes, the new climate zoning will be based on the ASHRAE standards, according to the map already shown in Chapter 4 – Fig. 27 and the methodology described for the definition of these zones in the paragraph 4.2.4.1. The ASHRAE climate zone grouping shall be implemented in accordance with the document - ANSI/ASHRAE/IES Standard 90.2-2018 "Energy-Efficient Design of Low-Rise Residential Buildings" (ASHARE, 2018). Building codes and recommendations for residential buildings are presented in this document. In this dissertation, only building standards for Low-Rise Residential Buildings from two regions in the south of Chile were used due to the absolute predominance of this type of dwellings in the housing stock of these regions.

5.3. Results

First, the results of the calculation of the WCS and SCS indexes and restoration of climate zones in the La Araucanía, Los Ríos, and Los Lagos regions according to CTE06-13 will be presented. Then, the results of the calculation of the WCS index and the definition of the CTE19 climate zones of the La Araucanía, Los Ríos, and Los Lagos regions will be presented. Finally, a proposal for a combined climate zoning of CTE19 and ASHRAE zones for the whole of southern Chile will be presented.

5.3.1. Results of the definition of CTE06-13 zones in La Araucanía, Los Ríos, and Los Lagos regions

5.3.1.1. Winter and summer climatic severity indexes CTE06-13 per meteorological stations

Table 25 presents 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. 5 and Eq. 6 (correlation between WCS and SCS indexes and meteorological parameters) were 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 the present chapter, for meteorological stations in Chile, the values of the WCS and SCS indexes were recalculated for the intervals [0.72;1.44] and [-0.05;0.54], respectively (Table 25).

Table 25 Calculated values of WCS and SCS (CTE06-13) for meteorological stations.

Num. of st.	Name of st.	WCS Val.	Years of meas.	% of data	SCS Val.	Years of meas.	% of data
1	Carillanca	1.01	7	99%	0.32	7	98%
2	Tranapuente	0.86	7	99%	0.10	7	100%
3	Quiripio	0.94	7	100%	0.10	7	100%
4	La Providencia	0.97	7	100%	0.38	7	92%
5	San Luis	1.12	7	99%	0.35	6	99%
6	Dominguez	0.87	7	100%	0.10	7	100%
7	C.Llollinco	0.99	7	100%	0.18	7	100%
8	Cuarta Faja	1.00	7	100%	0.33	7	100%
9	Sta. Adela	0.95	7	100%	0.31	6	100%
10	Lago Verde	1.12	6	100%	0.14	5	100%
11	Remehue	1.11	7	100%	0.19	7	98%
12	Los Canelos	1.11	7	99%	0.03	7	100%
13	La Pampa	1.11	7	97%	0.15	7	93%
14	Octay	1.10	7	98%	0.06	5	100%
15	El Cardal	1.09	6	100%	0.23	5	100%
16	Huyar Alto	1.20	7	100%	0.01	7	100%
17	Butalcura	1.20	7	100%	0.03	7	100%
18	Tara	1.21	6	100%	0.00	6	91%
19	Polizones	1.12	6	100%	0.15	5	100%
20	Colegual	1.16	5	100%	0.10	5	100%
21	Las Lomas	1.04	4	100%	0.36	3	100%
22	Santa Carla	1.19	4	100%	0.18	3	100%
23	Palermo	1.00	3	100%	0.29	3	100%
24	Est. Exp. Austral	0.94	2	96%	0.29	1	100%
25	Desague Rupanco	1.10	4	91%	0.10	3	100%
26	Ensenada	1.05	4	91%	0.15	3	100%
27	Quilacahuin	1.00	3	100%	0.36	2	100%
28	Sta Ines	0.99	2	100%	0.37	1	100%
29	Surco y Semilla	0.97	2	97%	0.52	1	100%
30	Las Palmas	1.05	2	99%	0.45	1	100%
31	San Fabian	0.99	2	100%	0.37	1	100%
32	Perales	0.93	2	100%	0.33	1	100%
33	Huiscapi	1.02	2	98%	0.33	1	100%
34	El Membrillo	0.96	2	96%	0.46	1	100%
35	Marimenuco	1.44	2	99%	0.44	1	100%
36	Valdivia MMA	1.01	4	89%	0.30	3	86%
37	Las Encias Temuco MMA	0.83	4	82%	0.21	4	79%
38	Osorno MMA	0.99	4	90%	0.24	5	89%
39	Pto. Montt MMA	0.72	6	92%	0.16	3	75%
40	La Araucanía	0.98	2	100%	0.33	2	94%
41	Pichoy	1.02	2	97%	0.35	2	90%
42	Lonquimay	1.35	3	63%	0.54	3	66%
43	Ancud	0.96	2	98%	0.03	2	91%
44	Nueva Chaiten	1.12	2	77%	-0.05	2	78%

The graphs of Fig. 42 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.

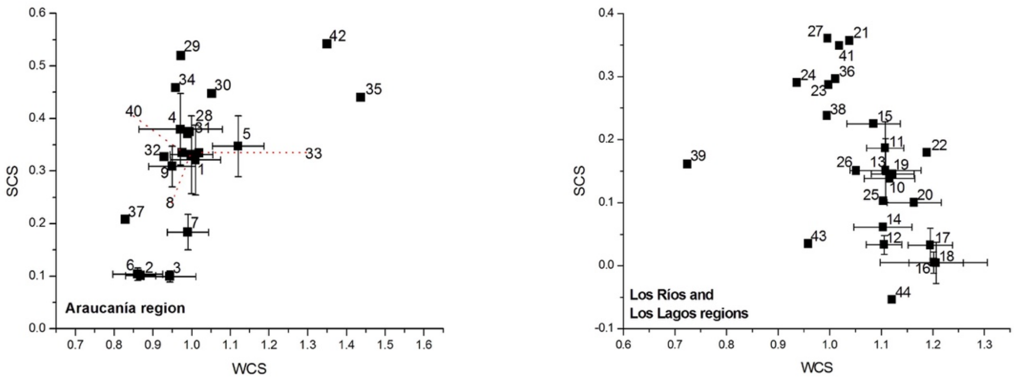


Fig. 42 Dependence between SCS and WCS in the meteorological stations (whiskers σ). The serial number of each station corresponds to the "Number of station" in Table 25.

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 20, 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. 6 from the input parameters.

At the urban meteorological stations, we found UHI effects in climatic zonings for building. 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 WCS 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.

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.

5.3.1.2. Reconstruction of spatial distribution 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. For example, Fig. 43 presents graphs of the dependence of indexes WCS (Fig. 43a) and SCS (Fig. 43b) on geographical parameters for the Araucanía region. 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.

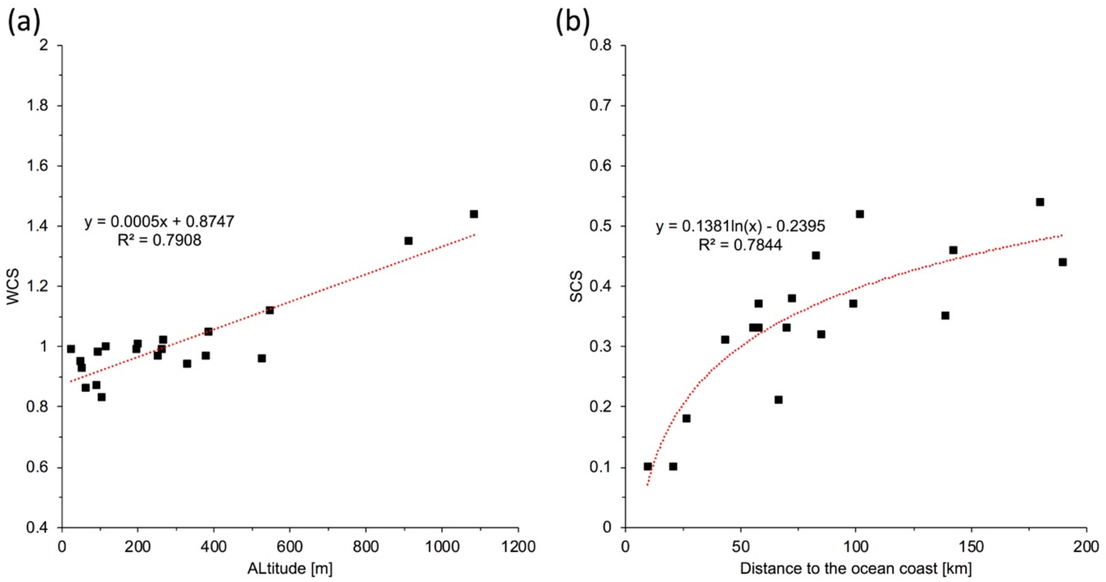


Fig. 43 Approximation equations of the WCS on altitude (a) and the SCS on the distance to the ocean coast (b) in Araucanía region.

Subsequently, the approximation equations for three regions used to calculate WCS and SCS values in 305 sites of the relief model. Finally, through the use of ArcGIS (ArcGIS, 2019) and the Kriging method (Oliver & Webster, 1990), maps with the spatial distribution of WCS and SCS in the study area were created.

5.3.1.3. 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. 44. 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) (Fig. 44a). 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 (Fig. 44b), 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 EC for cooling.

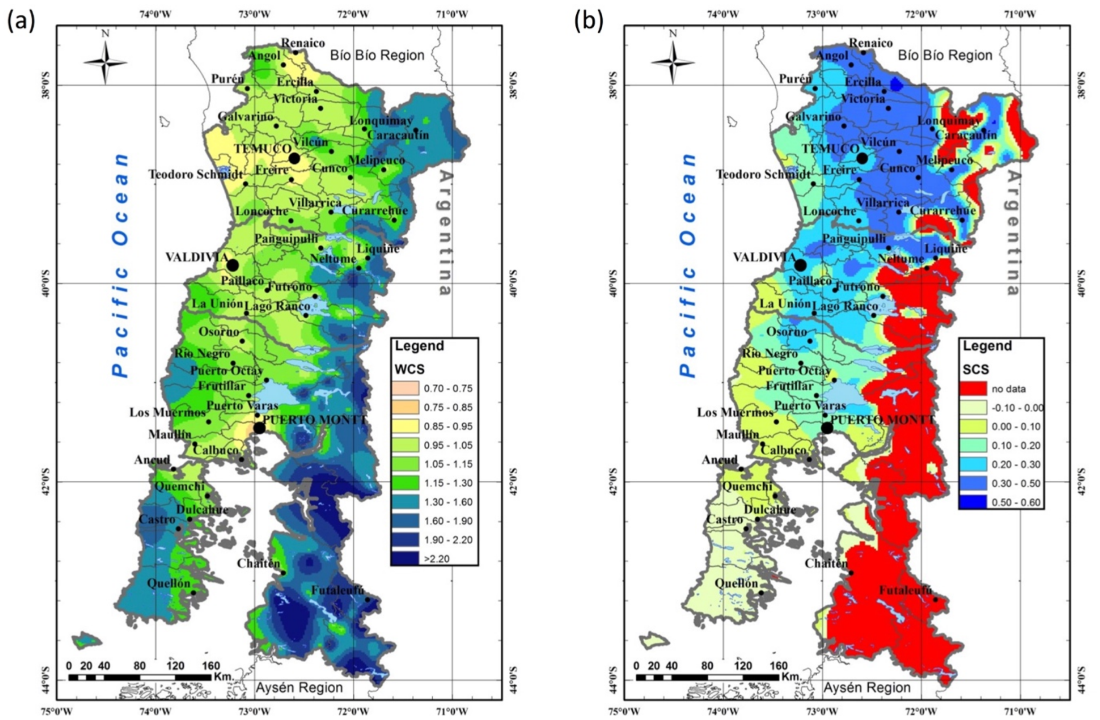


Fig. 44 Maps of spatial distribution of WCS (a) and SCS (b) CTE06-13.

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.

5.3.1.4. Complex results for communes (CTE06-13)

By the end of the study, and according to Table 20, three climatic zones C1, D1, and E1 were obtained (Table 26, Fig. 45). Climatic zones for 74 municipalities of the three regions were estimate 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.

Table 26 Recovered values of WCS and SCS for capital cities of the communes and climate zones of CTE06-13.

Capital city of commune	CTE06-13			Capital city of commune	CTE06-13		
	WCS	SCS	Climate zone		WCS	SCS	Climate zone
La Araucanía				Los Ríos			
Angol	0.92	0.40	C1	Los Lagos	1.08	0.30	D1
Carahue	0.94	0.09	C1	Máfil	1.04	0.36	D1
Cholchol	0.95	0.35	C1	S.J. de la Mariquina	1.03	0.29	D1
Collipulli	0.94	0.47	C1	Paillaco	1.04	0.25	D1
Cunco	1.04	0.35	D1	Panguipulli	1.05	0.32	D1
Curacautín	1.12	0.35	D1	Rio Bueno	1.09	0.23	D1
Curarrehue	1.05	0.33	D1	Valdivia	0.95	0.29	C1
Ercilla	0.97	0.52	D1	Los Lagos			
Freire	0.95	0.34	C1	Ancud	0.96	0.04	D1
Galvarino	0.99	0.37	D1	Calbuco	1.02	0.05	D1
Gorbea	1.00	0.33	D1	Castro	1.35	-0.05	E1
Lautaro	0.99	0.58	D1	Chaitén	1.12	-0.05	D1
Loncoche	1.09	0.28	D1	Chonchi	1.29	-0.06	D1
Lonquimay	1.35	0.54	E1	Cocharnó	1.27	0.01	D1
Los Sauces	1.12	0.28	D1	Curaco de Vélez	1.22	-0.05	D1
Lumaco	1.02	0.27	D1	Dalcahue	1.20	0.005	D1
Melipeuco	0.96	0.46	D1	Fresia	1.15	0.12	D1
Nueva Imperial	0.94	0.47	C1	Frutillar	1.11	0.14	D1
Padre Las Casas	0.86	0.27	C1	Futaleufú	1.75	-	E1
Perquenco	1.05	0.38	D1	Hualaihué	1.5	-0.08	E1
Petrufquén	0.92	0.29	C1	Llanquihue	1.02	0.14	D1
Pucón	0.97	0.29	D1	Los Muermos	1.11	0.03	D1
Purén	1.03	0.25	D1	Maullín	0.99	0.04	D1
Renaico	0.87	0.49	C1	Osorno	0.99	0.24	D1
Saavedra	0.86	0.11	C1	Palena	1.45	-	E1
Temuco	0.83	0.21	C1	Puerto Montt	0.72	0.16	C1
Teodoro Schmidt	0.99	0.18	D1	Puerto Octay	1.10	0.07	D1
Toltén	1.03	0.17	D1	Puerto Varas	0.95	0.14	C1
Traiguén	0.97	0.38	D1	Puqueldón	1.22	-0.06	D1
Victoria	0.99	0.41	D1	Purranque	1.11	0.15	D1
Vilcún	1.05	0.40	D1	Puyehue	1.07	0.19	D1
Villarrica	1.05	0.39	D1	Quellén	1.22	-0.06	D1
Los Ríos				Quellón	1.23	-0.07	D1
Corral	1.02	0.19	D1	Quemchi	1.14	0.02	D1
Futrono	1.04	0.23	D1	Quínchao	1.20	0.005	D1
La Unión	0.99	0.29	D1	Rio Negro	1.11	0.15	D1
Lago Ranco	1.05	0.20	D1	San Juan de la Costa	1.07	0.21	D1
Lanco	1.05	0.28	D1	San Pablo	1.09	0.23	D1

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 UHI effects belonged to the Climatic zone C1.

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).

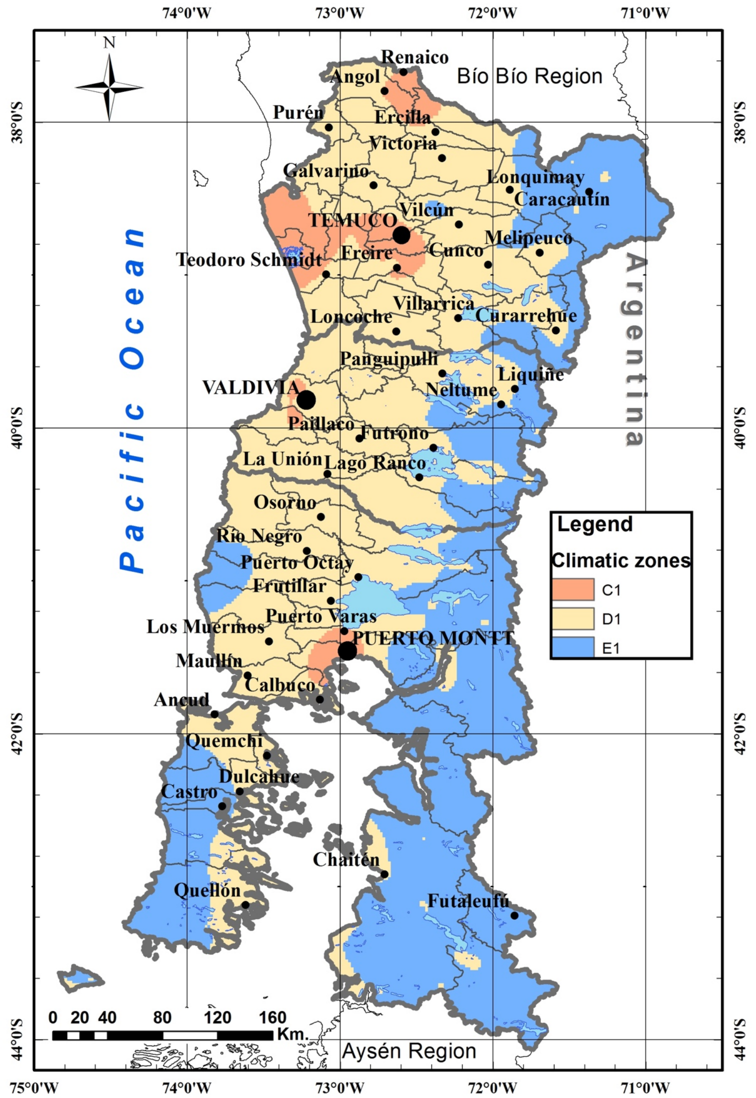


Fig. 45 Map of climatic zones according to the CTE06-13.

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.

The study area is located in Thermal zones 4-7 of RT OGUC, according to Fig. 11. Therefore it is possible to compare the thermal transmittance recommendations for buildings according to the Chilean and Spanish building codes. Table 27 presents the recommendations of thermal transmittance for roofs, walls, and floors for four thermal zones of the RT OGUC and three climatic zones of the CTE13.

Table 27 Maximum thermal transmittance thresholds for building elements according to CTE13 and RT OGUC.

Thermal transmittance U[W/m^{2}K]			
CTE13			
	Roofing	Walls	Floors
Climate zone C1	0.41	0.73	0.50
Climate zone D1	0.38	0.66	0.49
Climate zone E1	0.35	0.57	0.48
RT OGUC			
	Roofing	Walls	Floors
Thermal zone 4	0.38	1.70	0.60
Thermal zone 5	0.33	1.60	0.50
Thermal zone 6	0.28	1.10	0.39
Thermal zone 7	0.25	0.60	0.32

It is possible to observe that the thermal transmittance interval for floors in the CTE13 0.48-0.50 W/m^{2}K was within the interval of the RT OGUC 0.32-0.60 W/m^{2}K. For roofs, the CTE13 determines thermal transmittance for three climatic zones in the interval 0.35-0.41 W/m^{2}K and the RT OGUC for four thermal zones in the interval 0.25-0.38 W/m^{2}K. However, the maximum difference was observed in the recommendations of thermal transmittance for walls. Thermal transmittance requirements for walls in Spain were approximately two times stricter than in Chile. In Spain, the CTE13 is defined within the interval 0.57-0.73 W/m^{2}K, which is in line with RT OGUC recommendations for the thermal zone 7 0.60 W/m^{2}K. Moreover, this zone covers only three communes in the south-west of the study area Fig. 11. These differences in the recommendations for the thermal transmission of building structural elements can be associated with different intervals of acceptable indoor thermal 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.

For this reason, the application of Spanish building standards can improve the energy performance of dwellings built in the study regions and help to minimise emissions of pollutants into the atmosphere.

5.3.2. CTE19 Climate Zoning Results

In the previous sections, the results of the determination of climatic zones based on the CTE06-13 methodology were presented. In the following sections, the results of the determination of zones based on the current Spanish CTE19 standard will be analysed.

5.3.2.1. Winter climatic severity index CTE19 per meteorological stations

In the first instance, the results of the index calculation for each weather station were analysed. Table 28 shows the results for each weather station. The average values of the WCS index of weather stations ranges from 0.69 to 2.09. The maximum value of the index was obtained for station "Marimenuco", located at an altitude of 1084 meters above sea level. The minimum value of the index was obtained for the urban meteorological station located in the city of Puerto Montt. This indicates the significant warming effect of the UHI. A similar result was obtained for the cities Temuco and Valdivia. At the same time, in Temuco, the WCS index value was 20% lower than in stations outside the city; in Valdivia, it was 10% lower; and in Puerto Montt, 40% lower. Excluding urban weather stations, the minimum value of the index is typical for the northernmost part of the study area.

Table 28 *Results of the calculation of the WCS index (CTE19) for meteorological stations.*

ID	Name	years	average	σ	ID	Name	years	average	σ
1	Vida Nueva	2018-2019	1.23	0.11	41	Collipulli	2013-2017, 2019	1.08	0.07
2	Huiscapi	2016-2020	1.22	0.10	42	Perales	2016-2020	1.10	0.08
3	Carillanca	2013,2016-2020	1.20	0.08	43	Tranapuente	2013-2020	0.94	0.08
4	Las Palmas	2016-2020	1.25	0.10	44	Quiripio	2013-2020	1.11	0.12
5	Traiguén	2013, 2015-2017, 2019	1.07	0.07	45	El Vergel	2018-2019	0.88	0.15
6	La Providencia	2014-2016, 2018-2020	1.10	0.07	46	El Cardal	2013-2014, 2016-2020	1.15	0.06
7	Galvarino	2013, 2016-2017	1.08	0.08	47	Austral	2017-2020	1.05	0.06
8	Los Arrayanes	2019-2020	1.00	0.07	48	La Union Norte	2016-2019	0.99	0.05
9	Pocoyan	2014-2016, 2019	1.00	0.06	49	La Union	2013-2018	1.06	0.07
10	C. Llollinco	2013-2016, 2018-2020	1.05	0.04	50	Lago Verde	2013-2016,2019-2020	1.18	0.06
11	Dominguez	2013-2020	0.93	0.06	51	Las Lomas	2013-2020	1.10	0.05
12	Renaico	2013-2017, 2019	0.76	0.06	52	Mafil	2016-2019	1.15	0.09
13	Manzanares	2016-2019	0.83	0.10	53	Mariquina	2013-2019	1.08	0.05
14	La Isla	2017-2018, 2020	1.09	0.05	54	Paillaco	2014-2019	1.19	0.07
15	San Enrique	2018-2020	1.29	0.07	55	Palermo	2015-2020	1.11	0.07
16	Loncoche	2013, 2015-2016, 2019	1.02	0.03	56	Río Bueno	2013,2018	1.08	0.02
17	Faja Maisan	2018-2020	1.11	0.08	57	Rucatayo	2017-2020	1.42	0.05
18	San Sebastián	2018-2020	1.27	0.08	58	Santa Carla	2014-2020	1.28	0.05
19	Taplon	2018-2020	1.09	0.08	59	Quilacahuin	2014-2020	1.04	0.05
20	Sta. Adela	2014-2020	1.00	0.06	60	Remehue	2013-2020	1.19	0.04
21	Nueva Imperial	2014, 2019	0.86	0.23	61	Desagüe Rupanco	2014-2020	1.29	0.09
22	El Membrillo	2017-2020	1.29	0.07	62	La Pampa	2013-2020	1.24	0.07
23	Gaby-Ranquilco	2018-2020	1.08	0.11	63	Huacamapu	2018-2020	1.23	0.07
24	San Rafael	2017-2020	0.96	0.09	64	Octay	2013-2020	1.17	0.07
25	Marimenuco	2016-2020	2.09	0.15	65	Ensenada	2014-2020	1.27	0.07
26	Pucon	2014, 2019	1.33	0.03	66	Polizones	2013-2020	1.28	0.08
27	La Paz	2018-2020	1.15	0.07	67	Colegual	2013-2020	1.31	0.06
28	Sta. Inés	2016-2020	1.18	0.09	68	Los Canelos	2013-2020	1.18	0.06
29	Gorbea	2013-2017, 2019	1.02	0.06	69	Carelmapu	2018-2020	1.16	0.03
30	Cuarta Faja	2013-2020	1.05	0.09	70	Butalcura	2013-2020	1.42	0.11
31	San Fabián	2016-2019	1.10	0.10	71	Tara	2013-2020	1.33	0.08
32	Radal	2019, 2020	1.11	0.08	72	Pid-Pid	2018-2020	1.32	0.04
33	Los Quilantos	2019	1.02	-	73	Nueva Chaitén	2020	1.23	-
34	Freire	2013-2014, 2016-2017	1.05	0.19	74	Futaleufu	2020	1.68	-
35	Pailahueque	2019	1.15	-	75	Isla Chelin	2018-2020	1.13	0.04
36	Puala	2016-2020	1.26	0.10	76	Padre las Casas	2014-2020	0.89	0.07
37	Curacautín-San Luis	2014-2020	1.38	0.10	77	Valdivia MMA	2014-2020	0.99	0.03
38	El Quincho	2013-2020	1.10	0.10	78	Puerto Montt MMA	2016-2017	0.69	0.12
39	Cunco	2016-2017, 2019	1.22	0.12	79	Alerce MMA	2019-2020	1.20	0.01
40	Surco y Semilla	2016-2020	1.13	0.11	80	Las Encias MMA	2014-2020	0.93	0.09

In this case, for the calculation of the WCE index, the formula based on sunshine duration (Eq. 9) according to the CTE19 has been used, in which the sunshine duration hour is directly related to the direct solar radiation, compared to the global solar radiation. As the heat balance of buildings is more dependent on direct solar radiation, the transition from the use of global solar radiation to sunshine duration hours will allow a more significant consideration of solar climatology in the climatic zoning for building in CTE. However, information on sunshine duration hours is not easily accessible as very few meteorological stations make these measurements in Chile; for this reason, for this study, data from meteorological modelling and not from *in situ* measurements were used.

In contrast, global solar radiation data from *in situ* measurements and meteorological models are more readily available. It was therefore decided, in the beginning, to compare the climatic values of the WCS indexes calculated by two different methods for identical meteorological stations of Table 25 and Table 28.

Fig. 46 shows a graph of the relationship between the two WCS indexes calculated by Eq. 5 (CTE06-13) and Eq. 9 (CTE19). The graph shows that the indexes calculated with the two equations correlate well, and, on average, the WCS CTE06-13 index is 15% lower than the WCS CTE19 index. The resulting relationship between the indexes will allow both equations to be used equally in the study area depending on data availability. This result showed the possibility to use the CTE 06-13 methodology to calculate the WCS index and to transform this index using the correlation formula into the WCS index of the CTE19 methodology.

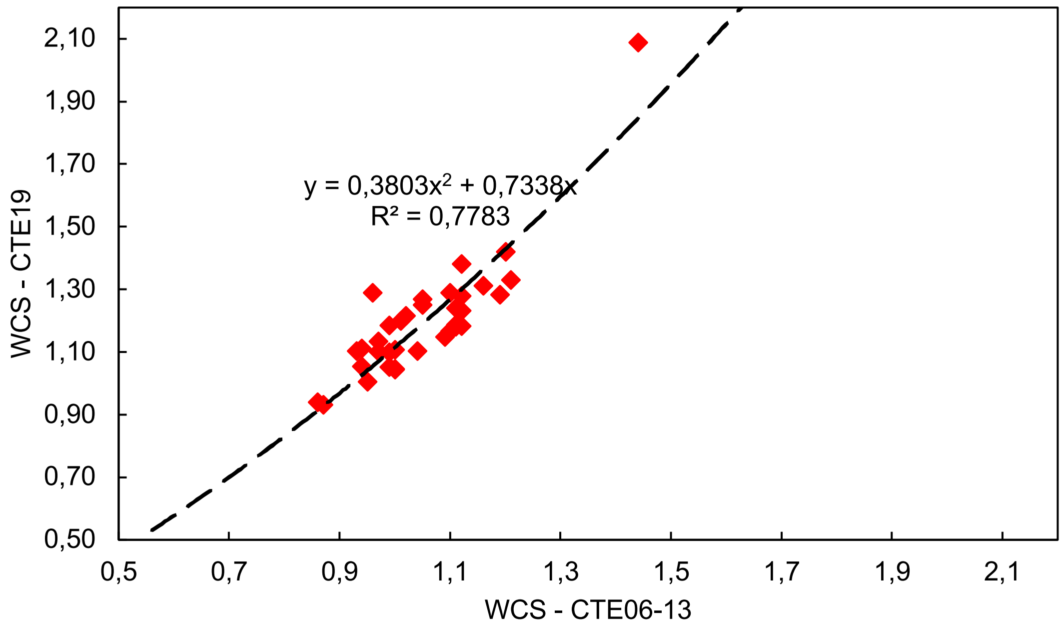


Fig. 46 The relationship between the WCS indexes calculated by CTE06-13 and CTE19.

5.3.2.2. Reconstruction of spatial distribution of winter climatic severity index

In the CTE19, the climatic building zones of all the provinces of Spain are represented. At the same time, for each province, the values of absolute height above sea level were determined, at which a change between climatic zones is observed. Therefore, in this chapter, it was decided to determine these heights for each study region. Fig. 47 presents three graphs of the dependence of the WCS index on the absolute height above sea level of the meteorological stations for the three regions analysed in this chapter. In all cases, this dependence is well described by a quadratic function. In Table 23, it can be seen that the change from winter Climate zone D to E occurs when the value of the WCS index is > 1.51. Therefore, using the quadratic function, the absolute height above sea level at which the climate zone D will change to E in each region can be calculated. So, this change of zones in the Araucanía region occurs at an altitude of 650 metres, in the Los Ríos region at an altitude of 365 metres and in the Los Lagos region at an altitude of 330 metres. These results are important as they will help to produce a detailed map of CTE19 climate zones in the study area.

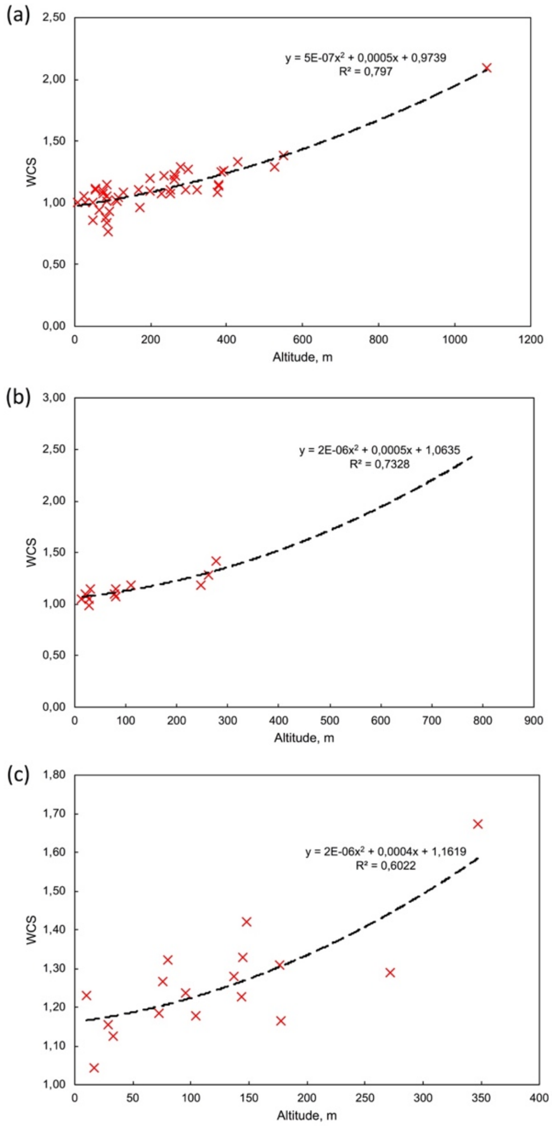


Fig. 47 Dependence of the WCS index on absolute height above sea level in the Araucanía (a), Los Ríos (b) and Los Lagos (c) regions.

5.3.2.3. Complex results for communes (CTE19)

As noted above in the work of Verichev and Carpio (Verichev & Carpio, 2018), the study area belongs to summer Climate zone 1, with SCS index values <0.50. Therefore, to determine the spatial distribution of the CTE19 climate zones, it was only necessary to determine the location of the winter climate zones. To do this, first of all, the spatial interpolation of the values obtained from the WCS indexes of CTE19 (Table 28) was carried out using the Kriging method (Oliver & Webster, 1990). Secondly, by applying the winter climate zone change altitudes from the previous paragraph and a digital surface model with a spatial resolution of ~ 30 metres (USGS SRTM, 2021), a map of the CTE19 climate zones was created (Fig. 48).

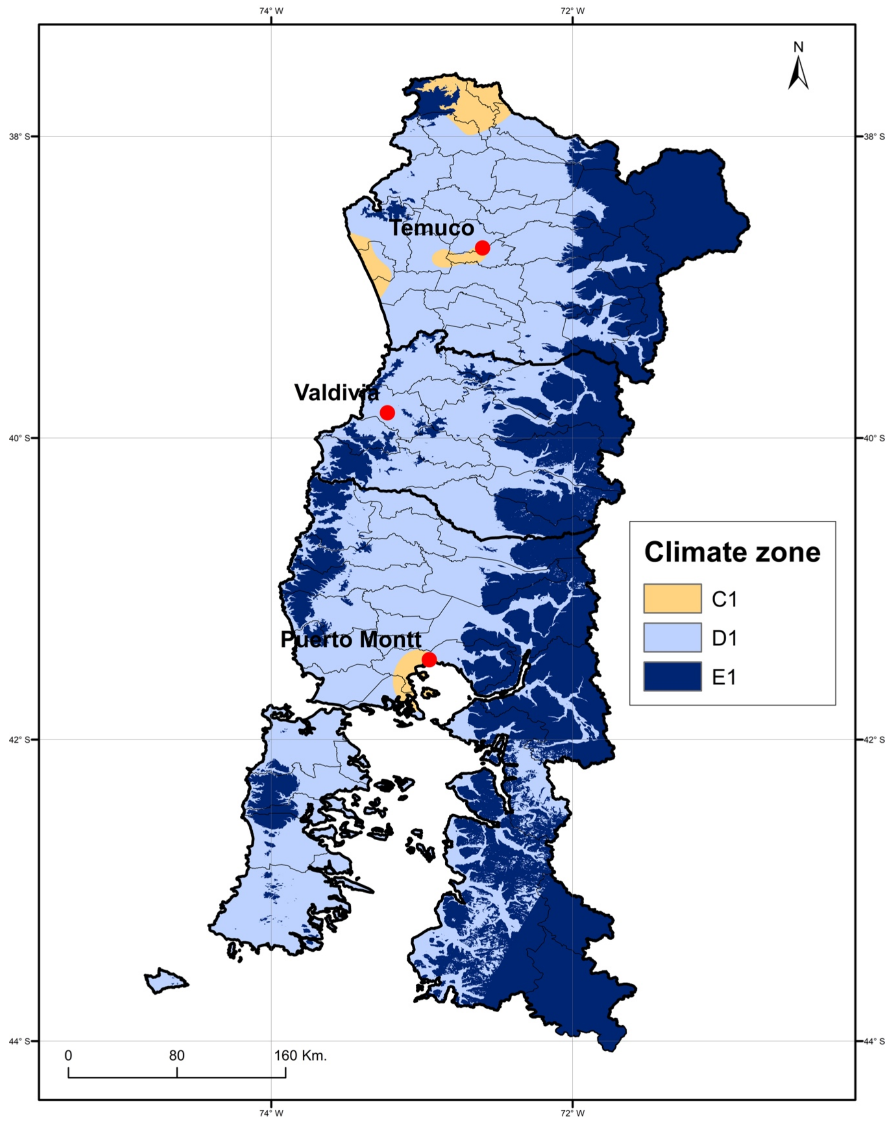


Fig. 48 Map of climatic zones according to the CTE19.

In this map, it can be seen that the layout of the zones is mainly similar to Fig. 45 of CTE06-13. Changes in the equations for the calculation of the indexes in CTE19, compared to CTE06-13, as well as changes in the intervals of the indexes for the zone determination, influenced the change of climatic zones for building in some geographical areas of the study area. Thus, for example Valdivia, in this map, and according to CTE19, has a Climate zone D1. Also, the use of a digital surface model allowed us to determine more precisely the boundaries between D1 and E1 zones in each region. In this way, the influence of the altitude of the coastal mountain range on the change of climatic zones in the Los Ríos and Los Lagos regions can be clearly traced. In addition, meso- and microclimatic differences are reflected in more detail in this map.

Table 29 CTE19 climate zones for communes.

La Araucanía		
Commune	<650m	>650m
Angol	C1	E1
Carahue	C1, D1	E1
Cholchol	D1	E1
Collipulli	C1, D1	E1
Cunco	D1	E1
Curacautín	D1	E1
Curarrehue	D1	E1
Ercilla	D1	-
Freire	D1	-
Galvarino	D1	-
Gorbea	D1	-
Lautaro	D1	E1
Loncoche	D1	-
Lonquimay	E1	E1
Los Sauces	C1, D1	E1
Lumaco	D1	E1
Melipeuco	D1	E1
Nueva Imperial	C1, D1	E1
Padre Las Casas	C1, D1	-
Perquenco	D1	-
Pitrufquén	D1	-
Pucón	D1	E1
Purén	D1	E1
Renaico	C1	-
Puerto Saavedra	C1, D1	-
Temuco	C1, D1	-
Teodoro Schmidt	C1, D1	-
Toltén	D1	-
Traiguén	D1	-
Victoria	D1	E1
Vilcún	D1	E1
Villarrica	D1	E1
Los Ríos		
Commune	<365m	>365m
Corral	D1	E1
Futrono	D1	E1
La Unión	D1	E1
Lago Ranco	D1	E1
Lanco	D1	E1
Los Lagos	D1	E1
Máfil	D1	E1
S.J. de la Mariquina	D1	E1
Paillaco	D1	E1
Panguipulli	D1	E1
Rio Bueno	D1	E1
Valdivia	D1	E1
Los Lagos		
Commune	<330m	>330m
Ancud	D1	E1
Calbuco	C1, D1	-
Castro	D1	E1
Chaitén	D1	E1
Chonchi	D1	E1
Cochamó	D1	E1
Curaco de Vélez	D1	-
Dalcahue	D1	E1
Fresia	D1	E1
Frutillar	D1	-
Futaleufú	E1	E1
Hualaihué	D1	E1
Llanquihue	D1	-
Los Muermos	D1	E1
Maullín	D1	-
Osorno	D1	-
Palena	E1	E1
Puerto Montt	C1, D1	E1
Puerto Octay	D1	E1
Puerto Varas	D1	E1
Puqueldón	D1	-
Purranque	D1	E1
Puyehue	D1	E1
Queilén	D1	-
Quellón	D1	E1
Quemchi	D1	-
Quínchao	D1	-
Rio Negro	D1	E1
San Juan de la Costa	D1	E1
San Pablo	D1	-

Table 29 presents the climate zones for all communes, depending on the absolute height above sea level. If there are two possible zones, to clarify in which geographical location the building project will be implemented, the map in Fig. 48 should be used. After defining the CTE19 zones, it is possible to move on to the analysis of the proposed climate zones for building and the revision of building codes and requirements.

5.3.3. Proposal for new climate zones for building

After analysing the feasibility of the application of the zoning methods - CTE06-13 and CTE19 in the three northern regions of the study area, it is possible to proceed to the phase of proposing new building zones. Because CTE19 is a current method in Spain, it was decided to use it for the proposal, and the CTE06-13 method is an alternative, as there is a possibility to relate the WCS indexes of both methodologies for three study regions.

From the combination of CTE19 and ASHRAE building climate zones for the study area, new climate zones emerge. Table 30 shows the correspondence between the new climate zones and the zones of these two standards that were combined. The result of the spatial distribution of the proposed climate zones is presented in the map Fig. 49.

Table 30 Correspondence of the new proposed climatic zones with the climatic zones of CTE19 and the ASHRAE.

Zona propuesta	Building code	Conformity to climate zones of CTE19 or ASHRAE
Zone I	CTE19	C1
Zone II	CTE19	D1
Zone III	CTE19	E1
Zone IV	ASHRAE	4A
Zone V	ASHRAE	4C, 5A and 5C
Zone VI	ASHRAE	6A and 6B
Zone VII	ASHRAE	7 and 8

It is important to note that each of the CTE19 zones corresponds to a proposed new zone because each zone – C1, D1 and E1 – has different building recommendations. It was decided to maintain the warmest climate zones for the main cities due to the UHI effect. Thus, Temuco and Puerto Montt belong to the warmest climate zone – Zone I, corresponding to climate zone C1 of CTE19. The requirements for the thermal transmittance of the roof are similar in both standards. Also, in the case of windows and doors, the Spanish standard has stricter requirements.

Table 31 shows the maximum permissible values of thermal transmittance of the building envelope for Zone I - Zone III. For the regions of La Araucanía, Los Ríos, and Los Lagos, the use of the Spanish current building code compared to the RT OGUC (Table 7) will significantly improve the thermal transmittance of walls – CTE19 range [0.37-0.49 $W/m^2 \cdot K$] compared to RT OGUC range [1.10-1.70 $W/m^2 \cdot K$] and floors in contact with air – CTE19 range [0.37-0.49 $W/m^2 \cdot K$] compared to RT OGUC range [0.39-0.60 $W/m^2 \cdot K$]. The requirements for the thermal transmittance of the roof are similar in both standards. Also, in the case of windows and doors, the Spanish standard has stricter requirements.

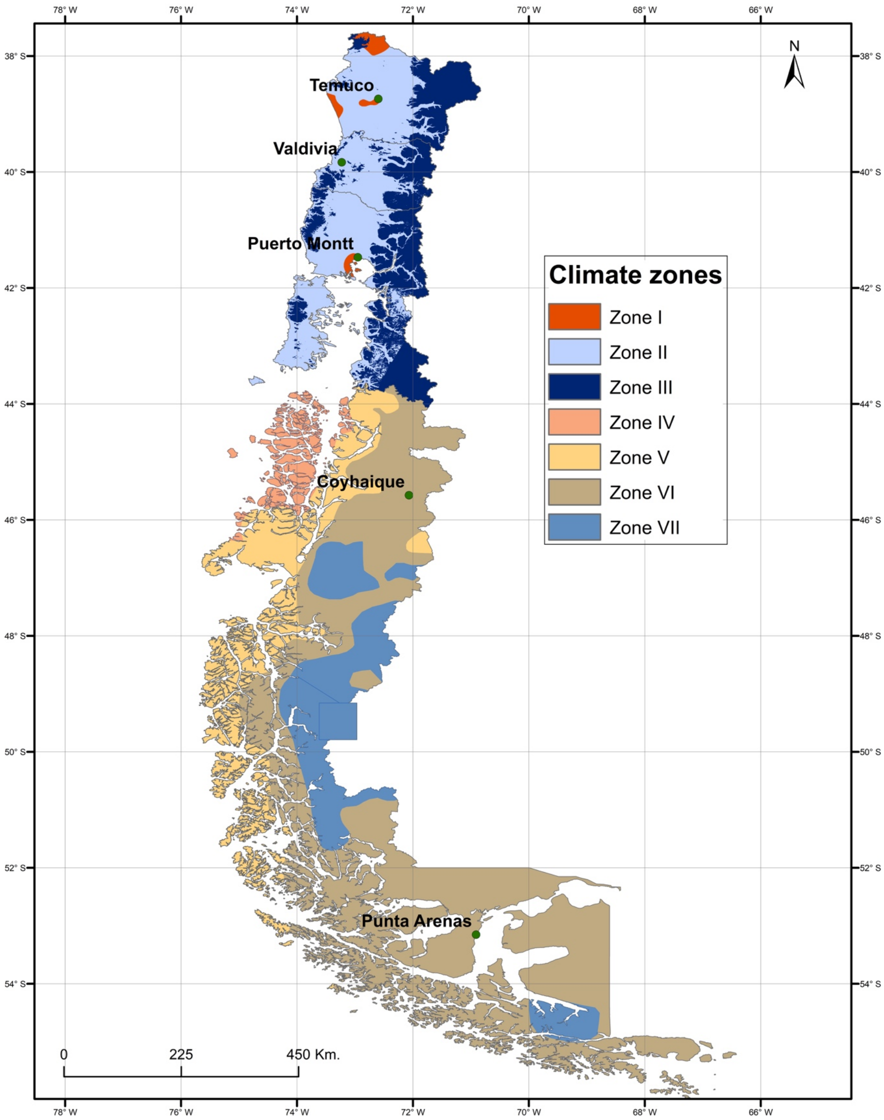


Fig. 49 Map of new climate zones for building in southern Chile.

Table 31 Thermal transmittance limit values and limitation of energy consumption for Zone I - Zone III.

New zone	CTE19 zone	Walls and floors in contact with outside air, W/m²·K	Roofs in contact with outside air, W/m²·K	Walls, floors, and roofs in contact with non-habitable spaces or with the ground, W/m²·K	Partition walls or interior partitions belonging to the thermal envelope, W/m²·K	Openings[*] (assembly of frame, glass and if applicable, roller shutter box), W/m²·K	Doors with semi-transparent surface equal to or less than 50%, W/m²·K	Non-renewable primary EC, kWh/m²/year	Total primary EC, kWh/m²/year
Zone I	C1	0.49	0.40	0.70	0.70	2.10	5.70	32[†] and 65[‡]	64 and 90
Zone II	D1	0.41	0.35	0.65	0.65	1.80	5.70	38 and 70	76 and 105
Zone III	E1	0.37	0.33	0.59	0.59	1.80	5.70	43 and 80	86 and 115

[*] Openings with shop window use in units with commercial activity can increase the value by 50%
[†] New buildings and extensions
[‡] Change of use to private residential and renovations

Additionally, CTE19 has limit values for non-renewable primary EC and total primary EC and contains a wealth of information to help builders and architects implement energy efficient building design; therefore, Spanish climate zones in three regions in southern Chile are used as a reference.

The use of the thermal transmittance requirements for climatic zones of CTE19, together with additional information from the Chilean and Spanish building codes, will allow the construction of more energy efficient buildings in the three regions of southern Chile.

In the case of the Aysén and Magallanes regions, it was decided to use ASHRAE climate zones and building standards. As indicated in the methodology of this chapter, ASHRAE has a special construction standard for Low-Rise Residential Buildings – ANSI/ASHRAE/IES Standard 90.2-2018. The grouping of climate zones into new ones was implemented in accordance with the grouping of building standards contained in this document. Thus, all climate zones 4, except for 4C, corresponding to the new zone IV. ASHRAE zone 4C plus zones 5 correspond to the new zone V. All climate zones 6 correspond to the new zone VI. ASHRAE zones 7 and 8 correspond to the new zone VII Table 30 because in the case of Low-Rise Residential Buildings, these two ASHRAE zones have the same building requirements.

Table 32 and Table 33 show the maximum allowed values of thermal transmittance of the building envelope elements for two situations: when the house has on-site power systems and when it does not. The ASHRAE standard recognizes the important role of renewable energy and on-site power systems to help reach the building performance targets. In general, it can be seen that the permissible thermal transmittances for houses with on-site power systems are more stringent.

Table 32 Envelope component maximum SHGC and U-value for buildings with on-site power systems.

New zone	ASHRAE zone	Maximum SHGC Glazed Fenestration		Maximum U-value, W/m^2·K							
			Skylights	Fenestration	Skylights	Celings	Frame walls	Mass Walls	Floors	Basement walls	Crawlspace walls
Zone IV	4 exept 4C	0.40	0.40	1.99	3.12	0.15	0.34	0.56	0.27	0.34	0.37
Zone V	4C and 5	-	N/A	1.82	3.12	0.15	0.34	0.47	0.19	0.28	0.31
Zone VI	6	-	N/A	1.82	3.12	0.15	0.26	0.34	0.19	0.28	0.31
Zone VII	7 and 8	-	N/A	1.82	3.12	0.15	0.26	0.32	0.16	0.28	0.31

Table 33 Envelope component maximum SHGC and U-value.

New zone	ASHRAE zone	Maximum SHGC Glazed Fenestration	Maximum U-value, W/m²·K							
			Fenestration	Skylights	Celings	Frame walls	Mass Walls	Floors	Basement walls	Crawlspace walls
Zone IV	4 exept 4C	-	1.99	3.41	0.17	0.47	0.80	0.27	0.34	0.37
Zone V	4C and 5	-	1.99	3.41	0.17	0.32	0.47	0.19	0.34	0.37
Zone VI	6	-	1.99	3.41	0.15	0.32	0.34	0.19	0.28	0.37
Zone VII	7 and 8	-	1.99	3.41	0.15	0.32	0.32	0.19	0.28	0.37

In the case of the ASHRAE standard, recommendations are given for the maximum allowed value of solar heat gain coefficient (SHGC); in our situation, only for dwellings with on-site power systems for climate zone IV (ASHRAE zone 4 except 4C), this limitation is applicable, in other zones it is not necessary to use this parameter. In the case of the maximum permissible thermal transmittance of the walls, the separation into two types of walls – frame walls and mass walls – is observed. According to ANSI/ASHRAE/IES Standard 90.2-2018, mass walls have a description:

Mass walls – above grade walls that comply with one of the following:

- Constructed of concrete block, concrete, insulated concrete form (ICF), masonry cavity, brick (other than brick veneer), earth (adobe, compressed earth block, rammed earth), and solid timber/logs.

- Weighing not less than 170 kg/m^2 of wall surface area.

- Weighing not less than 120 kg/m^2 of wall surface area, where the material weight is not more than 1920 kg/m^3.

- Having a heat capacity exceeding 143 kJ/m^{2}K.

- Having a heat capacity exceeding 102 kJ/m^{2}K, where the material weight is not more than 1920 kg/m^3.

In comparison to the Chilean or Spanish standard, ASHRAE gives recommendations for basement walls and crawlspace walls. In any case, the maximum allowed values of thermal transmittance are much stricter (Table 32 and Table 33) than in RT OGUC (Table 7), and their practical application can help to build more energy efficient dwellings in the two southernmost regions of Chile. Thus, the thermal transmittance range for roofs in new zones is [0.15-0.17 W/m^2·K], in comparison to RT OGUC which has a requirement of 0.25 W/m^2·K. For walls, the new zones have an allowable range of [0.26-0.47 W/m^2·K], compared to RT OGUC, where 0.60 W/m^2·K is required. Also, the resulting four new climate zones for the two regions in the south (Fig.

49) represent the climatic diversity of these regions to a greater extent than an RT OGUC or ECS climate zone (Fig. 11).

Furthermore, building standards for high-rise buildings are presented in the ANSI/ASHRAE/IES Standard 90.1-2019 "Energy Standard for Buildings Except Low-Rise Residential Buildings". The use of the map shown in Fig. 27 and these standards will allow the construction of high-rise, multi-apartment buildings in the two southern regions under ASHRAE standards.

Table 34 presents the principal cities of communes of the regions under study and the corresponding thermal zones of the official document RT OGUC, as well as the new climate zones. It should be noted that, to one degree or another, all seven new climate zones are included in this table. Of course, new climate zones such as zones IV, V and VII will find their application in less densely populated regions. In addition, to accurately determine the climatic zones of a project located outside the main urban centres, it is recommended to use the maps included in Fig. 27 and Fig. 48.

Of course, in recent years, ASHRAE has been adapting its climate zoning to make it universally applicable, e.g., by adding climate zone 0 for a hot climate type. It should be pointed out that Canada's climate zones are based entirely on the ASHRAE methodology. This is achieved through clarity and sufficient simplicity of the zoning methodology.

Additionally, in this dissertation, it was shown that the Spanish CTE climate zoning methodology also has prospects for application in other geographical regions of the world. This is mainly because it is an understandable methodology for determining climate zones, which is also reproducible. Not only its reproducibility in other parts of the world is important, but also the reproducibility of a given zoning methodology in the context of future climate change. In the framework of this research, the evolution of the zones in the future will not be considered, but this topic will be an incentive for future research in this direction. The ability to replicate climate zoning methodology was fundamental in the choice of zoning methods for the study area; of course, another aspect is the similarity of climatic conditions. At the same time, another important question on the verification of building standards and codes and their applicability in Chile provides a broad basis for future scientific research. As well as the analysis of the effects – energy, environmental, and economic – to be derived from the use of new climate zones and building codes.

Table 34 New zones for capital cities of the communes.

Commune capital city	RT OGUC	CTE19	New zone
La Araucanía			
Angol	4	C1	Zone I
Carahue	5	D1	Zone II
Cholchol	4	D1	Zone II
Collipulli	4	D1	Zone II
Cunco	5	D1	Zone II
Curacautín	6	D1	Zone II
Curarrehue	6	D1	Zone II
Ercilla	4	D1	Zone II
Freire	4	D1	Zone II
Galvarino	5	D1	Zone II
Gorbea	4	D1	Zone II
Lautaro	5	D1	Zone II
Loncoche	5	D1	Zone II
Lonquimay	6	E1	Zone III
Los Sauces	4	D1	Zone II
Lumaco	5	D1	Zone II
Melipeuco	5	E1	Zone III
Nueva Imperial	5	C1	Zone I
Padre Las Casas	4	C1	Zone I
Perquenco	5	D1	Zone II
Pitrufquén	4	D1	Zone II
Pucón	5	D1	Zone II
Purén	4	D1	Zone II
Renaico	4	C1	Zone I
Puerto Saavedra	5	C1	Zone I
Temuco	4	C1	Zone I
Teodoro Schmidt	5	D1	Zone II
Toltén	5	D1	Zone II
Traiguén	5	D1	Zone II
Victoria	4	D1	Zone II
Vilcún	5	D1	Zone II
Villarrica	5	D1	Zone II
Los Ríos			
Corral	5	D1	Zone II
Futrono	6	D1	Zone II
La Unión	4	D1	Zone II
Lago Ranco	6	D1	Zone II
Lanco	5	D1	Zone II
Los Lagos	5	D1	Zone II
Máfil	5	D1	Zone II
S.J. de la Mariquina	5	D1	Zone II
Paillaco	5	D1	Zone II
Panguipulli	5	D1	Zone II
Rio Bueno	5	D1	Zone II
Valdivia	4	D1	Zone II
Los Lagos			
Ancud	6	D1	Zone II
Calbuco	6	D1	Zone II
Castro	6	D1	Zone II

Commune capital city	RT OGUC	CTE19/ASHRAE	New zone
Los Lagos			
Chaitén	6	D1	Zone II
Chonchi	6	D1	Zone II
Cochamó	6	D1	Zone II
Curaco de Vélez	6	D1	Zone II
Dalcahue	6	D1	Zone II
Fresia	6	D1	Zone II
Frutillar	6	D1	Zone II
Futaleufú	7	E1	Zone III
Hualaihué	6	D1	Zone II
Llanquihue	6	D1	Zone II
Los Muermos	6	D1	Zone II
Maullín	6	D1	Zone II
Osorno	5	D1	Zone II
Palena	7	E1	Zone III
Puerto Montt	6	C1	Zone I
Puerto Octay	5	D1	Zone II
Puerto Varas	6	D1	Zone II
Puqueldón	6	D1	Zone II
Purranque	6	D1	Zone II
Puyehue	6	D1	Zone II
Queilén	6	D1	Zone II
Quellón	6	D1	Zone II
Quemchi	6	D1	Zone II
Quínchao	6	D1	Zone II
Rio Negro	6	D1	Zone II
San Juan de la Costa	6	D1	Zone II
San Pablo	5	D1	Zone II
Aysén			
Caleta Tortel	7	6A	Zone VI
Chile Chico	7	5C	Zone V
Cochrane	7	6A	Zone VI
Coyhaique	7	6A	Zone VI
Lago Verde	7	6A	Zone VI
Melinka (Guaitecas)	7	4A	Zone IV
Puerto Aysén	7	5A	Zone V
Puerto Cisnes	7	5A	Zone V
Puerto Ingeniero Ibáñez	7	5C	Zone V
Villa O'Higgins	7	7	Zone VII
Magallanes			
Cerro Castillo	7	6B	Zone VI
Cerro Sombrero	7	6B	Zone VI
Puerto Natales	7	6B	Zone VI
Puerto Williams	7	6A	Zone VI
Punta Arenas	7	6A	Zone VI
Punta Delgada	7	6B	Zone VI
Porvenir	7	6A	Zone VI
Río Verde	7	6A	Zone VI
Villa Cameron	7	6A	Zone VI
Villa Tehuelches	7	6B	Zone VI

In any case, this chapter provides a practical solution to the problem of the adequacy of the current national climate zoning for building in the study area by aligning the building codes and climatic zones of southern Chile with the building standards of Spain and the United States, which are constantly being improved and updated. And of course, the results obtained can be applied in practice by civil engineers, architects, construction companies and decision-makers in the field of civil engineering and architecture.

5.4. Conclusions

A methodology for reconstructing the spatial distribution of WCS index, calculated according to CTE19, depending on altitude, was shown. In the case of the WCS, a quadratic relationship was found between the two equations for the calculation of the indexes, according to documents CTE06-13 and CTE19. This allows both formulas to be used to determine the CTE climate zones in the study regions. In the case of the SCS index, this is not necessary, since according to the CTE19, this index depends only on the CDD, which facilitates its calculation and the definition of the zones.

This chapter proposed a combined climate zoning for buildings in southern Chile based on two methodologies: the CTE19 methodology for the Araucanía, Los Ríos, and Los Lagos regions and the ASHRAE methodology for the Aysen and Magallanes regions.

Furthermore, the proposed climate zoning methodology is easily reproducible and replicable, making it suitable for use in the context of future climate change. The proposed climate zoning reflects a significant extent the actual meso- and microclimatic characteristics of southern Chile, rather than current national zonings. The proposed climate zoning has stricter building standards and requirements compared to existing national building codes, which could substantially improve the energy efficiency of remodelled and planned dwellings in southern Chile.

The application of the proposed climate zoning has the potential to constantly update building codes and requirements, as it is characterised by a clear link to building codes in Spain and the United States.

Lately, in the area of energy efficiency regulation in buildings, there has been a tendency to combine standards limiting certain structural or technical parameters of construction in certain climate zones with standards limiting the maximum allowable EC of buildings. Therefore, in the next chapter, the methodology for optimising the thermal transmittance of dwellings to maintain the maximum permissible level of EC, not only in different geographical locations but also under conditions of future climate change, will be considered.

CHAPTER 6.-

ADAPTATION AND MITIGATION TO CLIMATE CHANGE OF ENVELOPE WALL THERMAL INSULATION OF RESIDENTIAL BUILDINGS IN A TEMPERATE OCEANIC CLIMATE [5]

[5] The results shown in this chapter were presented in: **Verichev, K.**, Zamorano, M., Fuentes-Sepúlveda A., Cárdenas N., and Carpio, M. **Adaptation and mitigation to climate change of envelope wall thermal insulation of residential buildings in a temperate oceanic climate** (2021) *Energy and Buildings* 235 V., 110719

6.1. Introduction

As noted in the previous chapter, there is a trend in the area of building energy efficiency to combine prescriptive building standards with limiting the maximum allowable EC of buildings, e.g., in ECS regulation. Thereby, Walsh *et al.* point out that 36% of the countries analysed have building codes and that in all of them, for different climatic zones, a maximum permitted value of total EC of the house is established (Walsh et al., 2017b). For example, the *"Réglementation Thermique 2012"* in France seeks to limit the consumption of primary energy in new buildings to a maximum of an average of 50 kWh/m²/year (France, 2020). In Finland, the maximum allowed value of total EC for a house depends on its total area; a house of 100 m^2 must have a total EC that does not exceed 140 kWh/m²/year (Finland, 2020).

To achieve these values of total EC, in the building design process, multi-parameter and multi-objective building optimization methodologies can be used. In this sense, one of the most important parameters to minimise and optimise the EC of a building is the correct thermal insulation of the building envelope (Eskin & Tuerkmen, 2008; Ihm & Krarti, 2012; C. Li et al., 2014; D. H. W. Li et al., 2013; Lollini, Barozzi, Fasano, Meroni, & Zinzi, 2006; L. Yang, Lam, & Tsang, 2008); in fact, various investigations have focused on the optimisation of the thermal insulation and the thermal transmittance of external walls (Perez & Capeluto, 2009; Ucar & Balo, 2009, 2010; L. Wang, Wong Nyuk, & Li, 2007), and more recently, Resalati *et al.* published a methodology for estimating the optimal U-value and thickness of the thermal insulation of external walls based on the total EC of the house as well as on the LCA method of the insulation materials (Resalati, Kendrick, & Hill, 2020). In this case, the optimal U-value and the optimal thickness of the thermal insulation are determined as a function of the minimum of the sum of the embodied carbon of the insulation materials and the building operation carbon.

In the context of global climate change, in recent decades, special attention has been paid to evaluating the effects of increased temperature in the world (IPCC, 2013). Particularlly, in the area of building construction, various scientific works have focused on the analysis of changes in cooling and heating EC in different types of buildings and in different parts of the world. In this sense, energy-optimal values of thermal insulation, found on the basis of current climatic conditions, and the future dynamics of heating and cooling EC of building cannot guarantee the stability of total EC during life cycle of dwelling; this affects the energy ranking of the house because it may not meet the energy requirements of future building standards.

In accordance with the above mentioned, the aim of this chapter is to present a methodology for determining the energetically optimal thermal transmittance and the thickness of the thermal insulation of external walls in single-family dwellings in a temperate oceanic climate through energy simulation to obtain energy stability under conditions of future climate change.

6.2. Material and methods

In the following sections, a description of the study region, the current building codes in the country, the type of studied dwelling, and the methodology used for this study will be presented. Fig. 50 summarises the methodology followed in this chapter.

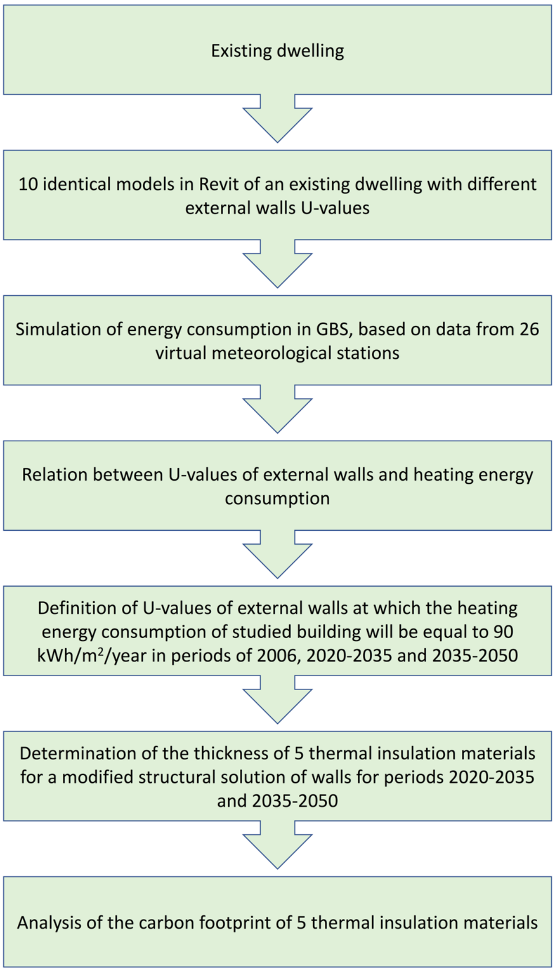


Fig. 50 Methodological structure of the Chapter 6.

6.2.1. Study area

The Los Ríos region was selected for this study. The climatic and geographical description of this region is presented in Chapter 2. Fig. 51b shows the profile of the relief at 40°S latitude. The choice of this area for the study has been motivated by the fact that in this area the cooling/heating of buildings is represented only by heating (Verichev & Carpio, 2018), and this area is characterised by notable climate variability. In addition, this area has a cold climate where in the future there will be a decrease in EC for cooling/heating generated by a decrease in heating EC that will exceed the rate of increase in EC for cooling.

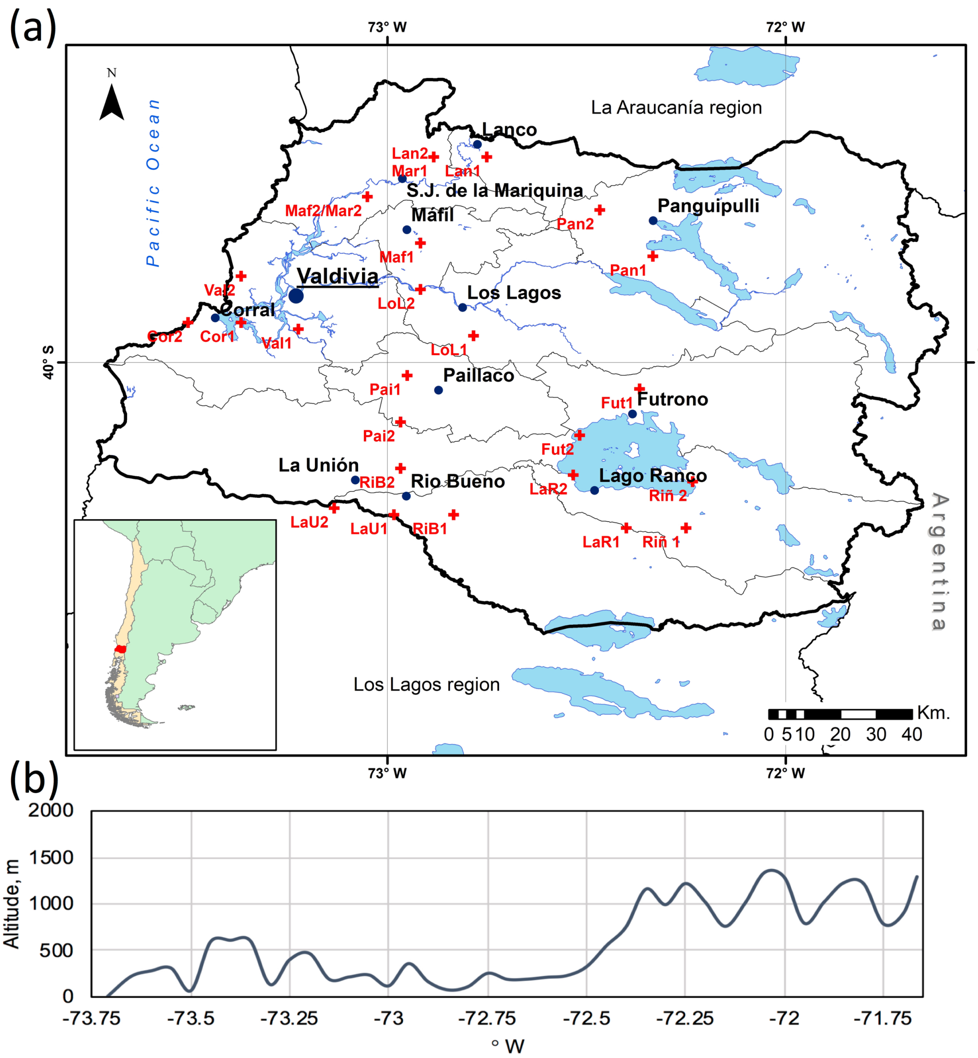


Fig. 51 Geographical location of the study area, main cities in the region and meteorological stations for energy simulation (a) and profile of the relief at 40°S latitude (b).

According to RT OGUC document, part of the coast of the Los Ríos region is located in Thermal zone 5 with an annual HDD15°C value of 1250–1500, while the area of the foothills of the region is located in Thermal zone 6, with an annual HDD15°C value of 1500–2000. On the other hand, in ECS terms, the Los Ríos region is located in two thermal zones: G and F (Fig. 11). Table 7 and Table 8 summarises the maximum U-values required for RT OGUC and ECS in the indicated thermal zones depending on the reference document; differences between RT OGUC and ECS can be observed. For example, floors have the same value in Thermal zone 6 of RT OGUC and in zone G of ECS; they also have the same value in Thermal zone 5 of RT OGUC and zone F of ECS. For roofs, the ECS zones have a U-value equal to the coldest RT OGUC zone 6, but for external walls the ECS standard is more stringent than the RT OGUC. The RT OGUC makes it possible to use monolithic glass windows in the climatic conditions of the study region; furthermore, the total percentage of glazing is limited in such a way that it sets a maximum glazed area regarding the vertical faces of the thermal envelope, which depends on the type of window and its U-values. The ECS, however, establishes a maximum permitted percentage of glazing depending on the orientation of the house, and it incorporates thermal transmittance requirements for doors that do not exist in the RT OGUC.

6.2.2. Case study and existing house

In this phase of study, a pilot house already described in Chapter 3 has been used (Fig. 17) and which component materials of the construction solution of the external walls have been described in Table 35. The structural system is made of timber, based on 41x90 mm uprights, with a distance between them of 40 cm, of lingue wood (*Persea lingue*), with fibre cement siding on the outer face and with an oriented strand board (OSB) and a plate of extra-resistant gypsum board on the inside; in the interior cavities and between uprights, a glass wool insulation is considered. Table 36 summarizes the thermal transmittance of the structural elements of the house used for 3D modelling and for energy simulation, showing that the house fully complies with the construction requirements set in the RT OGUC for Thermal zone 5, corresponding to the study zone; however, in the case of ECS, the house does not meet the recommendations for roof, external walls, and allowable thermal transmittance for windows.

Table 35 Structural solution of the external walls of the existing house.

Insulation:				
	Thickness, [m]	λ (Chile, 2006b, 2018c), [W/mK]	R_t (Chile, 2006b, 2007, 2018c), [m^2K/W]	U_{insul}, [W/m^2K]
Fibre cement siding 920 kg/m^3	0.0060	0.22	0.0273	
OSB 690 kg/m^3	0.0111	0.12	0.0925	
Glass wool 11kg/m^3	0.0600	0.0424	1.4151	
Non-ventilated air chamber	0.0300		0.0165	
Gypsum board 650 kg/m^3	0.0150	0.24	0.0625	
Σ	0.1221		1.7624	0.567
Frame:				
	Thickness, [m]	λ (Chile, 2006b, 2018c), [W/mK]	R_t (Chile, 2006b, 2018c), [m^2K/W]	U_{frame}, [W/m^2K]
Fibre cement siding 920 kg/m^3	0.0060	0.22	0.0273	
OSB 690 kg/m^3	0.0111	0.12	0.0925	
Lingue wood 640 kg/m^3	0.0900	0.136	0.6618	
Gypsum board 650 kg/m^3	0.0150	0.24	0.0625	
Σ	0.1221		0.8441	1.185

$U_{tot}= U_{insul.}·0.9+U_{frame}·0.1=0.629$

Table 36 Thermal transmittance of existing dwelling structural elements and compliance with standards for thermal zones of RT OGUC and ECS.

Structural elements	Modelling	Compliance to RT OGUC (Table 7)		Compliance to ECS (Table 8)	
		Zone 5	Zone 6	Zone F	Zone G
Roof – U [$W/m^2·K$]	0.329	Yes	No	No	No
Walls – U [$W/m^2·K$]	0.629	Yes	Yes	No	No
Floors – U [$W/m^2·K$]	0.266	Yes	Yes	Yes	Yes
Doors – U [$W/m^2·K$]	1.060	N/A	N/A	Yes	Yes
Hermetically double-glazed windows – U [$W/m^2·K$]	3.160	Yes	Yes	No	No
Maximum glazed surface with respect to vertical thermal envelope [%]	16	Yes	Yes	Yes	Yes

6.2.3. Parameters for energy simulation

This chapter focuses on finding the optimal thickness of insulation for external walls, in terms of meeting the requirements for EC; therefore, the other elements of the building including in Table 36 will not be subjected to changes. To study the effect of the thermal transmittance of the external walls on the heating EC, energy simulations of the same house were implemented with 10 different values of the thermal transmittance of the walls (0.5137 W/m^2K; 0.5023 W/m^2K; 0.4483 W/m^2K; 0.373 W/m^2K; 0.2915 W/m^2K; 0.2385 W/m^2K; 0.2018 W/m^2K; 0.1749 W/m^2K; 0.1544 W/m^2K; 0.1381 W/m^2K). In other words, there are 10 identical houses, but with different U-values of walls.

The 3D modelling of these houses was carried out following the BIM methodology through Revit software (AUTODESK, 2020b) and energy simulations were executed using GBS (AUTODESK, 2020a). To do that, two GBS virtual weather stations were selected for being close to the main cities of the study region and with a minimum and maximum value of HDD18.3°C (Table 37). A description of the GBS meteorological data and their comparison with real meteorological data for the study region is provided in the Chapter 3 and, in addition, in the mountain range area, two more stations were selected (Riñ1 and Riñ2). To find a relationship between the U-value of the external walls and the amount of heating energy consumed by the house, the energy simulations were carried out 10 times in each of the 26 meteorological stations (Table 37 and Fig. 51a); to do that, in which at each geographical point a certain equal value of heating EC (90 kWh/m^2/year) was chosen to demonstrate the methodology. The detailed methodology for the energy simulation, the technical characteristics of the HVAC system and the house´s occupancy schedule is described in a previously Chapter 3.

Table 37 GBS virtual weather stations where energy simulation was performed.

ID	Alt. [m]	Lat.	Lon.	HDD18.3°C*
Val1	180	-39.9167	-73.2233	2602
Val2	104	-39.7833	-73.3667	2449
Cor1	174	-39.9000	-73.3667	2556
Cor2	44	-39.7833	-73.5000	2355
Pal1	275	-40.0333	-72.9500	2829
Pal2	232	-40.1500	-72.9667	2790
LaU1	100	-40.3833	-72.9833	2727
LaU2	110	-40.3667	-73.1333	2684
LaR1	657	-40.4167	-72.4000	3552
LaR2	277	-40.2833	-72.5333	2963
Lan1	234	-39.4833	-72.7500	2718
Lan2	168	-39.4833	-72.8833	2586
LoL1	213	-39.9333	-72.7833	2819
LoL2	171	-39.8167	-72.9167	2674
Maf1	101	-39.7000	-72.9167	2586
Maf2	88	-39.5833	-73.0500	2486
Mar1	168	-39.4833	-72.8833	2586
Mar2	88	-39.5833	-73.0500	2486
Pan1	434	-39.7333	-72.3333	3202
Pan2	309	-39.6167	-72.4667	2975
RiB1	132	-40.3833	-72.8333	2857
RiB2	149	-40.2667	-72.9667	2727
Fut1	571	-40.0667	-72.3667	3338
Fut2	225	-40.1833	-72.5167	2854
Riñ1	803	-40.4167	-72.2500	3800
Riñ2	462	-40.3000	-72.2333	3246

*Calculated with ASHRAE method

6.2.4. Energetically optimal thermal envelope of walls in the future

To carry out the estimation of the energetically optimal envelope of the house in the future, the following study stages have been followed: (i) determination of the optimal U-value of external walls for future periods, (ii) determination of the optimal thickness of 5 types of thermal insulators and (iii) evaluation of the carbon footprint of thermal insulators. The procedure used in each of the indicated phases is described below.

6.2.4.1. Determination of the optimal U-value of external walls for future periods

If national building regulations establish for the future the maximum limit allowed for the EC of a house for heating, the effect of global climate change must be considered. Therefore, the results of the previous Chapter 3, which determined the percentage value by which the heating EC of the house under study will decrease under the conditions of climate change based on two scenarios (RCP2.6 and RCP8.5) for future periods, were used. Table 38 shows average values (between scenarios RCP2.6 and RCP8.5) of the decrease in heating EC of the house in the main cities of the study area.

Table 38 Estimated percentage decrease in energy consumption (average between RCP2.6 and RCP8.5 projections) according to Chapter 3 and reference values for heating EC.

ID	Decrease in energy consumption for heating compared to 2006, [%]		Reference value of heating energy consumption to define optimal U-value, [kWh/m^2/year]	
	2020-2035	2035-2050	2020-2035	2035-2050
Val1	10.5	15.5	100.6	106.5
Val2	10.5	15.5	100.6	106.5
Cor1	10.5	16.0	100.6	107.1
Cor2	10.5	16.0	100.6	107.1
Pal1	9.5	14.5	99.4	105.3
Pal2	9.5	14.5	99.4	105.3
LaU1	10.0	15.0	100.0	105.9
LaU2	10.0	15.0	100.0	105.9
LaR1	9.0	14.0	98.9	104.7
LaR2	9.0	14.0	98.9	104.7
Lan1	10.0	15.5	100.0	106.5
Lan2	10.0	15.5	100.0	106.5
LoL1	9.5	14.5	99.4	105.3
LoL2	9.5	14.5	99.4	105.3
Maf1	10.5	15.5	100.6	106.5
Maf2	10.5	15.5	100.6	106.5
Mar1	10.5	15.5	100.6	106.5
Mar2	10.5	15.5	100.6	106.5
Pan1	9.0	13.5	98.9	104.0
Pan2	9.0	13.5	98.9	104.0
RiB1	10.0	14.5	100.0	105.3
RiB2	10.0	14.5	100.0	105.3
Fut1	9.0	13.0	98.9	103.4
Fut2	9.0	13.0	98.9	103.4
Riñ1	9.0	14.8	98.9	105.6
Riñ2	9.0	14.8	98.9	105.6

For the period 2020–2035 it was shown that the heating EC will decrease between 9 and 10.5%, depending on the geographical location of the meteorological stations, compared to 2006. For the period 2035–50, the decrease will be between 13.5 and 16%. To demonstrate the methodology of this chapter, it is necessary that houses in future periods have a heating EC equal to or less than 90 kWh/m^2/year. For example, for Val1, if an optimal U-value for external walls, determined for 2006 and corresponding to a heating EC of 90 kWh/m^2/year, is used, it would follow that, according to Table 38, in the period 2035–2050, the heating EC would be 76 kWh/m^2/year, corresponding to a reduction of 15.5% compared to 2006. For this reason, an optimal U-value of 106.5 kWh/m^2/year for the year 2006 should be used for a consumption reference point (Table 38), since in the period of interest (2035–2050) the EC will decrease by 15.5%, reaching 90 kWh/m^2/year, the maximum permitted value. Thus, the search for optimal U-values of external walls was implemented such that the house had a heating EC of 90 kWh/m^2/year during two future periods of time in different areas of the Los Ríos region.

6.2.4.2. Determination of the optimal insulation thickness for future periods

Once the optimal U-values for the future were determined, the optimal thicknesses of 5 different types of thermal insulation for external walls were explored. To carry out this phase of the research, two modifications were made to the construction solutions (Table 35) of the external walls of the existing house: (i) lingue wood was replaced by a more popular, accessible and economical type of timber, insigne pine (41x90mm) of $\lambda = 0.104$ W/mK and $\rho = 410$ kg/m^3 and (ii) gypsum board of $\rho = 650$ kg/m^3 was replaced by gypsum board of $\lambda = 0.31$ W/mK and $\rho = 870$ kg/m^3, while the total thickness of the external walls remained unchanged (Table 39 compared to Table 35). These modifications were made because the existing house was built with timber that is not usually used in construction practices in Chile. The insigne pine wood frame and the highest density gypsum board in the structure of the external wall correspond to a structural solution recommended by the *Corporación Chilena de la Madera* (CORMA) (Chilean Wood Corporation) (Chile, 2020a).

The thermal insulators that were analysed are (i) glass wool ($\lambda = 0.042$ W/mK; $\rho = 11$ kg/m^3), which was used in the existing house and is inorganic and recyclable; (ii) expanded polyurethane ($\lambda = 0.025$ W/mK; $\rho = 40$ kg/m^3), a flammable material that, when in contact with fire, releases toxic fumes, making it dangerous in the event of a fire, in addition to releasing greenhouse gases and containing non-renewable fossil fuel derivatives (CChC, 2015); (iii) cork ($\lambda = 0.039$ W/mK; $\rho = 40$ kg/m^3), an organic, biodegradable and waterproof material that does not produce toxic gases in the event of fire; (iv) rockwool ($\lambda = 0.040$ W/mK; $\rho = 100$ kg/m^3), an inorganic and recyclable material; and (v) sheep wool ($\lambda = 0.040$ W/mK; $\rho = 25$ kg/m^3), an organic material that is biodegradable, sustainable and permeable to water vapour and which does not emit any type of irritating or harmful particle during its handling and use.

Table 39 Structural solution for external walls for restoration of optimal insulation thickness.

Insulation:				
	Thickness, [m]	λ (Chile, 2006b, 2018c), [W/mK]	R_t (Chile, 2006b, 2007, 2018c), [m²K/W]	U_{insul}, [W/m²K]
Fibre cement siding 920 kg/m³	0.0060	0.22	0.0273	
OSB 690 kg/m³	0.0111	0.12	0.0925	
Thermal insulator	x_1	x_2	x_3	
Not ventilated air chamber	y_1		y_2	
Gypsum board 870 kg/m³	0.0150	0.31	0.0484	
∑	0.1221		–	–
Frame:				
	Thickness, [m]	λ(Chile, 2006b, 2018c), [W/mK]	R_t (Chile, 2006b, 2018c), [m²K/W]	U_{frame}, [W/m²K]
Fibre cement siding 920 kg/m³	0.0060	0.22	0.0273	
OSB 690 kg/m³	0.0111	0.12	0.0925	
Insigne pine wood 410 kg/m³	0.0900	0.104	0.8654	
Gypsum board 870 kg/m³	0.0150	0.31	0.0484	
∑	0.1221		1.0336	0.965

$U_{tot} = U_{insul.} \cdot 0.9 + U_{frame} \cdot 0.1$

Glass wool insulation fully corresponds to a solution recommended by CORMA (Chile, 2020a) and complies with all Chilean building and fire safety standards (Chile, 2020b). In addition, the construction solutions of external walls contain a non-ventilated air chamber. According to the Chilean standard, NCh853 (Chile, 2007), the correspondence between the thickness of the air chamber with horizontal thermal flow (y_1 in Table 39) and the value of R_t (y_2 in Table 39) should be as follows: 5 mm – 0.105 m²K/W; 10 mm – 0.140 m²K/W; 15 mm – 0.155 m²K/W; 20-100 mm – 0.165 m²K/W. Taking this into account for each optimal U-value of the external walls, optimal thicknesses of thermal insulators were calculated (x_1 in Table 39).

6.2.4.3. Estimation of carbon footprint of the insulation materials

To demonstrate differences in the carbon footprint that will be produced by the use of different types of thermal insulation, carbon footprint values from other investigations were used (Hammond, Jones, Lowrie, & Tse, 2008; Soler, Salandin, & Bevivino, 2020). In these works, the environmental impact of insulation materials was analysed with the "cradle to gate" variant, according to the common LCA with the methodology of ISO 14040:2006 (Hammond et al., 2008; Soler et al., 2020). Carbon footprints for insulation materials were also compared with other studies (Kunič, 2016, 2017). Based on data of carbon footprint values for each insulation material studied (Table 40), an analysis of the environmental benefits of the possible replacement of one wall insulation with another for future periods is presented. The calculation of carbon footprints was carried out in meteorological stations where it is possible to apply the 5 insulators for the construction solution of external walls presented in Table 39. The total surface of insulating external walls in the house under study is 75.3 m^2.

Table 40 Carbon footprints of thermal insulation materials.

Insulation materials	Carbon footprint per mass, [kg CO_2/kg]	Ref.
Glass wool	1.35	(Hammond et al., 2008)
Expanded polyurethane	4.30	(Soler et al., 2020)
Cork	0.60	(Soler et al., 2020)
Rockwool	1.05	(Hammond et al., 2008)
Sheep wool	2.13	(Soler et al., 2020)

6.3. Results and discussion

Considering the work methodology described, first, the results of determining the optimal U-value of external walls are presented and analysed for the periods of the energy simulations. Then, the results of determining the optimal thickness of the 5 types of thermal insulators are presented to finally analyse the results obtained for the evaluation of the carbon footprint of thermal insulators.

6.3.1. Energy simulation and optimal U-value definition

6.3.1.1. Period 2006

First, the simulation results of the heating EC of the house under study will be analysed (Fig. 52). This figure shows the relationship between the heating EC and the U-value of the external walls. A clear linear relationship is observed between the two parameters: The angles of inclination of the lines decreases from the oceanic coast toward the interior of the region due to the continental effect of the climate. Table 41 shows the results of the intercept and slope values of the lines that describe the relationship between the value of heating EC and the U-value of the external walls of the house in all meteorological stations selected for this study.

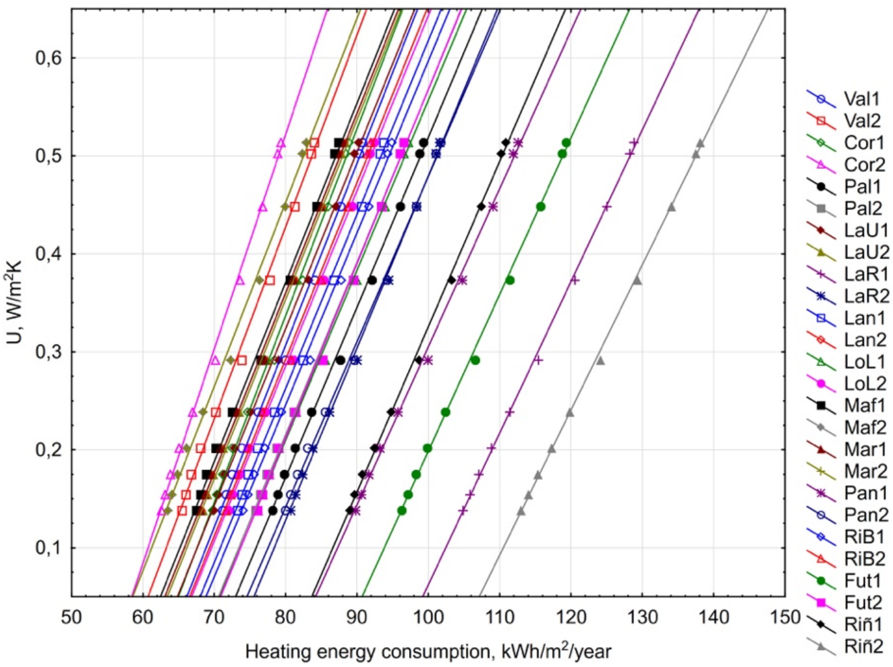


Fig. 52 Linear relationship between the U-value of external walls and the heating energy consumption of the studied house in different meteorological stations.

Using the formulas obtained for each meteorological station, the optimal U-values of the external walls were calculated such that the simulated house has a heating EC of 90 kWh/m²/year, as shown in Table 41.

Table 41 Intercepts and slopes values for lineal relationships of Fig. 52

	Intercept		Slope					
ID	Value	St. error	Value	St. error	R^2	HDD18.3°C	Energy consumption interval [kWh/m²/year]	Optimum U-value 2006, [W/m²K]
Val1	-1.17348	0.02822	0.01850	0.00035	0.99670	2602	71-91	0.492
Val2	-1.13632	0.02814	0.01954	0.00038	0.99660	2449	65-84	0.622
Cor1	-1.18471	0.02809	0.01902	0.00036	0.99683	2556	70-89	0.527
Cor2	-1.22447	0.02704	0.02182	0.00038	0.99751	2355	63-79	0.739
Pal1	-1.21293	0.02583	0.01731	0.00029	0.99742	2829	78-99	0.345
Pal2	-1.18904	0.02705	0.01756	0.00032	0.99738	2790	76-97	0.391
LaU1	-1.11602	0.02553	0.01799	0.00032	0.99712	2727	70-90	0.503
LaU2	-1.10940	0.02612	0.01828	0.00034	0.99696	2684	68-88	0.536
LaR1	-1.48548	0.02068	0.01548	0.00018	0.99881	3552	105-129	N/A
LaR2	-1.27305	0.02411	0.01752	0.00027	0.99792	2963	81-102	0.304
Lan1	-1.15458	0.02702	0.01771	0.00033	0.99695	2718	73-94	0.439
Lan2	-1.10122	0.02789	0.01827	0.00036	0.99650	2586	68-88	0.543
LoL1	-1.17528	0.02682	0.01731	0.00031	0.99707	2819	76-97	0.383
LoL2	-1.13972	0.02685	0.01782	0.00033	0.99692	2674	72-92	0.464
Maf1	-1.08682	0.02816	0.01822	0.00037	0.99636	2586	68-87	0.553
Maf2	-1.04525	0.02845	0.01871	0.00039	0.99605	2486	64-83	0.639
Mar1	-1.10122	0.02789	0.01827	0.00036	0.99650	2586	68-88	0.543
Mar2	-1.04525	0.02845	0.01871	0.00039	0.99605	2486	64-83	0.639
Pan1	-1.30618	0.02536	0.01611	0.00025	0.99779	3202	90-113	0.144
Pan2	-1.20451	0.02510	0.01683	0.00028	0.99753	2975	80-102	0.310
RiB1	-1.15542	0.02653	0.01752	0.00032	0.99706	2857	74-95	0.421
RiB2	-1.14688	0.02567	0.01799	0.00032	0.99721	2727	72-92	0.472
Fut1	-1.39861	0.02497	0.01597	0.00023	0.99808	3338	96-119	N/A
Fut2	-1.20909	0.02464	0.01776	0.00029	0.99764	2854	76-97	0.389
Riñ1	-1.35835	0.02397	0.01684	0.00024	0.99814	3246	89-111	0.157
Riñ2	-1.53583	0.02042	0.01480	0.00016	0.99890	3800	113-138	N/A

It can be seen that in the stations where the formula was found for heating EC values greater than 90 kWh/m^2/year, it is impossible to find an optimal U-value (stations with a value of HDD18.3°C >3300). This is because the relationship between the U-value and the energy for heating acquires a non-linear dependence. In these stations, the house would need a change in the construction solution for external walls as well as improvements in other construction elements or the installation of more efficient HVAC systems. For example, in the case of Riñ2 and other geographic points with excessive EC, it is possible to improve the SCOP of the HVAC system to achieve the desired level of EC of the house under study. In addition, consideration should be given to replacing the original HVAC system with one that is more efficient in terms of the technological progress expected in the future. But, in present research, this type of approach will not be considered because of the scope of the study. This improvement may be considered in future studies.

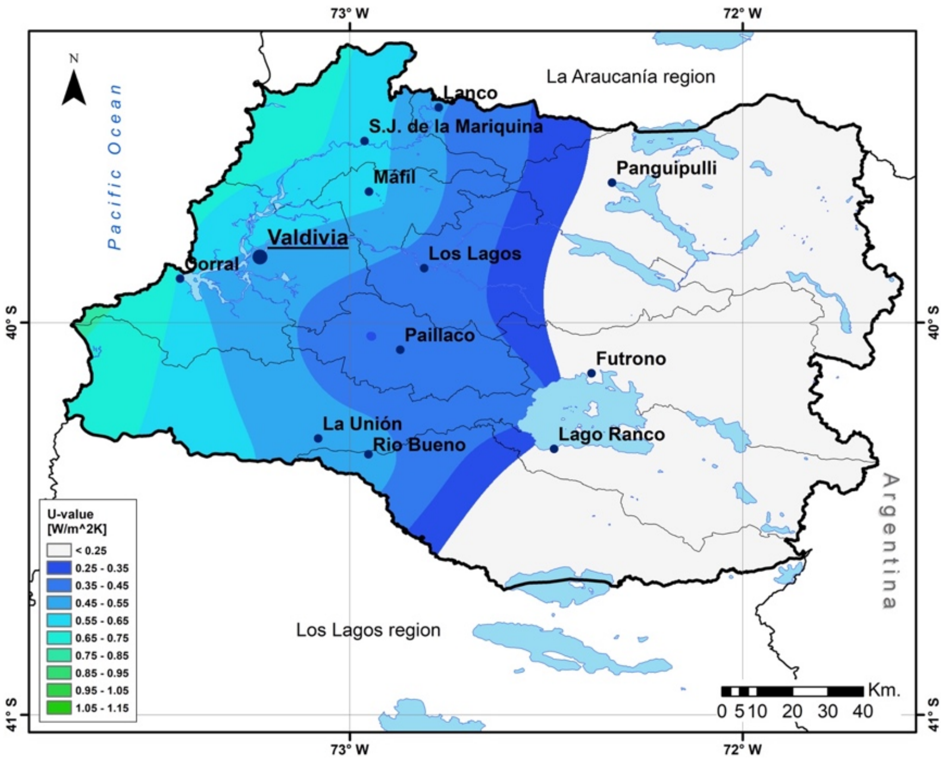


Fig. 53 Optimal U-value of external walls of the house under study with a heating energy consumption of 90 kWh/m^2/year in 2006.

Next, the spatial distribution of the optimal U-value in the region for the study dwelling was considered. Fig. 53 shows the map of the distribution of this parameter, showing that when moving away from the ocean coast, the optimal U-value decreases, reaching its minimum in the mountain range. For example, the U-value should be equal to 0.65 W/m^{2}K if the house is located in the city of Corral and approximately 0.40 W/m^{2}K if the house is located in the city of Paillaco if the energy costs for heating are to reach 90 kWh/m^2/year without any change to construction systems in the dwelling or HVAC systems. Such spatial distribution of the U-value for external walls is not in accordance with the recommendations proposed by the ECS. In this building standard, the most stringent construction recommendations for thermal transmittance are the characteristics of Thermal zone G, located on the ocean coast (Fig. 11 and Table 8). In other words, the ECS contains a climate logic mismatch in building zoning in the study region.

6.3.1.2. Future periods

Table 42 shows the optimal U-values for the external walls of the dwelling under study for different geographical points of the analysed region and Fig. 54 presents the optimal U-value maps, in which the dwelling under study will have a heating EC equal to 90 kWh/m^2/year in the two future periods.

Table 42 Optimal U-value of external walls of the house under study for future periods in the different meteorological stations.

ID	Optimum U-value, [W/m^{2}K] 2020-2035	2035-2050
Val1	0.687	0.797
Val2	0.829	0.945
Cor1	0.728	0.853
Cor2	0.970	1.113
Pal1	0.509	0.609
Pal2	0.557	0.659
LaU1	0.683	0.789
LaU2	0.719	0.826
LaR1	N/A	N/A
LaR2	0.460	0.560
Lan1	0.616	0.732
Lan2	0.726	0.845
LoL1	0.546	0.647
LoL2	0.632	0.736
Maf1	0.745	0.854
Maf2	0.836	0.948
Mar1	0.736	0.845
Mar2	0.836	0.948
Pan1	0.287	0.370
Pan2	0.460	0.547
RiB1	0.597	0.689
RiB2	0.652	0.747
Fut1	N/A	N/A
Fut2	0.547	0.628
Riñ1	0.307	0.419
Riñ2	N/A	N/A

For example, for the city of Lago Ranco, in the period 2020–2035, the optimal U-value of the external walls is equal to 0.30 W/m^{2}K (Fig. 54a), and for the period 2035–2050 (Fig. 54b) this value is 0.39 W/m^{2}K. The consideration of one of these values when implementing a project will help to maintain the average level of heating EC in the house in accordance with the building codes recommendations for future periods . If the optimal U-value of the current period is used (Table 41), it can cause an excessive use of thermal insulating materials in the project realisation stage. This means that each year in the future, there will be a decrease in the value of heating EC, which can change the energy rating of the house.

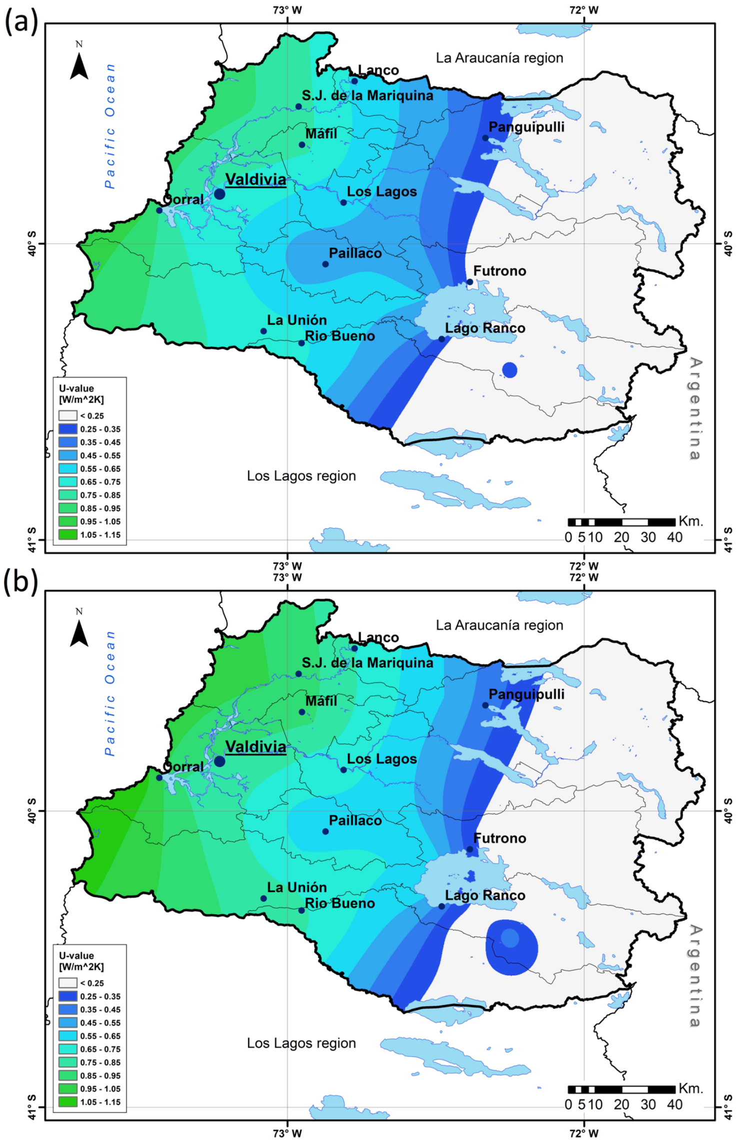


Fig. 54 Optimal U-value of external walls of studied house with a heating energy consumption of 90 kWh/m²/year in the future periods of 2020–2035 (a) and 2035–2050 (b).

In any case, whether it is a positive or negative change in the energy rating of a building, the problem of considering changes in EC for heating and cooling under future climate conditions arises. Therefore, this problem needs a more detailed study applied in different parts of the world (X. Wang, Chen, & Ren, 2011).

Additionally, it can be noted that the methodology presented can have a practical application for clients, construction companies, public administrations, users, and so forth. Having only one housing model and only needing to transform the construction solutions of the external walls can make it energy efficient, in terms of national building recommendations, in the context of climate change and for a wide geographic area. This is a good example of the possibility of optimising the production, prefabrication and implementation of construction projects. Next, it will be shown how to get from an optimal U-value to the optimal thickness of the thermal insulation of a specific construction solution for external walls of houses.

6.3.2. Optimal insulation thickness in future periods

Table 43 provides the optimal thicknesses for the 5 thermal insulation materials in the weather stations and for the two future periods for the construction solution with 41x90 mm insigne pine wood frame. In the case of the use of glass wool, the minimum U-value of walls should be 0.492 W/m^{2}K (Table 39) when it is possible to use it as an insulator (8.5 cm thick) and maintain the energy performance of the dwelling. For this reason, in the period of 2006, the use of glass wool was possible only in 11 of the 26 geographical locations (Table 41); however, as can be seen in Table 43, for the two future periods 2020–2035 and 2035–2050 it will already be possible to use glass wool in 19 and 22 geographical locations, respectively (without changing the timber frame). In addition, for the LaR2 and Pan2 stations in the 2020–2035 period, there is the possibility of using glass wool if the 41x90 mm insigne pine frame is replaced by a 41x114 mm frame (use recommended by CORMA).

Table 43 Insulation thickness (x_1) for the construction solution of external walls with timber frame 41x90mm (Table 39).

ID	2020-2035 Glass wool (λ=0.0424 W/mK; ρ=11kg/m³), e [m]	2020-2035 Expanded Polyurethane (λ=0.025 W/mK; ρ=40kg/m³), e [m]	2020-2035 Cork (λ=0.039 W/mK; ρ=40kg/m³), e [m]	2020-2035 Rock/sheep wool (λ=0.040 W/mK; ρ=100/25 kg/m³), e [m]	2035-2050 Glass wool (λ=0.0424 W/mK; ρ=11kg/m³), e [m]	2035-2050 Expanded Polyurethane (λ=0.025 W/mK; ρ=40kg/m³), e [m]	2035-2050 Cork (λ=0.039 W/mK; ρ=40kg/m³), e [m]	2035-2050 Rock/sheep wool (λ=0.040 W/mK; ρ=100/25 kg/m³), e [m]
Val1	0.051	0.030	0.046	0.048	0.040	0.024	0.037	0.038
Val2	0.038	0.022	0.035	0.036	0.031	0.018	0.028	0.029
Cor1	0.046	0.027	0.043	0.044	0.036	0.021	0.033	0.034
Cor2	0.030	0.017	0.027	0.028	0.023	0.014	0.022	0.022
Pai1	0.080	0.046	0.072	0.074	0.060	0.036	0.056	0.057
Pai2	0.069	0.041	0.063	0.065	0.054	0.032	0.049	0.051
LaU1	0.051	0.030	0.047	0.048	0.041	0.024	0.038	0.039
LaU2	0.047	0.028	0.043	0.045	0.038	0.023	0.035	0.036
LaR1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LaR2	mod[1]	0.054	0.086	0.086	0.068	0.040	0.063	0.064
Lan1	0.059	0.035	0.055	0.056	0.046	0.027	0.042	0.043
Lan2	0.047	0.027	0.043	0.044	0.037	0.022	0.034	0.035
LoL1	0.071	0.042	0.065	0.067	0.055	0.033	0.051	0.052
LoL2	0.057	0.034	0.053	0.054	0.046	0.027	0.042	0.043
Maf1	0.045	0.026	0.041	0.042	0.036	0.021	0.033	0.034
Maf2	0.037	0.022	0.034	0.035	0.031	0.018	0.028	0.029
Mar1	0.046	0.027	0.042	0.043	0.037	0.022	0.034	0.035
Mar2	0.037	0.022	0.034	0.035	0.031	0.018	0.028	0.029
Pan1	N/A	mod.[3]	N/A	N/A	mod.[5]	0.074	mod.[8]	mod.[10]
Pan2	mod[2]	0.054	0.086	0.088	0.071	0.042	0.065	0.067
RiB1	0.062	0.037	0.057	0.059	0.050	0.030	0.046	0.047
RiB2	0.055	0.032	0.050	0.051	0.045	0.026	0.041	0.042
Fut1	N/A	N/A	N/A	N/A	N/A	mod.[7]	N/A	N/A
Fut2	0.071	0.042	0.065	0.067	0.058	0.034	0.053	0.055
Riñ1	N/A	mod.[4]	N/A	N/A	mod.[6]	0.061	mod.[9]	mod.[11]
Riñ2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

2020-2035: [1] LaR2 – 41x114mm timber frame with e=0.086 m of glass wool. [2] Pan2 – 41x114mm timber frame with e=0.086 m of glass wool. [3] Pan1 – 41x114mm timber frame with e=0.100 m of expanded polyurethane. [4] Riñ1 – 41x114mm timber frame with e=0.090 m of expanded polyurethane.
2035-2050: [5] Pan1– 35x124mm timber frame with e=0.115 m f glass wool. [6] Riñ1 – 41x114mm timber frame with e=0.098 m de of glass wool. [7] Fut1 – 35x124mm timber frame with e=0.118 m of expanded polyurethane. [8] Pan1 – 41x114mm timber frame with e=0.108 m of cork. [9] Riñ1– 41x114mm timber frame with e=0.090 m of cork.[10] Pan1– 35x124mm timber frame with e=0.108 m of rock/sheep wool. [11] Riñ1– 41x114mm timber frame with e=0.092 m of rock/sheep wool.

Also, for the period 2035–2050, there is the possibility of using this type of insulation in the Riñ1 station with the same replacement of the timber frame. It was decided to show, using a cartographic method, the spatial distribution of the recommended optimal glass wool thickness values for the construction solution for external walls (Table 43). Fig. 55 presents the maps with the glass wool thickness that will guarantee a heating EC of the house studied of 90 kWh/m^2/year for the two future periods. A clear increase in the thickness of the thermal insulation can be observed by moving from the ocean coast to the interior of the region and to the mountain range. In addition, the geographical area of the possible application of the proposed construction solution (Table 39) of using glass wool as an insulator will increase in the period 2035–2050 (Fig. 55b) compared to the period 2020–2035 (Fig. 55a).

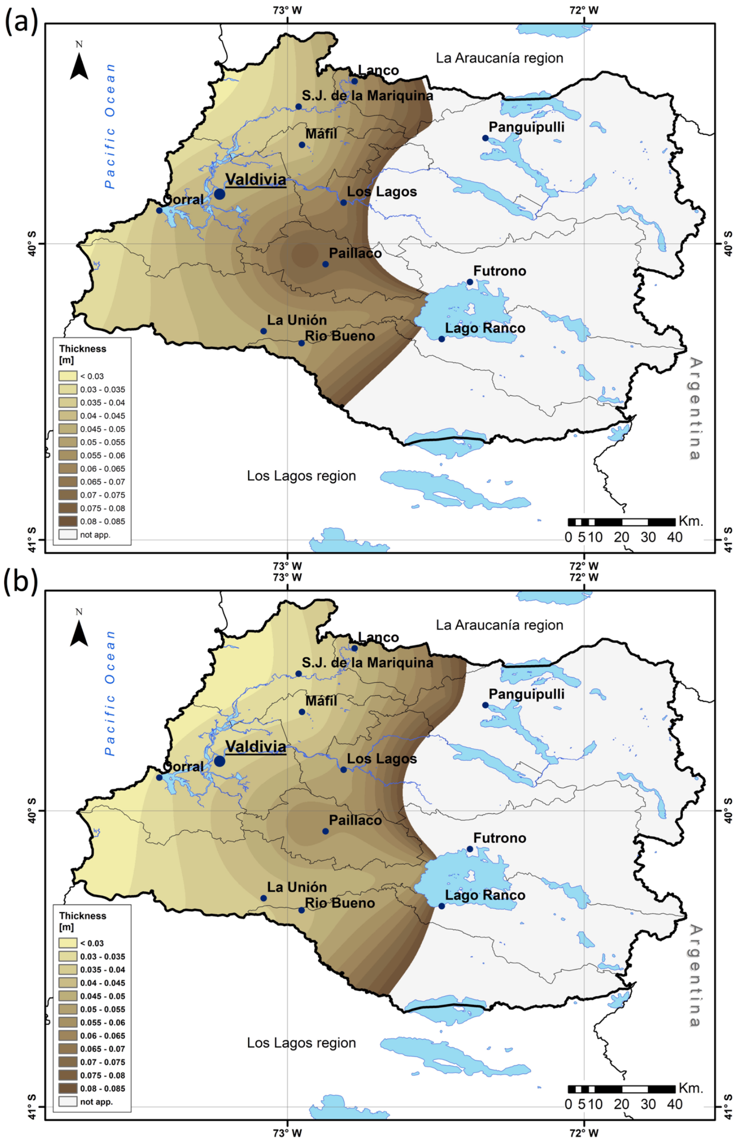


Fig. 55 Optimum thickness of glass wool insulation for the periods 2020–2035 (a) and 2035–2050 (b).

Due to its low value of thermal conductivity (0.025 W/mK) compared to glass wool, the use of expanded polyurethane as a thermal insulator for external walls (Table 43) will allow the application of the proposed construction solution for external walls with a 41x90 mm timber frame in the LaR2 and Pan2 stations in the 2020–2035 period and at Pan1 and Riñ1 stations in the 2035–2050 period. In this way, the replacement of insulation material will help to increase the geographical area of application of the construction solution for the external walls (Table 39). In addition, the geographical area could be further increased by replacing the timber frame with frames with larger dimensions, such as 41x114 mm or 41x124 mm. Finally, cork, rockwool, and sheep wool have thermal conductivities similar to glass wool. For this reason, there is not a great difference in the thickness values of these materials (Table 43), although there is in their environmental impact due to their diverse nature, so they will be analysed in the next section.

Finally, it should be noted that in the case of methodologies in which the insulation of the building envelope is improved and the HVAC system is replaced by a more efficient one in climates where heating prevails (Ismailos & Touchie, 2017), the expected climate changes should be considered.

6.3.3. Carbon footprint of the insulation materials

The materials studied as insulation can be classified into three groups: (i) those of an organic nature, such as cork and sheep wool, characterised by being biodegradable, sustainable and not emitting any type of irritating or harmful particle during handling, use or in case fire; (ii) those of an inorganic nature, recyclable and non-flammable, which include fiberglass and rockwool; and (iii) expanded polyurethane, of inorganic and flammable nature, with toxic emissions in case of fire and release of greenhouse gases since it is manufactured with fossil fuels.

The use of each material will depend on the environmental responsibility of both the client and the construction company or construction agent that carries out the building (CChC, 2015). The carbon footprint of each material will be analysed below (until the end of the production stage) according to the LCA and assuming that the house in the study is built in different geographical locations in the region. For this, the values of the estimates of the carbon footprint of insulating materials from current investigations, such as those of Soler *et al.* (Soler et al., 2020), are used. In the research of Resalati *et al.* the results of the evaluation of embodied carbon footprints in houses are shown but have great uncertainty (Resalati et al., 2020). These uncertainties depend on many factors and difficulties in carbon footprint estimation methodologies. Among these factors, there is one to determine in which life cycle stage the carbon footprint was evaluated – “cradle to gate,” “cradle to gate with options” or “cradle to grave.” Consequently, quantitative estimates of the carbon footprint are debatable results; however, percentage changes between time periods in the future can be considered sufficiently reliable results.

Table 44 shows the results of the calculation of the carbon footprint of the use of each material as thermal insulation for the proposed construction solution for external walls with a 41x90 mm timber frame. For the period 2020–2035, the average carbon footprint of glass wool insulation is 59 kg CO_2, the lowest carbon footprint of the materials studied. Replacing this material with rockwool would increase the average carbon footprint 6.7 times, while if materials of an organic nature are used this increase is 1.5 and 3.4 times for cork and sheep wool, respectively. In the case where the design of the house is made with a projection to the period 2035–2050, it is possible to minimise the carbon footprint of the materials used as thermal insulation by an average of 20% compared to the period 2020–2035. It was also noted that in order to expand the geographical area of application of external walls with a wooden frame of 41x90 mm, it is possible to replace glass wool with expanded polyurethane. Table 44 shows that the carbon footprint of expanded polyurethane is, on average, 6.8 times greater than the carbon footprint of glass wool. For this reason, it is advisable to apply the change of wooden frame as in the LaR2 and Pan2 stations for the period 2020–2035 (Table 43).

Table 44 Carbon footprints [kg CO_2] of thermal insulation materials applied for housing in study and constructive solution of exterior walls (Table 39).

	2020-2035					2035-2050				
ID	Glass wool	Expanded Polyurethane	Cork	Rock wool	Sheep wool	Glass wool	Expanded Polyurethane	Cork	Rock wool	Sheep wool
Val1	57.0	388.5	83.1	379.5	192.5	44.7	310.8	66.9	300.4	152.4
Val2	42.5	284.9	63.3	284.6	144.4	34.7	233.1	50.6	229.3	116.3
Cor1	51.4	349.7	77.7	347.9	176.4	40.3	272.0	59.6	268.8	136.3
Cor2	33.5	220.2	48.8	221.4	112.3	25.7	181.3	39.8	173.9	88.2
Pai1	89.5	595.8	130.1	585.1	296.7	67.1	466.3	101.2	450.7	228.6
Pai2	77.2	531.0	113.9	513.9	260.6	60.4	414.5	88.6	403.2	204.5
LaU1	57.0	388.5	84.9	379.5	192.5	45.8	310.8	68.7	308.4	156.4
LaU2	52.6	362.6	77.7	355.8	180.4	42.5	297.9	63.3	284.6	144.4
Lan1	66.0	453.3	99.4	442.8	224.5	51.4	349.7	75.9	340.0	172.4
Lan2	52.6	349.7	77.7	347.9	176.4	41.4	284.9	61.4	276.7	140.3
LoL1	79.4	544.0	117.5	529.7	268.7	61.5	427.4	92.2	411.1	208.5
LoL2	63.7	440.4	95.8	427.0	216.5	51.4	349.7	75.9	340.0	172.4
Maf1	50.3	336.7	74.1	332.1	168.4	40.3	272.0	59.6	268.8	136.3
Maf2	41.4	284.9	61.4	276.7	140.3	34.7	233.1	50.6	229.3	116.3
Mar1	51.4	349.7	75.9	340.0	172.4	41.4	284.9	61.4	276.7	140.3
Mar2	41.4	284.9	61.4	276.7	140.3	34.7	233.1	50.6	229.3	116.3
RiB1	69.3	479.2	103.0	466.5	236.6	55.9	388.5	83.1	371.6	188.5
RiB2	61.5	414.5	90.4	403.2	204.5	50.3	336.7	74.1	332.1	168.4
Fut2	79.4	544.0	117.5	529.7	268.7	64.9	440.4	95.8	434.9	220.5

It should also be noted that due to the meso- and microclimatic diversity of the study area, it is important for each geographical point to find the optimum thickness of the thermal insulation, because the carbon footprint of the thermal insulation of the walls can be 2.54-2.71 times smaller at the warmest point in the study region (Cor2), compared to the coldest point (Pai1) (Table 44). This will help to implement of climate-responsible construction projects.

Of course, the contribution of thermal insulation to the total life cycle carbon footprint of existing homes in temperate climates is not as significant as, for example, operational energy use. But, in any case, the carbon footprint of all stages of the life cycle of residential houses is 5 times higher than acceptable values (not significant for the climate system). Therefore, any methodology to reduce the carbon footprint is useful for the product, maintenance and replacement stage, which represent up to 25% of the total life cycle carbon footprint of the housing (Chandrakumar, McLaren, Dowdell, & Jaques, 2020).

6.4. Conclusions

In the present chapter, a methodology was presented and implemented to determine the optimal U-value for external walls as well as the thickness of the insulating material through energy simulation in the context of maintaining the energy performance of the house under conditions of climate change. The implementation of this methodology was motivated by the fact that there was no evidence of studies in the scientific literature analysed that address the same set of problems. In the present study, the problem of accounting for information on the expected change in a dwelling's EC in the future in the context of climate change was considered in the process of designing a dwelling. In addition, the need for a locally oriented approach was identified in the search for energetically optimum insulation to optimize the carbon footprint of this material in different geographical locations and under conditions of climate change. The main conclusions reached are summarised below:

- The optimal U-values were determined for the external walls such that the house under study will have a heating EC equal to 90 kWh/m^2/year. The average value for the study region was 0.49±0.11 W/m^{2}K for 2006; 0.67±0.13 W/m^{2}K for the period 2020–2035; and 0.78±0.14 W/m^{2}K for the period 2035–2050.
- It was shown that, considering climatic changes, the geographical area of possible application of glass wool as an insulating material for the studied external wall construction solution is almost doubled for the period 2035–2050 compared to 2006.
- It was demonstrated that with just the replacement of the insulation material, it is possible to increase the geographical area of construction of the studied house model without changes in energy performance.
- In addition, a carbon footprint assessment was carried out on 5 external wall insulation materials, revealing that glass wool has the lowest carbon footprint of all the materials studied. By designing housing from an energy performance perspective with

targets for 2035–2050, the carbon footprint can be reduced by 20% compared to 2020–2035.

- The effects of climate change must be taken into consideration for methodologies where the search of the optimal thickness of the thermal insulation depends on the total carbon emissions, on the building operational carbon emissions or on the EC of the house in the future.

CONCLUSIONES

A continuación se exponen las conclusiones más relevantes obtenidas en esta investigación, que van a ser presentadas, de acuerdo a las obtenidas en las tres partes que componen este documento.

En relación al análisis de las publicaciones más citadas en el campo de la edificación orientadas al clima:

- Se ha demostrado la importancia que tienen las zonas climáticas para la construcción de edificios en múltiples aspectos, particularmente en la eficiencia energética de los edificios.
- Se ha constatado que la correcta definición de las zonas climáticas para la edificación y las adecuadas recomendaciones de construcción para diferentes ubicaciones geográficas permitirán la implementación de viviendas energéticamente eficientes.
- Considerando el aspecto dinámico del clima, se ha argumentado la importancia de tener en cuenta las técnicas de adaptación y mitigación del cambio climático en la edificación.

En relación a la definición de los aspectos clave para establecer la zonificación climática para la edificación en el sur de Chile, se han obtenido las siguientes conclusiones:

- Basándose en datos meteorológicos de alta resolución espacial y simulación de consumo energético de edificios residenciales en el área de estudio, se confirmó la inconsistencia de las zonas térmicas actuales y de los estándares de construcción RT OGUC para la implementación de edificios energéticamente eficientes en las condiciones climáticas actuales y futuras.
- Se ha demostrado la inconsistencia de las zonas térmicas de la ECS para reflejar las realidades meso- y microclimáticas en las regiones de Aysén y Magallanes. Así mismo, se identificó un error en la lógica climatológica en la definicion de las zonas térmicas de la ECS en la región de Los Ríos.
- Durante el proceso de validación de las zonas de edificación actuales y en el proceso de análisis de la posibilidad de utilizar zonas bioclimáticas de Köppen y zonas basadas a la clusterización de cinco parámetros climáticos (HDD, radiación solar global, humedad relativa, precipitación y velocidad del viento), se determinó que los principales

parámetros y características que deben tenerse en cuenta para determinar nuevas zonas climáticas son: HDD, CDD y datos de radiación solar directa.

- Los datos meteorológicos utilizados para la zonificacion deben ser de alta resolución espacial y la metodología de zonificación debe ser reproducible para su actualización y análisis de su dinámica.

Finalmente, para mejorar la eficiencia energética de la edificación en la zona de estudio:

- Se ha propuesto una nueva zonificación climática basada en una metodología reproducible que, además, puede utilizarse para analizar el efecto del dinámismo climático. Esto se ha hecho a partir de la combinación de las metodologías incluidas en el CTE y ASHRAE, siendo aplicable la primera de ellas a las las regiones de La Araucanía, Los Ríos y Los Lagos, en base a los datos de HDD, CDD y duración de la insolación. En el caso de las regiones de Aysén y Magallanes, se utilizó ASHRAE, basada en los parámetros HDD, CDD y precipitaciones.
- Se ha demostrado que las aplicación de las normas de edificación de CTE y ASHRAE en el área de estudio, mejoraría el rendimiento energético de los edificios en comparación con RT OGUC.
- La importancia de tener en cuenta el dinamismo climático se presentó en la metodología de optimización de muros exteriores para la mitigación y adaptación al cambio climático, con el propósito de mantener la estabilidad energética de los edificios y optimizar el efecto ambiental, lo que podría conducir al desarrollo de futuras investigaciones sobre zonas climáticas dinámicas y sobre estándares de construcción dinámicos.

CONCLUSIONS

The following are the most relevant conclusions obtained in this research, which will be presented in accordance with those obtained in the three parts that compose this document.

In relation to the analysis of the most cited publications in the field of climate-oriented building:

- The importance of climate zones for building construction has been demonstrated in many aspects, particularly in the energy efficiency of buildings.
- It has been noted that the correct definition of climate zones for building and appropriate building recommendations for different geographical locations will enable the implementation of energy efficient housing.
- Considering the dynamic aspect of the climate, the importance of considering climate change adaptation and mitigation techniques in buildings has been argued.

In relation to the definition of the key aspects for establishing climate zoning for building in southern Chile, the following conclusions have been drawn:

- Based on high spatial resolution meteorological data and simulated energy consumption of residential buildings in the study area, the inconsistency of current thermal zones and RT OGUC building standards for the implementation of energy efficient buildings under current and future climatic conditions was confirmed.
- The inconsistency of the ECS thermal zones to reflect the meso- and microclimatic realities in the Aysén and Magallanes regions has been demonstrated. Likewise, an error in climatological logic was identified in the definition of the ECS thermal zones in the Los Ríos region.
- During the validation process of the current building zones and in the process of analysing the possibility of using Köppen bioclimatic zones and zones based on the clustering of five climatic parameters (HDD, global solar radiation, relative humidity, precipitation and wind speed), it was determined that the main parameters and characteristics to be addressed in determining new climate zones are: HDD, CDD and direct solar radiation data.
- The meteorological data used for zoning should be of high spatial resolution, and the zoning methodology should be reproducible for updating and dynamics analysis.

Finally, to improve the energy efficiency of buildings in the study area:

- A new climate zoning has been proposed based on a reproducible methodology that can also be used to analyse the effect of climate dynamism. This has been done by combining the methodologies included in the CTE and ASHRAE, with the first one being applicable to the regions of La Araucanía, Los Ríos, and Los Lagos, based on HDD, CDD and insolation duration data. In the case of the Aysén and Magallanes regions, ASHRAE was used, based on the parameters HDD, CDD and precipitation.
- It has been shown that the application of CTE and ASHRAE building standards in the study area would improve the energy performance of buildings compared to RT OGUC.
- The importance of taking climate dynamism into account was presented in the methodology of optimising external walls for climate change mitigation and adaptation, with the aim of maintaining the energy stability of buildings and optimising the environmental effect, which could lead to the development of future research on dynamic climate zones and dynamic building standards.

LÍNEAS FUTURAS DE INVESTIGACIÓN

Del desarrollo de esta investigación se han derivado algunos aspectos los cuales necesitan ser estudiados en profundidad, por lo que se proponen las siguientes líneas futuras de investigación:

- Ampliar la propuesta de zonificación climática al resto de regiones de Chile.
- Analizar la zonificación climática y los códigos de edificación propuestos mediante la simulación del consumo energético de las viviendas representativas del área de estudio.
- Determinar la evolución de las zonas climáticas propuestas en el contexto del cambio climático en períodos de tiempo futuros para proponer zonas climaticas y normativas de construcción dinámicas.
- Establecer otras regiones geográficas del mundo donde, debido a la similitud del clima, será posible aplicar la zonificación climática y los códigos de edificación CTE de España.
- Diseñar soluciones constructivas y configuraciones adaptadas a los estándares propuestos de CTE19 y de ASHRAE de acuerdo con la realidad de la práctica constructiva para área de estudio.

FUTURE LINES OF RESEARCH

From the development of this research, some aspects have been derived which need to be studied in depth, so the following future lines of research are proposed:

- Extend the climate zoning proposal to the rest of the Chilean regions.
- Analyse climate zoning and proposed building codes by simulating the energy consumption of representative dwellings in the study area.
- Determine the evolution of proposed climate zones in the context of climate change in future periods to propose dynamic climate zones and building regulations.
- Establish other geographical regions of the world where, due to the similarity of the climate, it will be possible to apply the Spanish climate zoning and CTE building codes.
- Design construction solutions and configurations adapted to the standards proposed by CTE19 and ASHRAE according to the reality of construction practice for the study area.

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ANNEXES

Table A. 1 Studies of Cluster 1– Mitigation of the effects of UHI and cooling of buildings.

Title	Year	DOI	CIT*	Theme	Type	Building type/Scale	Type of climate-oriented study	Type of climatic zoning	Region/CZ	Principal conclusions
Study on Auto-DR and pre-cooling of commercial buildings with thermal mass in California	2010	10.1016/j.enbuild.2010.01.008	73	ES/ HVAC systems	Simulation with previous validation of field experiment	Commercial buildings	V	Bioclimatic	California (warm climate)	The electrical demand during the peak period was reduced by 15–30% on the auto-demand response event days.
Residential response to critical-peak pricing of electricity: California evidence	2010	10.1016/j.energy.2009.07.022	82	ES/ HVAC systems	Results of a field experiment	3 types of buildings	II	SPP	California, 4 climatic zones	Critical-peak pricing can help to the possibility of achieving a 5% reduction in residential energy consumption.
Peak load reductions: Electric load shifting with mechanical pre-cooling of residential buildings with low thermal mass	2015	10.1016/j.energy.2015.02.011	46	ES/ HVAC systems	Simulation	Residential buildings	I	IECC	12 cities of 12 climate zones of the USA	Pre-cooled strategy can help to shift of 50%-99% of annual peak cooling electricity to off-peak (% depending on climate zone).
A state of the art review of evaporative cooling systems for building applications	2016	10.1016/j.rser.2015.10.066	68	ES/ HVAC systems	Review	–	II	Bioclimatic	–	The evaporative cooling systems have great potential to save energy in hot and arid climatic zones.
Temperature and cooling demand reduction by green-roof types in different climates and urban densities: A co-simulation parametric study	2017	10.1016/j.enbuild.2017.03.066	48	Outdoor thermal comfort/ ES potential	Simulation	Neighbourhood	I	Köppen	16 cities of the world	Cooling demand reduction by 5.2% was observed in hot-arid climate on the hottest day of the year with fully intensive green roofs, and the smallest savings of 0.1% were found with semi-extensive green roofs in a temperate climate.
Temporal and spatial variability of urban heat island and thermal comfort within the Rotterdam agglomeration	2015	10.1016/j.buildenv.2014.08.029	112	Outdoor thermal comfort	Results of the field experiment	City	VII	Urban climate zone	Rotterdam	Urban areas show a larger number of discomfort hours compared to the reference rural area. These results can be related to the much lower wind velocities in urban areas.
Urban form and density as indicators for summertime outdoor ventilation potential: A case study on high-rise housing in Shanghai	2013	10.1016/j.buildenv.2013.08.019	52	Urban planning/ Outdoor thermal comfort	Simulation	City	II	Urban climate zone	Shanghai, China	Increasing the sky view factor by 10% with a finding of the optimal form and location of high-rise buildings, could increase the wind velocity ratio by 7–8% in the urban area and can help to improve outdoor thermal comfort.
A holistic approach to energy efficient building forms	2010	10.1016/j.enbuild.2010.03.013	87	UHI mitigation	Simulation	City	VI	Location	Latitude 48.00°	Residential Solar Block supports strategies for mitigating the UHI through increased airflow between buildings. This effect can be different in different parts of the world.
Modeling impacts of roof reflectivity, integrated photovoltaic panels and green roof systems on sensible heat flux into the urban environment	2011	10.1016/j.buildenv.2011.06.012	97	UHI mitigation	Simulation with previous validation	Roof	I	ASHRAE	6A, 5A, 4C ,4A, 3B, 2A	Simulation of roof heat balance. Replaced black membrane roof by a PV–covered white or a PV-covered green roof can reduce the total sensible flux by 50%.

Table A.1 Studies of Cluster 1– Mitigation of the effects of UHI and cooling of buildings (continued).

Title	Year	DOI	CIT*	Theme	Type	Building type/Scale	Type of climate-oriented study	Type of climatic zoning	Region/CZ	Principal conclusions
Experimental measurements and numerical model for the summer performance assessment of extensive green roofs in a Mediterranean coastal climate	2013	10.1016/j.enbuild.2013.30.054	55	Green roofs/ Potential energy saving	Results of field experiment/ Mathematical model	Roof	IV	Köppen	Mediterranean coastal climate Italy-Agugliano	The roof with dense vegetation has a thermal gain reduction by about 60% compared with the roof with no vegetation.
A model of vegetated exterior facades for evaluation of wall thermal performance	2013	10.1016/j.buildenv.2013.04.027	89	Green façades	Mathematical model and validation	Façade	IV	Location	Chicago	A layer of plants added to a façade can improve its thermal resistance by 0.0–0.7m^2K/W, depending on a range of inputs for wall parameters, climatic zones, and plant characteristics (especially leaf area index).
Monitoring the energy-use effects of cool roofs on California commercial buildings	2005	10.1016/j.enbuild.2004.11.013	78	Cool roofs/ ES	Results of field experiment/ Numerical modelling	Retail store, elementary school, and a four-building cold storage facility	I	California EC	16 climate zones of California	Energy savings with the installation of a cool roof can reach 6–15 kWh/m^2/year; 3–6 kWh/m^2/year and 4.5–7.4 kWh/m^2/year of conditioned area for a retail store, school, and cold storage facility respectively in different climate zones.
Inclusion of cool roofs in nonresidential Title 24 prescriptive requirements	2005	10.1016/S0301-4215(03)00206-4	63	Cool roofs/ ES	Simulation	Non-residential building	I	California EC	16 climate zones of California	Average annual cooling energy savings of approximately 3.2 kWh/m^2 by using cool roofs in California
Numerical simulation of phase change material composite wallboard in a multi-layered building envelope	2013	10.1016/j.enconman.2013.02.003	75	PCM/ ES potential	Numerical modelling	Residential buildings	I	IECC	Minneapolis, Louisville, and Miami (3 zones)	PCM performance highly depends on the weather conditions, emphasising the necessity to choose different PCMs in different climate zones.
Energy saving potential of phase change materials in major Australian cities	2014	10.1016/j.enbuild.2014.04.027	61	PCM/ ES potential	Simulation	Residential buildings	II	Australia BC	8 cities in 6 climate zones of Australia	PCM has the potential to reduce the building energy consumption by 17–23% in Australian cities under cold temperate, mild temperate and warm temperate zones. For each city PCM with an optimum melting point was found.
Simulating the effects of cool roof and PCM (phase change materials) based roof to mitigate UHI (urban heat island) in prominent US cities	2016	10.1016/j.energy.2015.11.082	61	PCM/ UHI mitigation/ ES potential	Simulation	Hospital	I	IECC	7 cities in 7 climate zones of USA	The maximum heat gains flux through the roof was 54% lower for the PCM roof than for the cool roof with different albedo values.
Simulation-based optimisation of PCM melting temperature to improve the energy performance in buildings	2017	10.1016/j.apenergy.2017.05.107	68	PCM/ ES potential	Simulation	Multi-family residential apartment	II	Köppen	57 cities and 19 climate zones	In a house cooling dominant climate the best melting point temperature for PCM (walls and roof) to reduce annual energy consumption is close to a maximum of 26 °C (melting range of 24–28°C), whereas in a house heating dominant climates PCM with a lower melting temperature of 20 °C (melting range of 18–22 °C) gives higher annual energy benefits.

Table A.1 Studies of Cluster 1– Mitigation of the effects of UHI and cooling of buildings (continued).

Title	Year	DOI	CIT *	Theme	Type	Building type/Scale	Type of climate-oriented study	Type of climatic zoning	Region/CZ	Principal conclusions
The economic impact of integrating PCM as passive system in buildings using the Fanger comfort model	2016	10.1016/j.enbuild.2015.12.006	59	PCM/ Thermal comfort/ES potential/ HVAC operational schedules	Simulation	residential and office operational schedules of HVAC system	IV	Köppen	Madrid	Fanger model to control HVAC thermostat operation used in PCM-incorporated buildings. In the Madrid climate zone, PCM with 27 °C achieved higher energy savings in summer (cooling period) whereas PCM with 23 °C was most effective in winter (heating period).
Annual energy analysis of concrete containing phase change materials for building envelopes	2015	10.1016/j.enconman.2015.06.068	42	PCM/ ES	Numerical modelling	Residential building	I	California EC	Climate zone 3 (San Francisco) and 9 (Los Angeles)	The addition of microencapsulated PCM to the walls of the building reduced the cooling load in the mid-size single-family home in San Francisco and Los Angeles by 85% to 100% and 53% to 82%, respectively.
Review of bioclimatic architecture strategies for achieving thermal comfort	2015	10.1016/j.rser.2015.04.095	69	Architectural strategies/ ES potential	Review	–	VII	Bioclimatic	–	Fourteen climate zones were established and recommended according to the possible bioclimatic strategies that would facilitate reductions in energy consumption.
Optimal design of residential building envelope systems in the Kingdom of Saudi Arabia	2015	10.1016/j.enbuild.2014.09.083	58	Envelope/ ES	Simulation	Residential building	III	Location	5 cities in Saudi Arabia	Finding optimal insulation for buildings can reduce energy consumption by up to 47.3%.
Life cycle energy analysis of a residential building with different envelopes and climates in Indian context	2012	10.1016/j.apenergy.2011.05.054	60	Envelope/ CZ/ ES	Simulation	Residential building	I	India BC	India 5 climate zones	Life cycle energy (LCE) savings are significant (10–30%) with the application of optimal insulation to the walls and roof. Maximum LCE savings with insulation are observed for a warm and humid climate and least for moderate climate.
Performance analysis of domestic rainwater harvesting systems under various European climate zones	2012	10.1016/j.resconrec.2012.02.006	52	Rainwater harvest systems/ CZ	Mathematical analysis	–	II	Köppen	46 geographical points in Europe	Optimum domestic rainwater harvesting system design under various precipitation regimes in Europe. The cold and humid temperate zones show the highest water-saving efficiency values.

**August 2020 WOS*

Table A. 2 Studies of Cluster 3 – Combined heating, cooling and power systems.

Title	Year	DOI	CIT*	Theme	Type	Building type	Type of climate-oriented study	Type of climatic zoning	Region/CZ	Principal conclusions
Energy conservation potential, HVAC installations and operational issues in Hellenic airports	2003	10.1016/j.enbuild.2003.09.006	50	Multi-criterial optimisation/ ES	Energy audit/ Simulation	Airports	II	Greece BC	3 climate zones	A set of ES measures is presented for airports, which will not affect thermal comfort and improve IEQ. At the same time, EC will be reduced by 15-35% in airport buildings.
Energy saving in airports by trigeneration. Part I: Assessing economic and technical potential	2006	10.1016/j.applthermaleng.2006.01.019	46	CHCP systems/ ES potential	Mathematical analysis	Airports	III	Location	Milan, Rome, Palermo	Economic and technical criteria are proposed for assessing the feasibility of using the CHCP system at Italian airports. The use of the system is possible throughout the year and in the south of Italy, the ES potential is greater.
A review on energy, economical, and environmental benefits of the use of CHP systems for small commercial buildings for the North American climate	2009	10.1002/er.1630	45	CHCP systems/ ES potential	Review	Commercial buildings	I	ASHRAE	9 cities in 9 climate zones (8, 7, 6B, 5B, 4C, 3B, 3A, 2A, 1A)	It is more profitable to operate a CHP system during normal working hours than to operate the system 24 hours a day. Also, the performance of a CHP system is highly dependent on the location where it is installed.
Life cycle assessment of a solar combined cooling heating and power system in different operation strategies	2012	10.1016/j.apenergy.2011.08.046	62	CHCP systems/ ES potential	Mathematical model	Office building	VI	Location	Beijing	Solar CHCP system in FEL and FTL operation strategies in the LCA context was analysed. It was found that for an office building in Beijing, in terms of performance the FTL mode of operation is better for the solar CHCP system, but in the ecological aspect, FEL operational mode is better.
Multi-objective optimisation design and operation strategy analysis of BCHP system based on life cycle assessment	2012	10.1016/j.energy.2011.11.014	56	CHCP systems/ ES	Mathematical analysis	Commercial building	VI	Location	Beijing	When the CHCP system runs FTL mode, the maximum ES can be achieved. When the CHCP system runs FEL the environmental benefits are better.
Analysis and optimisation of the use of CHP-ORC systems for small commercial buildings	2010	10.1016/j.enbuild.2010.03.019	50	CHCP systems/ ES	Simulation	Commercial office building	III	ASHRAE	6 cities USA (8, 7, 3B, 3A, 2A, 1A)	The CHP–ORC system performance strongly depends on the location where it is installed. For all the evaluated cities, the use of a CHP–ORC system reduces the cost, primary EC and carbon CO_2 for the same building operating solely with a CHP system. To achieve effective results, the system must have a 12-hour operating mode in all climate zones.
Multi-criteria analysis of combined cooling, heating and power systems in different climate zones in China	2010	10.1016/j.apenergy.2009.06.027	119	CHCP systems/ ES potential	Mathematical analysis	Hotels	I	China BC	5 climate zones	The results indicate that the CHCP system in FTL mode in the cold climate, where the building requires more heating during the year, achieves more benefit over a separate system while the CHCP system in FEL mode suits the building having stable thermal demand in mild climate zone.
Effects of load-following operational methods on combined heat and power system efficiency	2014	10.1016/j.apenergy.2013.10.063	44	CHCP systems/ ES	Mathematical model	Hotels	I	ASHRAE	8 ,7, 6B, 6A, 5B, 5A, 4C, 4B, 4A, 3C, 3B(2), 3A, 2B, 2A, 1A)	In different climatic zones, the hybrid method of functioning of the CHP system based on the hourly change method and the monthly change method can raise the CHP system efficiency value to 71-87% and 74-86%, respectively.

Table A.2 Studies of Cluster 3 – Combined heating, cooling and power systems (continued).

Title	Year	DOI	CIT*	Theme	Type	Building type	Type of climate-oriented study	Type of climatic zoning	Region/CZ	Principal conclusions
Influence analysis of building types and climate zones on energetic, economic and environmental performances of BCHP systems	2011	10.1016/j.apenergy.2011.03.016	63	CHCP systems/ ES potential	Mathematical model	Hotel, school, office, hospital	I	China BC	5 climate zones	The CHP system in the office building consumes less energy, spends less and emits less CO_2 among the four categories of buildings throughout the year in 5 climate zones.
Integrated assessment of combined cooling heating and power systems under different design and management options for residential buildings in Shanghai	2012	10.1016/j.enbuild.2012.04.023	48	CHCP systems/ ES potential	Mathematical model	Residential buildings	VI	Köppen (without ref.)	Shanghai (Subtropical maritime monsoon climate)	According to the simulation results, gas engine and fuel cell based CHCP systems are feasible options from the energy and environmental viewpoints, but at the cost of poor economic performance.
Analysis of the economic feasibility and reduction of a building's energy consumption and emissions when integrating hybrid solar thermal/PV/micro-CHP systems	2016	10.1016/j.apenergy.2015.12.080	69	CHCP systems/ ES	Simulation	Residential buildings	I	Spain BC	Cadiz, Seville, Barcelona, Madrid, Burgos (5 climate zones)	Integrating hybrid solar thermal/PV/micro-CHP systems have an average of 28% less CO_2 emissions in all climates in comparison with conventional systems. Primary EC is 9.8% less in warm climates and 16% less in cold climates, while LCC is 40% more in a warm climate and 26% more in a cold climate.
Optimal option of distributed energy systems for building complexes in different climate zones in China	2012	10.1016/j.apenergy.2011.08.044	50	CHCP systems/ ES potential	Mathematical model	Residential, Public and Mixed building complex	I	China BC	5 climate zones	The Distributed Energy Resource (DER) system is particularly preferable in Shanghai from both the economic and environmental benefits, followed by Guangzhou, Beijing and Harbin; while, the benefits in Kunming are marginal. Although the concept of renewable energy town results in reasonable environmental performance cutting more than 20% CO_2 emissions for most systems, minor or even negative economic benefits are encountered in all cities.
Analysis of energy saving potential of air-side free cooling for data centers in worldwide climate zones	2013	10.1016/j.enbuild.2013.04.013	67	ES/ HVAC systems	Simulation	Data centres	I	ASHRAE	1A, 1B, 2A, 2B, 3A-C, 4A-C, 5A-C, 6A, 6B, 7, 8)	High energy saving potential of the free cooling energy efficiency of data centres was observed in mixed-humid and warm-marine climate zones.
What drives the carbon mitigation in Chinese commercial building sector? Evidence from decomposing an extended Kaya identity	2018	10.1016/j.scitotenv.2018.04.043	55	Standards for ES and carbon mitigation	Mathematical model	Commercial buildings	–	–	–	The reduction in carbon emissions in the commercial buildings sector in China was 625.9 $MtCO_2$ in 2001-2015, which is the result of the effective building energy efficiency policy.
Impact of climate change on energy use in the built environment in different climate zones - A review	2012	10.1016/j.energy.2012.03.044	146	Climate change and EC	Review	Different types of buildings	–	–	–	Mitigation of the effects of climate change in warm climates can be achieved through raise summer setpoint temperature, lower lighting load, adaptive thermal comfort application, solar-powered cooling, and climate data update.

**August 2020 WOS*

Table A. 3 Studies of Cluster 5 – Indoor thermal comfort.

Title	Year	DOI	CIT*	Theme	Type	Building type	Type of climate-oriented study	Type of climatic zoning	Region/CZ	Principal conclusions
The adaptive model of thermal comfort and energy conservation in the built environment	2001	10.1007/s00484010 0093	214	Thermal comfort	Results of the field experiment	160 buildings	II	Köppen	Different climate zones	The importance of applying the adaptive thermal comfort model for free-running or naturally ventilated buildings was noted, as well as the ES potential of using this model for air conditioning and ventilation of buildings in moderate climates of the world.
Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55	2002	10.1016/S0378-7788(02)00005-1	564	Thermal comfort/ ES potential	Results of the field experiment	160 buildings	II	Köppen	Different climate zones	General description of the adaptive thermal comfort model and the spatial distribution of the hypothetical ES potential when this comfort model is applied in the USA.
An adaptive thermal comfort model for the Tunisian context: a field study results	2005	10.1016/j.enbuild.2004.12.003	82	Thermal comfort	Results of the field experiment	Residential and office buildings	II	Tunis BC	5 cities in 2 climate zones	Description of the methodology of the development of an adaptive thermal comfort model in residential and office buildings in Tunisia. It has also been shown that the population of Tunisia has great potential for adaptation to climate and seasons.
Thermal comfort in naturally ventilated and air-conditioned buildings in humid subtropical climate zone in China	2008	10.1007/s00484-007-0133-4	58	Thermal comfort	Results of the field experiment	Residential and office, flats or two-story buildings	V	Köppen (without ref.)	5 cities in the Humid Subtropical Climate zone of China	Thermal comfort analysis in 111 buildings in 5 cities of China. The range of accepted temperature in naturally ventilated buildings (25.0~31.6°C) was wider than that in air-conditioned buildings (25.1~30.3°C), which suggests that occupants in naturally ventilated buildings seemed to be more tolerant of higher temperatures.
Air movement acceptability limits and thermal comfort in Brazil's hot humid climate zone	2010	10.1016/j.buildenv.2009.06.005	100	Thermal comfort	Results of the field experiment	Educational building, classrooms	IV	Köppen	Maceio city in Hot-Humid Climate zone	The effect of wind speed on thermal comfort inside a natural ventilated building. The minimal air velocity required was at least 0.4 m/s for 26°C reaching 0.9 m/s for operative temperatures up to 30°C.
Quantifying the relevance of adaptive thermal comfort models in moderate thermal climate zones	2007	10.1016/j.buildenv.2005.08.023	62	Thermal comfort/ ES potential	Simulation	Office buildings	V	Köppen	Moderate Maritime Climate zones	For moderate climate zones, the adaptive model is only applicable during summer and can reduce by 10% of the EC in naturally conditioned buildings or buildings with a high degree of occupant control.
Assessing the natural ventilation cooling potential of office buildings in different climate zones in China	2009	10.1016/j.renene.2009.05.015	44	Ren. energy systems/ Thermal comfort/ ES potential	Simulation	Office buildings	I	China BC	5 climate zones	The cooling potential of natural ventilation (with the application of adaptive thermal comfort) depends on climatic zones and varies over a wide range.
Forty years of Fanger's model of thermal comfort: comfort for all?	2008	10.1111/j.1600-0668.2007.00516.x	271	Thermal comfort	Review	–	–	–	different climate zones	Criticism and improvement opportunity of the PMV model of thermal comfort in different climates.

Table A.3 Studies of Cluster 5 – Indoor thermal comfort (continued).

Title	Year	DOI	CIT*	Theme	Type	Building type	Type of climate-oriented study	Type of climatic zoning	Region/CZ	Principal conclusions
Thermal sensation of Hong Kong people with increased air speed, temperature and humidity in air-conditioned environment	2010	10.1016/j.buildenv.2010.03.016	60	Thermal comfort	Results of the field experiment	Office buildings	IV	Köppen (without ref.)	Warm and Humid Climate zone, Hong Kong	Were noted gender differences in heat sensation, and Hong Kong citizens are sensitive to temperature and air speed, but not humidity. With air speed at 0.1–0.2 m/s, clothing level 0.55 clo. and metabolic rate 1 met., the neutral temperature was found around 25.4°C for a sedentary working.
Adaptive thermal comfort model for different climatic zones of North-East India	2011	10.1016/j.apenergy.2011.01.019	77	Thermal comfort	Results of the field experiment	Naturally ventilated buildings	II	India BC	3 climate zones	The seasonal variability of the adaptive thermal comfort model is revealed. The adaptive thermal comfort model more suitable in comparison with the PMV model in these climatic conditions.
Field studies of thermal comfort across multiple climate zones for the subcontinent: India Model for Adaptive Comfort (IMAC)	2016	10.1016/j.buildenv.2015.12.019	104	Thermal comfort	Results of the field experiment	Office buildings	II	India BC	5 climate zones	Development of Indian Model of Adaptive Comfort for office buildings in 5 cities (for naturally ventilated, mixed-mode and air-conditioned buildings)
Field studies on human thermal comfort - An overview	2013	10.1016/j.buildenv.2013.02.015	130	Thermal comfort	Review	Office, residential, classroom	II	Köppen	4 climate zones	Conditioned spaces have narrower comfort zones compared to free-running buildings. Across climatic zones, the most popular means of adaptation are related to the modification of air movement and clothing.
Adaptive thermal comfort in Australian school classrooms	2015	10.1080/09613218.2015.991627	72	Thermal comfort	Results of the field experiment	Educational building, classrooms	II	Australia BC	4 climate zones	The comfortable temperature for children was 1-2°C lower than for adults.
Thermal comfort in educational buildings: A review article	2016	10.1016/j.rser.2016.01.033	84	Thermal comfort	Review	Educational buildings	II	Köppen	4 macro zones	Analysis of the results of field experiments over the past 50 years in educational buildings. Principal idea is to design buildings that will facilitate learning and overcome the state of discomfort with minimum energy consumption.
Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings	2015	10.1016/j.buildenv.2014.09.010	153	ES /HVAC systems	Simulation	Office buildings	I	ASHRAE	7, 5A, 4A, 3C, 3B, 2B, 1A	The correct definition of the set-point temperature of thermostat can help to reduce energy consumption.
Thermostat strategies impact on energy consumption in residential buildings	2011	10.1016/j.enbuild.2010.09.024	62	ES/HVAC systems	Mathematical analysis	Residential buildings	I	IECC	Detroit, Miami - 2 climate zones	Setting the thermostat can optimise cooling and heating energy consumption in a residential building in 2 cities in the USA
Performance analysis of integrated earth-air-tunnel-evaporative cooling system in hot and dry climate	2012	10.1016/j.enbuild.2011.12.024	40	Ren. energy systems/ ES	Simulation with validation of field test	–	IV	India BC	Ajmer city (India)	The earth–air-tunnel heat exchanger system provides 4500 MJ of cooling effect during the summer period and 4856 MJ of heating effect during winter with the thermal comfort zone specified ay ASHRAE-55.

**August 2020 WOS*

Table A. 4 Studies of Cluster 9 – Energy simulation, conservation and meteorological data.

Title	Year	DOI	CIT*	Theme	Type	Building type	Type of climate-oriented study	Type of climatic zoning	Region/CZ	Principal conclusions
Multivariate regression as an energy assessment tool in early building design+D40	2012	10.1016/j.buildenv.2012.04.021	86	Methodologies/ EC	Mathematical analysis/ Simulation	Office buildings	I	ASHRAE	4 cities in the 4 climate zones (6A, 4B, 4A, 1A)	The multivariate regression method used to estimate the EC of a building in the early design stages based on 27 parameters showed a high level of compliance with the simulation of EC in Energy Plus (R^2=0.97), except for EC for heating in warm climates.
Heating and cooling building energy demand evaluation; a simplified model and a modified degree days approach	2014	10.1016/j.apenergy.2014.04.067	81	Methodologies/ EC	Mathematical analysis/ Simulation	The standard building block of two floors	III	Location	Cities in Europe	A dynamic model was presented to estimate heating/cooling EC in buildings as a function of degree days. This model retains linearity even for small values of CDD. Method error is not more than 8.2% compared to Energy Plus and TRNSYS.
Thermal comfort and building energy consumption implications - A review	2014	10.1016/j.apenergy.2013.10.062	409	Thermal comfort/EC	Review	–			–	Increasing the summer operating temperature has good ES potential as it can be applied in both new and existing buildings.
Energy and visual comfort analysis of lighting and daylight control strategies	2014	10.1016/j.buildenv.2014.04.028	74	ES potential/ Visual comfort	Simulation	–	I	ASHRAE	Abu-Dhabi, London, Baltimore (1B, 4A (2))	Fully integrated lighting and daylight control with blind tilt angle and height control can reduce EC for lighting by a maximum average of 90% in studied cities.
Comparative study of energy regulations for buildings in Italy and Spain	2008	10.1016/j.enbuild.2008.03.007	47	Building standards/ Energy efficiency	Simulation	Residential buildings	I	Italy BC and Spain BC	4+3 climate zones	The difference in climatic zoning and building standards of the two countries makes it impossible to use a unified procedure for energy certification of housing in Spain and Italy.
Comparative study on the indoor environment quality of green office buildings in China with a long-term field measurement and investigation	2015	10.1016/j.buildenv.2014.10.015	54	IEQ	Results of field experiment	Office buildings	II	China BC	Cold climate (2) and Hot summer and cold winter (1)	The result of the questionnaire survey shows that the green buildings in China demonstrate a significantly higher satisfaction level than the conventional buildings at the aspect of the thermal, acoustic environment, visual, IAQ, and the overall environment.
An energy benchmarking model based on artificial neural network method utilising US Commercial Buildings Energy Consumption Survey (CBECS) database	2016	10.1002/er.1232	43	Energy benchmarking	Mathematical analysis	Commercial buildings	II	US census division	9 zones	The implementation of the energy benchmarking model based on the method of artificial neural networks gives more correct predicted results of EC if the housing stock is divided by climatic zones.
Sub-theme 1										
Energy performance of building envelopes in different climate zones in China	2008	10.1016/j.apenergy.2007.11.002	133	CZ/Envelope/Multi-par. opt.	Simulation	Office buildings	I	China BC	5 cities/ 5 climate zones	It has been demonstrated that, in different climatic zones, the chiller load/heat load is more dependent on thermal gains/losses through the floor in comparison with walls and roof.

Table A.4 *Studies of Cluster 9 – Energy simulation, conservation and meteorological data (continued).*

Title	Year	DOI	CIT *	Theme	Type	Building type	Type of climate-oriented study	Type of climatic zoning	Region/CZ	Principal conclusions
Analysis of annual heating and cooling energy requirements for office buildings in different climates in Turkey	2008	10.1016/j.enbuild.2007.05.008	97	Multi-par. opt.	Simulation	Office buildings	I	Turkish BC	4 cities in 4 climate zones	Optimal characteristics of parameters such as insulation and thermal mass, building aspect ratio, colour of external surfaces, shading, window systems including window area and glazing system, ventilation rates and strategies for each climate zones can help to reduce building EC.
Building energy efficiency in different climates	2008	10.1016/j.enconman.2008.01.013	93	Arch. strategies/ Multi-par. opt.	Simulation	Office buildings	I	China BC	5 cities/ 5 climate zones	Passive solar designs have great ES potential in cold climates, and energy efficient lighting designs and office equipment will help reduce EC.
Thermal and economic windows design for different climate zones	2011	10.1016/j.enbuild.2011.08.019	48	Façades and windows/ Multi-par. opt.	Simulation/ LCC analysis	Residential buildings	III	Location	Amman, Aqaba, Berlin)	Triple glazed windows have shown the best energy saving results in all types of climate, but from an economic point of view, double glazing is weatherproof.
A comparative life cycle assessment of a transparent composite facade system and a glass curtain wall system	2011	10.1016/j.enbuild.2011.09.006	42	Façades and windows/ Multi-par. opt.	Simulation/ LCA analysis	Office buildings	VI	Location	USA, Detroit	Transparent composite façade systems have 7% less total life cycle energy and 11% less carbon emissions than glass curtain wall systems.
Design optimisation of energy efficient residential buildings in Tunisia	2012	10.1016/j.buildenv.2012.06.012	85	Multi-par. opt.	Simulation	Residential buildings	I	Tunis BC	4 cities/ climate zones	The presented multi-parameter optimisation method was able to reduce the building's energy consumption by 50%. Also, for each climatic zone, the optimal designs of the building under study were presented.
The effect of geometry factors on fenestration energy performance and energy savings in office buildings	2013	10.1016/j.enbuild.2012.10.035	54	Façades and windows/ Multi-par. opt.	Simulation	Office buildings	I	ASHRAE	Zone2-7	Geometric factors (window orientation, window to wall ratio, and room width to depth ratio) significantly affect energy consumption in hot climates and cold climates, but only marginally in temperate climates. Energy savings averaged 3% and 6%, reaching a maximum of 10% and 14% in hot climates and 1% in temperate and cold climates.
Impact of building design and occupancy on office comfort and energy performance in different climates	2014	10.1016/j.buildenv.2013.10.001	50	Multi-par. opt.	Simulation	Office buildings	I	Köppen	Alice Springs; Athens; Hamburg	The relationship between climate, building design, building occupancy, thermal comfort, and energy efficiency was presented.
An insight into actual energy use and its drivers in high-performance buildings	2014	10.1016/j.apenergy.2014.06.032	63	Multi-par. opt.	Energy audit	Office buildings	III	Location	USA, China, Asia, Europa, Australia	Only a holistic approach to building design that takes into account climate, technology, human behaviour, and operation and maintenance practices can help maximise energy savings.
Commercial Building Energy Saver: An energy retrofit analysis toolkit	2015	10.1016/j.apenergy.2015.09.002	67	Tools and methodologies/ Multi-par. opt.	Simulation tool	Commercial buildings	I	California EC	16 climate zones of California	The application programming interface provides estimates of energy conservation and the search for the optimal design of buildings based on 100 parameters.

Table A.4 Studies of Cluster 9 – Energy simulation, conservation and meteorological data (continued).

Title	Year	DOI	CIT*	Theme	Type	Building type	Type of climate.-oriented study	Type of climatic zoning	Region/CZ	Principal conclusions
A novel approach for the simulation-based optimisation of the building's energy consumption using NSGA-II: Case study in Iran	2016	10.1016/j.enbuild.2016.05.052	47	Multi-par. opt.	Simulation	Office buildings	I	Iran BC	4 cities/ 4 climate zones	The climate and the appropriate choice of architectural parameters are very important and critical in reducing a building's energy consumption.
Passive performance and building form: An optimisation framework for early-stage design support	2016	10.1016/j.solener.2015.12.020	59	Tools and methodologies	Simulation tool	Office buildings	I	ASHRAE	4 cities/4 climate zones (6A, 4A, 3B, 3A)	A passive performance optimisation framework (in urban conditions) can provide 4-17% EC reduction while improving daylight performance by 27-65% depending on terrain and climatic conditions.
Zero energy buildings and sustainable development implications - A review	2013	10.1016/j.energy.2013.01.070	214	Sys. with ren. energy sources	Review	–	–	–	–	Energy efficiency measures and the introduction of renewable energy sources and other technologies for buildings have regionally and climate dependence.
Sub-theme 2										
Applicability of air-to-air heat recovery ventilators in China	2009	10.1016/j.applthermaleng.2008.04.003	50	HVAC systems/ ES	Mathematical analysis	–	II	China BC	Severe cold (3), Cold (2), Mild (2), Hot summer and warm winter (1)	The applicability of air-to-air heat recovery ventilators with mixed or separated fresh air unit with or without humidity-controlled depend on 5 climatic zones
Efficiency of energy recovery ventilator with various weathers and its energy saving performance in a residential apartment	2010	10.1016/j.enbuild.2009.07.009	54	HVAC systems/ES	Simulation	Residential buildings	II	China BC	2 cities in each of 5 climatic zones	Demonstrated seasonal dependence of weighted coefficients (latent and sensible heat efficient) of enthalpy efficiency of the energy recovery ventilator in different cities. Demonstrated that saved energy percentages by ERV depend on different enthalpy efficiencies.
Adequacy of air-to-air heat recovery ventilation system applied in low energy buildings	2012	10.1016/j.enbuild.2012.08.008	50	HVAC systems/ES	Simulation	Flat, house, office	III	Bioclimatic	7 cities of France	The applicability of air-to-air heat recovery ventilators depends on the building types, the heating loads, and ventilation device characteristics in different climatic zones.
Sub-theme 3										
Air-conditioning usage conditional probability model for residential buildings	2014	10.1016/j.buildenv.2014.06.022	60	HVAC systems/Occupant behaviour	Results of field experiment/ Mathematical model	Residential buildings	II	China BC	Cold (1), Hot summer and cold winter (6), Hot summer and warm winter (1)	The air-conditioning usage conditional probability model was developed based on 34 residential buildings in 7 cities. This model reflects real Air-conditioning usage very well.
Occupant behavior and schedule modeling for building energy simulation through office appliance power consumption data mining	2014	10.1016/j.enbuild.2014.07.033	117	HVAC systems/Occupant behaviour	Numerical modelling	Office buildings	I	ASHRAE	17 cities/17 climate zones (1A, 1B, 2A, 2B, 3A-C, 4A-C, 5A-C, 6A, 6B, 7, 8)	Occupant behaviour and schedule modelling method are developed and tested in a medium-size office building. The simulation result shows an average of 8.39% increase in heating EC, 2.80% decrease in cooling EC, and 4.07% decrease in fan EC for all the climate zones.
Energy savings from temperature setpoints and deadband: Quantifying the influence of building and system properties on savings	2016	10.1016/j.apenergy.2015.12.115	68	HVAC systems/ES	Simulation	Office buildings	I	ASHRAE	8 ,7, 6B, 6A, 5B, 5A, 4C, 4B, 4A, 3C, 3B(2), 3A, 2B, 2A, 1A	The potential savings from selecting daily optimal setpoints for HVAC system in the range of 22.5 ± 3 °C in different climates and for small, medium and large office buildings, would lead to 10.09 – 37.03%, 11.43 – 21.01%, and 6.78 – 11.34 % savings, respectively, depending on the climate.

Table A.4 *Studies of Cluster 9 – Energy simulation, conservation and meteorological data (continued).*

Title	Year	DOI	CIT*	Theme	Type	Building type	Type of climate-oriented study	Type of climatic zoning	Region/CZ	Principal conclusions
					Sub-theme 4					
Solar powered net zero energy houses for southern Europe: Feasibility study	2011	10.1016/j.solener.2011.11.008	49	Ren. energy systems/ES	Simulation	Residential NZEH	IV	Bioclimatic	Mild southern European climate	The optimal size of the PV system varies by a factor of three and a half, depending on the efficiency of the building and electrical appliances used.
Energy performance of solar-assisted liquid desiccant air-conditioning system for commercial building in main climate zones	2014	10.1016/j.enconman.2014.09.006	44	Ren. energy systems/ES	Mathematical analysis	Commercial building	I	Bioclimatic	5 cities 5 climate zones	Use of solar energy for liquid desiccant AC system can help to reduce total building EC by 40% in humid climates such as Houston and Singapore.
Investigation on the feasibility and performance of ground source heat pump (GSHP) in three cities in cold climate zone, China	2015	10.1016/j.renene.2015.06.019	67	Systems with ren. energy sources	Simulation	Office buildings	V	China BC	Cold climate	In a cold climate zone, soil temperature modelling for ten years was found to be important to assess the performance of the ground source heat pump.
Feasibility and performance study of the hybrid ground-source heat pump system for one office building in Chinese heating dominated areas	2017	10.1016/j.renene.2016.10.006	121	Systems with ren. energy sources	Simulation	Office buildings	IV	China BC	Cold climate	Auxiliary heat source could improve ground source heat pump energy performance in cold climate.
					Sub-theme 5					
Building energy simulation using multi-years and typical meteorological years in different climates	2008	10.1016/j.enconman.2007.05.004	63	Meteo. data/Energy simulation	Simulation	Office building	I	China BC	5 cities/ 5 climate zones	The results of the simulation of energy use based on the TMY data quite closely matched the results of the simulation based on long-term mean data in different climatic zones (mean bias errors ranged from −4.3% to 0%)
A new method to develop typical weather years in different climates for building energy use studies	2011	10.1016/j.energy.2011.07.053	35	Meteo. data/Energy simulation	Simulation	Office building	I	China BC	5 cities/ 5 climate zones	The TPCY methodology for generating weather data was presented, the results of the simulation of EC showed slight differences with the results of simulation with TMY data and long-term average data.
Development of weighting factors for climate variables for selecting the energy reference year according to the EN ISO 15927-4 standard	2012	10.1016/j.enbuild.2011.11.031	87	Meteo. data/Energy simulation	Mathematical analysis	–	I	Finland BC	4cities/ 4 climate zones	The energy reference year's selection method was improved with weighting factors. In a cold boreal climate, during the summer, temperature and solar radiation have a similar influence on heating and cooling energy demand, whereas air humidity and wind speed have a minor effect. The energy reference year cannot be used to find the optimal HVAC system parameters.
A fresh look at weather impact on peak electricity demand and energy use of buildings using 30-year actual weather data	2013	10.1016/j.apenergy.2013.05.019	68	Meteo.data/ Energy simulation	Simulation	Office building	I	ASHRAE	1A, 1B, 2A, 2B, 3A-C, 4A-C, 5A-C, 6A, 6B, 7, 8	It is crucial to run multi-decade simulations with AMY weather data to fully assess the impact of weather on the long-term performance of buildings, and to evaluate the energy savings potential of energy conservation measures for new and existing buildings from a life cycle perspective.

Table A.4 Studies of Cluster 9 – Energy simulation, conservation and meteorological data (continued).

Title	Year	DOI	CIT*	Theme	Type	Building type	Type of climate-oriented study	Type of climatic zoning	Region/CZ	Principal conclusions
Climate change adaptation pathways for Australian residential buildings	2011	10.1016/j.buildenv.2011.05.022	55	Climate change/ES	Mathematical analysis	Residential buildings	I	Australia BC	8 climate zones	The measures for adaptation to climate change in energetical and economical aspects are presented and vary by climatic zones.
Impact of climate change on building energy use in different climate zones and mitigation and adaptation implications	2012	10.1016/j.apenergy.2011.11.048	91	Climate change/ES	Simulation	Office building	I	China BC	5 cities/ 5 climate zones	In the future, in Harbin, the EC for air conditioning a building will have a decreasing trend compared to other cities. Mitigation/adaptation methods - envelop, indoor design conditions and lighting load density, coefficient of performance of the HVAC system.
Modelling the energy demand projection of the building sector in Greece in the 21st century	2012	10.1016/j.enbuild.2012.02.043	68	Climate change/Energy demand	Simulation	Building stock	II	Greece BC	4 climate zones	The results show that the demand for heating energy for the construction sector in Greece could fall by about 50%, while the corresponding demand for cooling energy could rise by as much as 248% by 2100.
Impact of climate change heating and cooling energy use in buildings in the United States	2014	10.1016/j.enbuild.2014.07.034	102	Climate change/EC	Simulation	Residential and commercial buildings	II	ASHRAE	15 cities in zones 7(1), 6A (2), 5B (1), 5A(1), 4C (1), 4A (2), 3C(2), 3B (1), 3A (2), 2A (1), 1A (1)	In 2080, for climate zones 1-4 of the ASHRAE, a net increase in EC is expected and for zones 6-7, a net decrease in energy consumption is expected.
Urban heat island and its impact on climate change resilience in a shrinking city: The case of Glasgow, UK	2012	10.1016/j.buildenv.2012.01.020	76	UHI	Mathematical analysis	–	VII	Urban climate zone	Glasgow, UK	It was revealed that the intensity of the urban heat island has increased over the past 50 years.

**August 2020 WOS*

Table A. 5 Studies without cluster.

Title	Year	DOI	CIT*	Theme	Type	Building type	Type of climate-oriented study	Type of climatic zoning	Region/CZ	Principal conclusions
A method of identifying and weighting indicators of energy efficiency assessment in Chinese residential buildings	2010	10.1016/j.enpol.2010.08.018	50	Energy efficiency	Questionnaire survey	Residential buildings	V	China BC	Climate dependence methodology	The group analytical hierarchical process made it possible to identify 17 basic parameters out of 83 parameters that should be used to assess the energy efficiency of residential buildings in the hot summer and cold winter zone in China.
Climatic zoning and its application to Spanish building energy performance regulations	2008	10.1016/j.enbuild.2008.05.006	46	CZ	Mathematical analysis	–	VII	Spain BC	Andalusia	A method for the formation of weather data and determination of building climatic zones at the level of the mesometeorological scale is presented.
Comparison of low-energy office buildings in summer using different thermal comfort criteria	2007	10.1016/j.enbuild.2007.02.005	58	Thermal comfort/ ES	Results of field experiment, measurements	Office buildings	II	German BC	3 summer climate zones of Germany	Assessment of comfort in 12 office buildings with low EC shows that the building in which natural heat sinks for cooling are used, provide good thermal comfort in a typical and warm summers in Germany.
Development of bio-climatic zones in north-east India	2007	10.1016/j.enbuild.2007.01.015	43	CZ/ ES potential	Measurements	Residential buildings	VII	India BC	North-east India	Provides psychometric diagrams for bioclimatic zones in north-eastern India that can be used to assess the potential of solar passive design strategies for residential buildings.
Effects of global warming on energy use for space heating and cooling in the United States	1995	https://www.jstor.org/stable/41323449	91	Climate change/EC	Mathematical analysis	The stock of residential and commercial buildings	II	US Energy Information Administration (EIA)	5 zones	It has been found that global warming of 1 ° C will reduce projected US energy costs in 2010 by $ 5.5 billion (1991).
Energy demands and potential savings in European office buildings: Case studies based on EnergyPlus simulations	2013	10.1016/j.enbuild.2013.05.039	77	Multi-criterial opt./ES potential	Simulation	Office buildings	I	Bioclimatic	Tallinn, London, Madrid	The ES potential of buildings is analysed based on three aspects - lighting optimisation; improved insulation of windows and external walls; optimisation of building orientation. It was found that there must be a careful approach to improving insulation in warm climates.
Evaluation of energy efficient design strategies for different climatic zones: Comparison of thermal performance of buildings in temperate-humid and hot-dry climate	2007	10.1016/j.enbuild.2006.08.004	75	CZ/Building envelope	Mathematical analysis/ Questionnaire survey	Residential buildings	I	Bioclimatic, Turkey BC	Istanbul and Mardin - two climatic zones	The importance of taking into account the thermal mass of the building envelope to simulate energy consumption in hot dry continental climates was noted.
Mitigation of CO_2 emissions from the EU-15 building stock - Beyond the EU directive on the energy performance of buildings	2006	10.1065/espr2005.12.289	58	Building standards	Mathematical model	Building stock	II	Zones based on HDD	3 climate zones	In Europe, it was found that 60% of carbon emissions in the building stock are from single-family dwellings, and 23% of emissions from non-residential buildings.

Table A.5 Studies without cluster (continued).

Title	Year	DOI	CIT*	Theme	Type	Building type	Type of climate-oriented study	Type of climatic zoning	Region/CZ	Principal conclusions
Optimal design and operation strategy for integrated evaluation of CCHP (combined cooling heating and power) system	2016	10.1016/j.energy.2016.01.060	84	CHCP systems/ES	Mathematical model	Residential, office, hotel	IV	Köppen (without ref.)	Dalian, China - Maritime climate	The use of the CHCP system in a hotel was shown the maximum ES potential (42.28%) compared to other types of buildings due to the significantly stable electrical load. From an economic point of view, this system is not applicable in residential buildings.
Optimal option of distributed energy systems for building complexes in different climate zones in China	2012	10.1016/j.apenergy.2011.08.044	50	CHCP systems/ ES potential	Mathematical analysis	Residential, Public and Mixed building complex	I	China BC	5 cities/5 climate zones	A distributed energy system can be used in Shanghai due to economic and environmental benefits, followed by Guangzhou, Beijing and Harbin; while the benefits from Kunming are negligible.
Passive Houses for different climate zones	2015	10.1016/j.enbuild.2015.07.032	59	Architectural strategies	Simulation	Residential buildings	I	Bioclimatic	Yekaterinburg, Tokyo, Shanghai, Las Vegas, Abu Dhabi, Singapore	It has been demonstrated how passive houses can be implemented in a variety of rather extreme climatic conditions, leading to the conclusion that they can be built almost anywhere in the world.
Potential for energy conservation in apartment buildings	2000	10.1016/S0378-7788(99)00028-6	99	Multi-criterial opt./ES potential	Energy audit	Residential buildings	I	Greece BC	3 climate zones in Greece	ES for space heating shows that savings from improved wall insulation range from 21–42% for insulation thicknesses of 3-5 cm. Improving floor insulation (5 cm) will also save 24-28% of the heating energy.
Solar air conditioning in Europe - an overview	2007	10.1016/j.rser.2005.02.003	264	Systems with ren. energy sources	Energy audit	Different types of buildings	–	–	Different climate zones	For southern Europe and the Mediterranean, solar cooling systems can result of 40-50% in primary ES.
Thermoeconomic analysis method for optimisation of insulation thickness for the four different climatic regions of Turkey	2010	10.1016/j.energy.2009.12.022	47	CZ/ Envelope	Mathematical model	–	I	Turkey BC	4 cities/ 4 climate zones	It is shown that an increase in the internal temperature from 18 to 22 C requires an increase in the optimal wall insulation thickness by 23% from 0.0663 m to 0.0816 m for the climatic zone of the city of Erzurum.

**August 2020 WOS*