Polytechnic University of Catalonia

Master

Environmental Engineering

Title

Study of the evolution of daily mean temperature in Catalonia below Climate change scenarios and analysis of the impact on energy consumption in buildings

Author

Maedeh Mahdavi

Tutor

Maria Gonçalves Ageitos

Date

September 2016

Abstract

Higher availability of future climate data sets, generated by regional climate models (RGMs) with fine temporal and spatial resolutions, improves and facilities the impact assessment of climate change.

Due to significant uncertainties in climate modelling, several climate scenarios should be considered in the impact assessment. Climate change is expected to decrease heating demand, increase cooling demand for buildings, and affect outdoor thermal comfort. All these indicators are important when it comes to energy management and energy consumptions of different sectors. In particular studying the temperature variations of a region during a specific period will provide an estimation of the change's trend and could be used as a measure for design energy management plans, energy saving, environmental friendly infrastructures and reduce the greenhouse gas emissions.

In this work, changes in residential Heating Degree Days (HDD) and Cooling Degree Days (CDD) for historical (1981-2005) and future (2031-2050) periods in Catalonia and Barcelona region are studied. The study was done using Cosmo Climate Limited-area Modelling Community (COSMO-CLM) regional climate model and Max Planck Institute for Meteorology (MPI) model, which is based on a coupled ocean-atmosphere GCM.

This study analyses the annual and seasonal CDD, HDD and temperature values over Catalonia and Barcelona by utilizing daily mean temperature series during the mentioned period from the EURO-CORDEX project.

The values of CDD and HDD have been calculated from a base temperature (for HDD is 18 °C, and for CDD is 22 °C). The result of future analysis shows that Barcelona will experience less heating degree-days and more cooling degree-days in the considered period (annual analysis). The same cannot be said for Catalonia case since each model shows a different trend and it is difficult to make a conclusion. The historical analysis shows that during the period of study, Barcelona's annual average of CDD has been increased while HDD has been decreased. For Catalonia, the annual HDD has decreased and the CDD has increased. It could be said that both in Barcelona and in Catalonia the need for increment in cooling requirements is higher than heating requirements.

Acknowledgment

I would like to express my gratitude to my supervisor Maria Gonçalves Ageitos for the useful comments, remarks, and engagement through the learning process of this master thesis. I would like to thank my parents and my sister, who have supported and helped me throughout the entire process.

I acknowledge the EOBS dataset from the EU-FP6 project ENSEMBLES (http://ensembles-eu.metoffice.com) and the data providers in the ECA&D project (http://www.ecad.eu) "Haylock, M.R., N. Hofstra, A.M.G. Klein Tank, E.J. Klok, P.D. Jones, M. New. 2008: A European daily high-resolution gridded dataset of surface temperature and precipitation. J. Geophys. Res (Atmospheres), 113, D20119, doi: 10.1029/2008JD10201"

And I acknowledge the EURO-CORDEX dataset.

Contents

Table of figures

1 Introduction

1.1 Climate system

The Earth's climate is a complex system of processes acting at manifold spatial and temporal scales. Observation indicates that the planet is warming, yet the assessment of the quality of such changes and the objections of those into the future requires the description of the system with the physically based climate model. Such climate models have been developed at a variety of levels of complexity, addressing different aspects of the climate system.

Models are only an approximation of the true system and therefore associated with uncertainty. These uncertainties have been heavily debated in the context of projected climate signals, as they are key for determining the actions of mitigation and adaptation to climate change.

The climate, as illustrated in Figure 1-1, is a complex system involving a series of interesting processes at various scales. This system is driven by the incoming solar radiation, in constant motion that transports energy, momentum, and mass from small-scale turbulent to large-scale flow in the Earth's atmosphere and ocean basins.

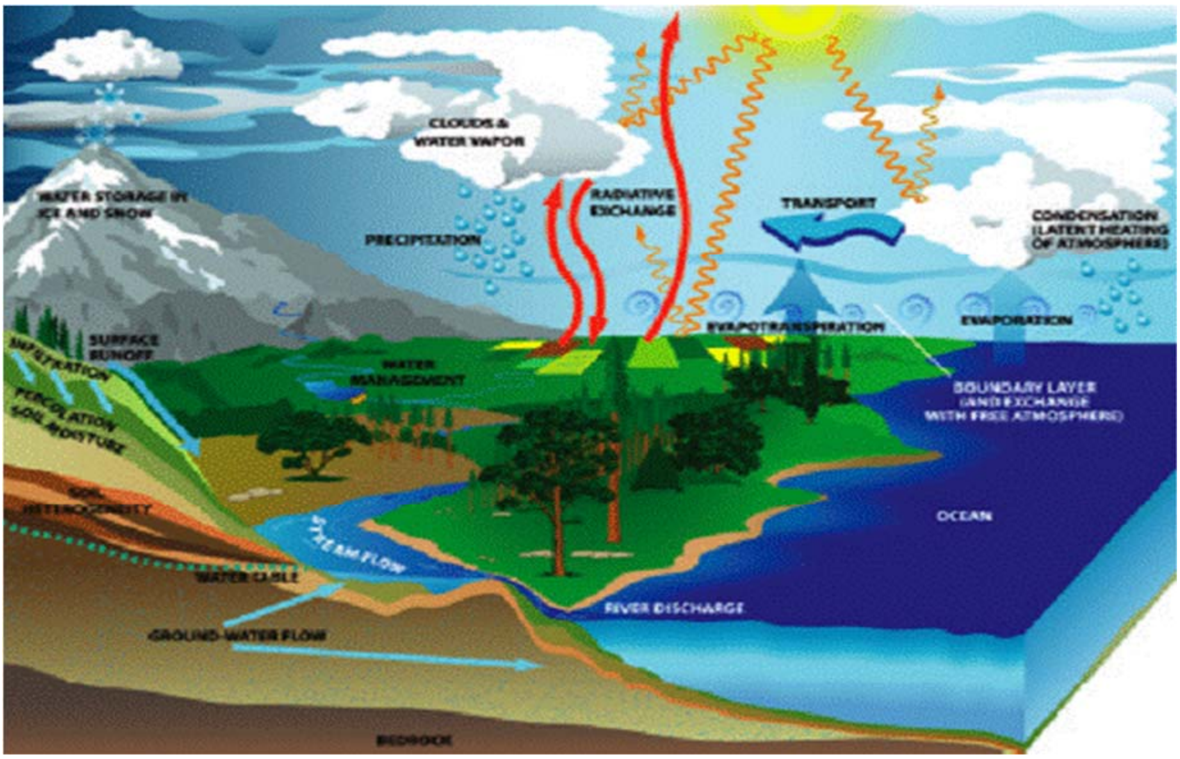

Figure 1-1: Climate system, Source: [1]

The climate is usually described in terms of the mean and variability of temperature, precipitation and wind over a period of time, ranging from months to millions of years [2]. The climate system evolves in time under the influence of its own internal dynamics and due to changes in external factors that affect climate. External forcing includes natural phenomena such as volcanic eruptions and solar variations, as well as human-induced changes in atmospheric composition.

In order to maintain a constant global average temperature, all of the sun's radiation that enters Earth's atmosphere must eventually be sent back to space. This is achieved through Earth's energy balance. Figure 1-2 depicts how the energy from the sun is absorbed, reflected, and emitted by the earth.

About half of the incoming solar radiation is absorbed by Earth's surface. This energy is transferred to the atmosphere by warming the air in contact with the surface (thermals), by evapotranspiration and by long wave radiation that is absorbed by clouds and greenhouse gases. The atmosphere, in turn, radiates longwave energy back to Earth as well as out of space. The amount of energy reaching the top layer of the Earth's atmosphere every second on a surface area of one square meter facing the sun during daytime is about 1,370 Watts, and the amount of energy per square meter per second averaged over the entire planet is one-quarter of this.

About 30% of the sunlight that reaches the top of the atmosphere reflects back to space. Roughly, two-thirds of this reflectivity are due to clouds and small particles in the atmosphere known as "aerosols" light-coloured areas of the Earth's surface- mainly snow, ice, and deserts- reflect the remaining one-third of the sunlight.

There are three fundamental ways to change the radiation balance of the Earth:

1. By changing the incoming solar radiation; for example, by changes in Earth's orbit or in the Sun itself.
2. By changing the fraction of solar radiation that is reflected ('albedo'); for example, by changing in cloud cover, atmospheric particles or vegetation.
3. By altering the long wave radiation from Earth, back towards space; for example, by changing greenhouse gas concentrations. Climate, in turn, responds directly to such changes, as well as indirectly, through a variety of feedback mechanisms [3].

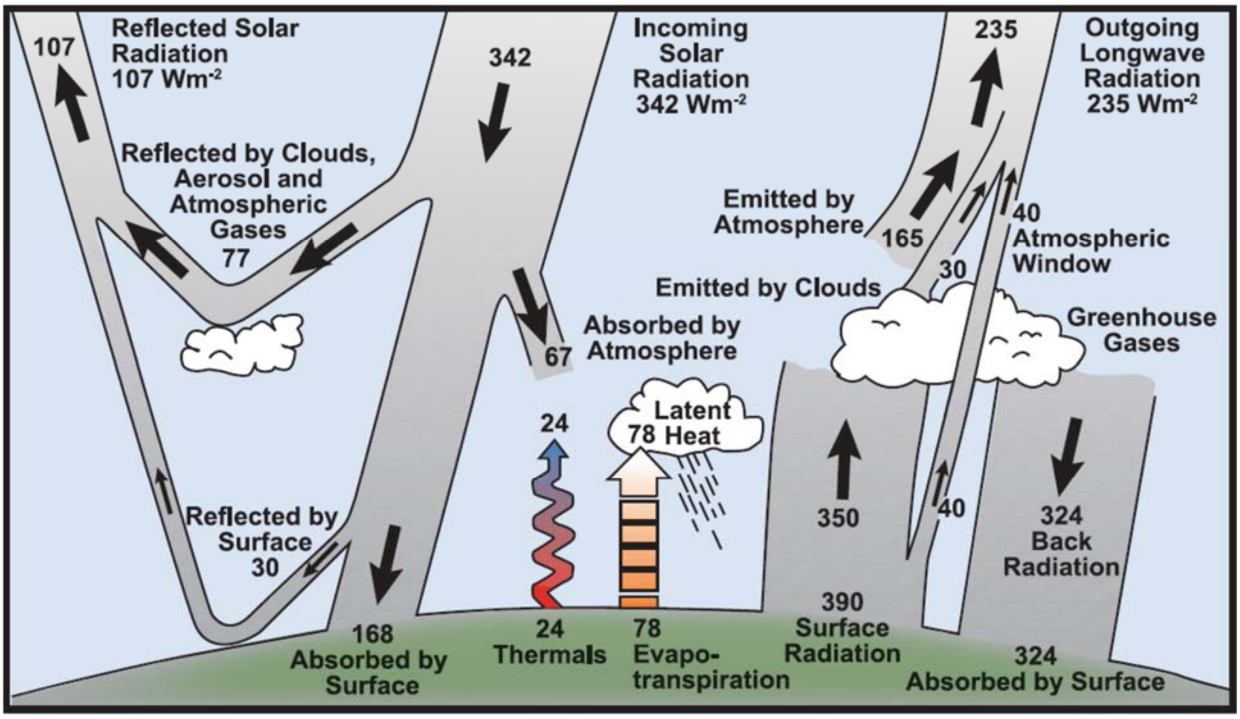

Figure 1-2: Estimate of the Earth's annual and global mean energy balance. Source: [4]

1.2 Climate change

1.2.1 Greenhouse gases

Rising fossil fuel burning and land use changes have emitted and are continuing to emit increasing quantities of greenhouse gases into the Earth's atmosphere. These greenhouse gases include carbon dioxide (CO_2), methane (CH_4), and nitrogen dioxide (N2O) (see Table 1-1), and a rise in these gases has caused a rise in the amount of heat from the sun withheld in the Earth's atmosphere. That is the heat, which would normally be radiated back into space.

This increase in heat has led to the greenhouse effect, resulting in climate change. The main characteristics of climate change are increasing in average global temperature (global warming), changes in cloud cover and precipitation, particularly over land, melting of ice caps and glaciers and reduced snow cover. It also causes an increase in ocean temperatures and ocean acidity since seawater absorbs heat and carbon dioxide from the atmosphere.

Climate change will have wide-ranging effects on the environment, and on socio-economic and related sectors, including water sources, agriculture, and food security, human health, terrestrial ecosystems and biodiversity and coastal zones.

Human intervention, by managing vegetated land surfaces, emitting atmospheric aerosols and greenhouse gases, and depleting the ozone layer affects both the global radiative balance and hydrological cycle.

Observation and climate models show that because of past human intervention surface temperatures are increasing and the hydrological cycle intensifying. Such changes have already started to affect the natural ecosystem and human living on earth in the present and will potentially also in the future [5].

1.2.2 Climate forcing

The power of a process to alter the climate is estimated by its “radiative forcing”, the change in the Earth’s energy balance due to that process. Some climate forcings are positive, causing globally averaged warming, and some are negative, causing cooling (see **Error! Reference source not found.**). Some, such as form increased CO_2 concentration, are well known, others, such as from aerosols, are more uncertain [6].

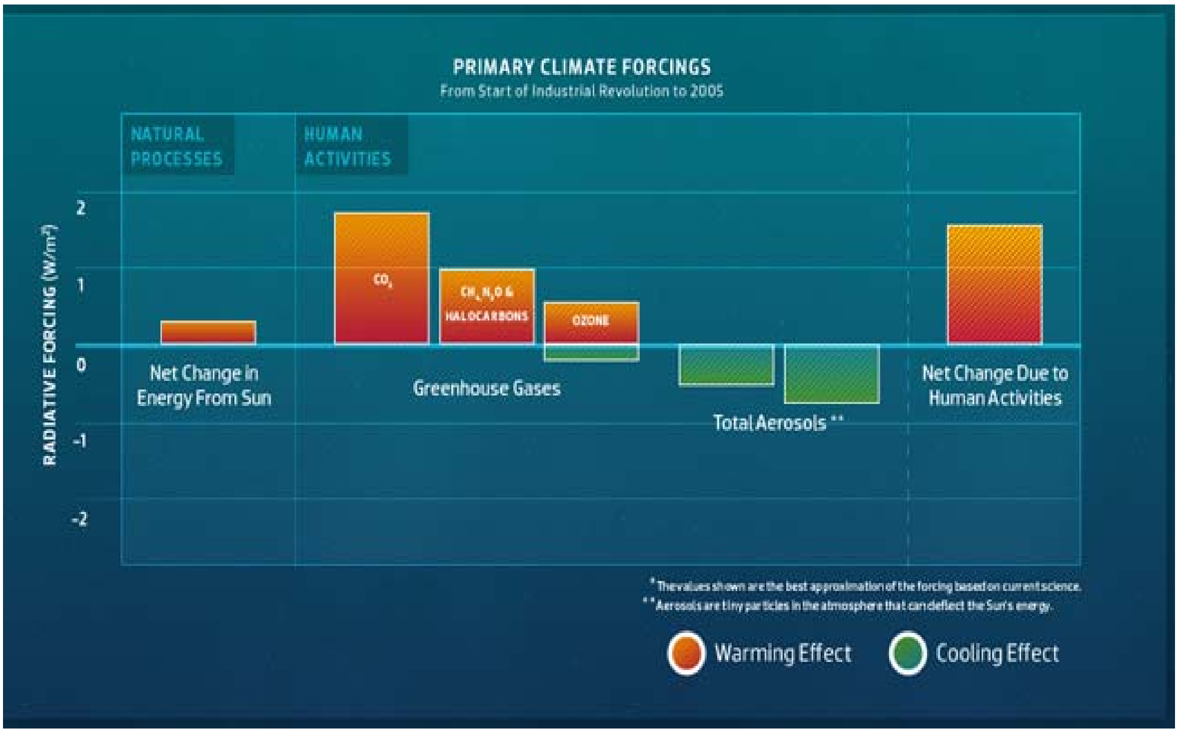

Figure 1-3 Altering the energy balance, Source: [7]

Table 1-1: Major long-lived GHGs and their characteristics. Source: [6]

Greenhouse gas	How it produced	Average lifetime in the atmosphere
Carbon dioxide (CO_2)	Emitted primarily through the burning of fossil fuels (oil, natural gas, and coal), solid waste, and trees and wood products. Changes in land use also play a role. Deforestation and soil degradation add carbon dioxide to the atmosphere while forest regrowth takes it out of the atmosphere.	Carbon dioxide lifetime cannot be represented with a single value because the gas is not destroyed over time, but instead moves among different parts of the ocean-atmosphere-land system. Some of the excess carbon dioxide is absorbed quickly (for example, by the ocean), but some will remain in the atmosphere for thousands of years, due in part to the very slow process by which carbon in transferring to ocean sediments.
Methane (CH_4)	Emitted during the production and transport of oil and natural gas as well as coal. Methane emissions also result from livestock and agricultural practices and from the anaerobic decay of organic waste in municipal solid waste landfills.	12.4 years
Nitrous oxide (N_2O)	Emitted during agricultural and industrial activities, as well as during the combination of fossil fuels and solid waste.	121 years
Fluorinated gases (F-gases)	A group of gases that contain fluorine, including hydrofluorocarbons, among other chemicals. These gases are emitted from a variety of industrial processes and commercial and household uses and do not occur naturally, sometimes used as substitutes for ozone-depleting substances such as chlorofluorocarbons (CFCs)	A few weeks to thousands of years

1.3 Global and regional climate models

A climate model is a numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions, and feedback processes and accounting for some of its known properties [8].

Climate models are based on well-established physical principles and have been demonstrated to reproduce observed features of recent climate and the past climate changes [9].

However, it should be considered that the evaluation of these models through comparing their results with the observations requires knowledge of the errors and uncertainties in the observations.

There are generally four main categories of climate models:

- Energy balance models (EBMs)
- One dimensional radiative-convective models (RCMs)[1]
- Two-dimensional statistical-dynamical models (SDMs)
- Three-dimensional general circulation models (GCMs)[2]

Among the mentioned models, we are focusing on the Global Climate Models (GCMs) and Regional Climate Models (RCMs).

Global climate models represent one of the most important tools for simulation of Earth's climate, but generally speaking, they are not able to reproduce local scale features of climate, therefore they do not provide sufficiently detailed information for certain applications.

GCMs grid resolution is typical of the order of 100 to 200 km. Because of a large number of processes included and their relatively high resolution, GCM simulations require a large amount of computer time. It is, therefore, common to downscale the results from the GCM through a nested high-resolution regional climate model (see Figure 1-6).

A global model output data are used to force the regional model at its boundaries and the regional model downscale the global model by producing fine-scale weather patterns consistent with the coarse-resolution features in the global model [10].

Regional climate models are integrated over limited area domains. For this study, RCM models are used because RCMs can afford higher resolution than the global domain models for the same dedication of computer resources.

[1] Regional Climate Models
[2] Global Climate Models

This feature offers the potential for better definition of spatial gradients of topography, land surface characteristics and the atmospheric variables involved in the model's integration and output.

More accurate gradients, in turn, improve the simulations and provide better detail in the model results of interest to use of climate data [11].

Regional climate model covers a limited area of the globe and is run at much finer spatial resolution 1-50 km grid spacing as opposed to 100-200 km grid spacing in a global model, thus they can simulate the interactions between large-scale weather patterns and the local terrain.

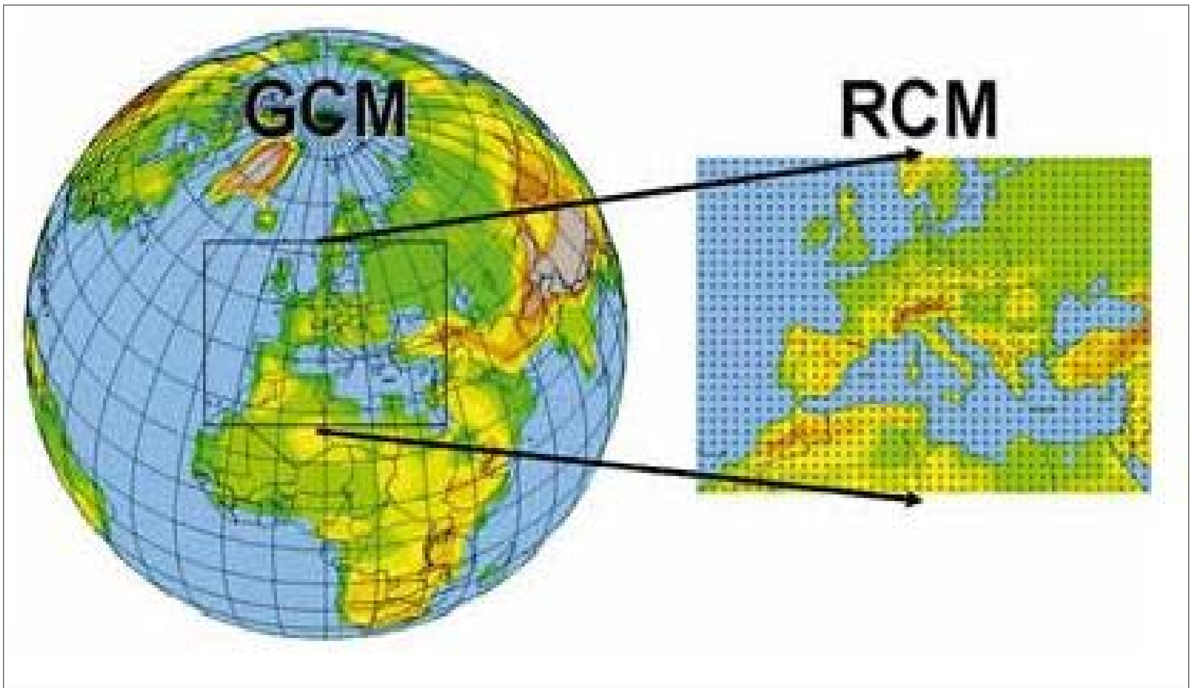

Figure 1-4: Regional Climate Model nesting approach. Source: [12]

The climate model calculations are based on emission scenarios or radiation scenarios (see Figure 1-6).

Emission scenarios are assumptions about future emission of greenhouse gases, based on estimates of the development of the world economy, population growth, globalization, increasing use of green technology.

The amount of greenhouse gases that are emitted depends on the global evolution. The previous approach of IPCC was called Special Reports on Emission Scenarios (SRES) which has been switched to Representative Concentration Pathways (RCPs) now [13].

SRES were run in sequence (see f). This resulted in the protracted development and delivery times. According to the IPCC: “Lags in the development process meant that it was often many years until climate and socioeconomic scenarios were available for use in studies of impacts, adaptation, and vulnerability". Not only that, but changes to prior processes in a sequential model meant going back and rerunning the simulation in order to incorporate the new or changed data.

The RCPs employ a process intended to make the modelling less time-consuming, more flexible, with a reduced economic cost of computation.

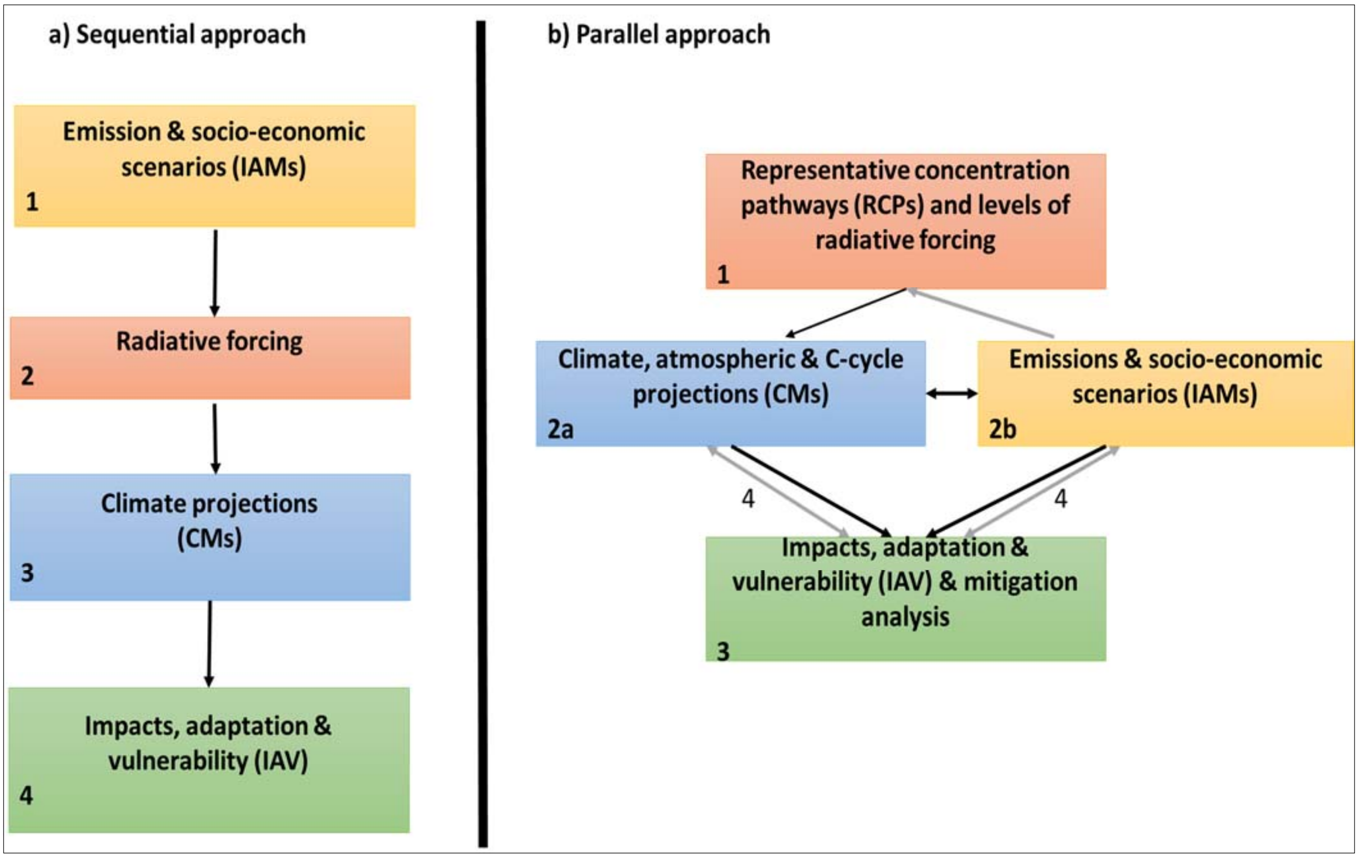

Figure 1-5 Approaches to the development of global scenarios: (a) previous sequential approach; (b) parallel approach of RCPs

In RCPs process the emissions and socioeconomic scenarios are developed in parallel, building on different trajectories of radiative forcing over time rather than starting with detailed socio-economic storylines to generate emissions and then climate scenarios, the new process begins with a limited number of alternative pathways (trajectories over time) of radiative forcing levels (or CO2-equivalent concentrations) that are both representative of the emissions scenario literature and span a wide space of resulting greenhouse gas concentrations that lead to clearly distinguishable climate futures [14].

Radiation scenarios are based on assumptions about how greenhouse effect will increase in the future, known as radiative forcing. If there is an increased emission of greenhouse gases, then there will be more radiative forcing [15].

The RCPs describe four possible climate futures, all of which are considered possible depending on how much greenhouse gases are emitted in the years to come.

The four RCPs, RCP2.6, RCP4.5, RCP6, and RCP8.5, are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m2, respectively) [15].

Table 1-2 Overview of representative concentration pathways (RCPs)

RCPs	Description
RCP 8.5	Rising radiative forcing pathway leading to 8.5 W/m2 (~1370 ppm CO2 eq) by 2100
RCP 6	Stabilization without overshoot pathway to 6 W/m2 (~850 ppm CO2 eq) at stabilization after 2100
RCP 4.5	Stabilization without overshoot pathway to 4.5 W/m2 (~650 ppm CO2 eq) at stabilization after 2100
RCP 2.6	Peak in radiative forcing at ~3 W/m2 (~490 ppm CO2 eq) before 2100 and then decline (the selected pathway declines to 2.6 W/m2 by 2100)

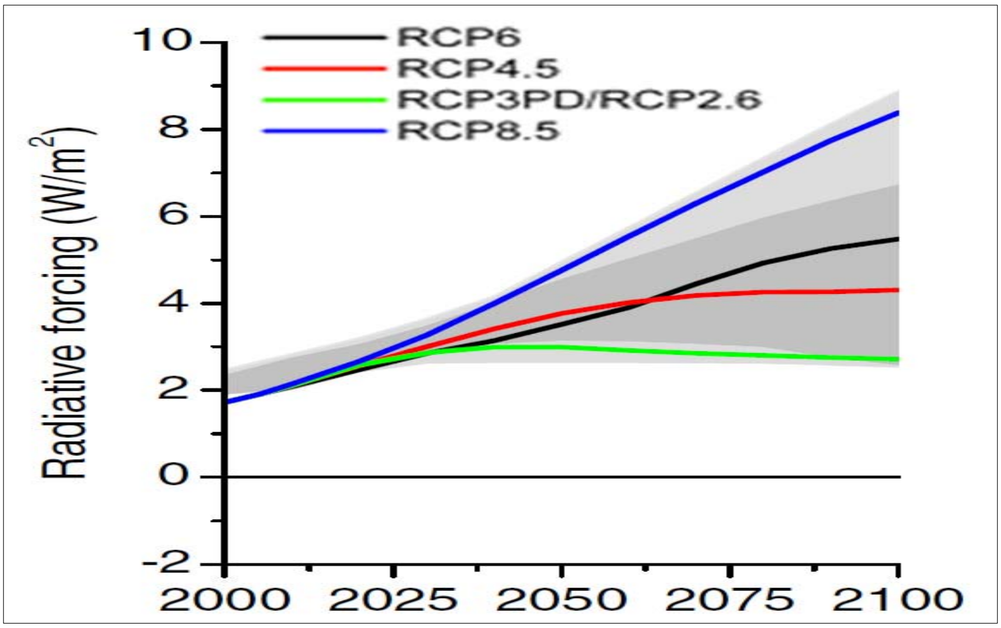

Figure 1-6: Representative Concentration Pathways, Source: [16]

1.3.1 Uncertainties in climate simulation

Large sources of uncertainty are existing in constructing and applying climate models.

Uncertainty in the climate system has two main sources. First, there is uncertainty over human action, including uncertainty due to unknown future emission concentrations of greenhouse gases and aerosols.

Second, there is uncertainty over how the climate system is likely to respond to our actions. Further research may reduce this uncertainty, but may also uncover previously unknown processes, thereby increasing uncertainty.

The greatest uncertainty in climate modelling, which features in all climates downscaling techniques, stems from the unpredictability of future anthropogenic greenhouse gas emissions and their resultant atmospheric concentrations.

The IPCC special report on Emissions Scenarios discusses several factors that impact on the atmospheric greenhouse gas concentrations projected over the present century: population growth, economic and social development, the development and utilization of carbon-free energy sources and technology and changes to agricultural practices and land use [17].

1.3.2 Verification and validation of climate models

There is no guarantee that a computer model will be adequate for its intended use.

Climate models have to be tested to assess their quality and evaluate their performance. A first step is to ensure that the numerical model solves the equation of the physical model adequately. This procedure often referred to as verification, only deals with the numerical resolution of the equations in the model, not with the argument between the model and reality. It checks that no coding errors have been introduced into the program.

The next step is the validation process, determining whether the model accurately represents reality. To do this, model results have to be compared with observation obtained in the same conditions. In particular, this implies that the boundary conditions and forcing must be correctly specified to represent the observed situation. Validation must be first performed on the representation of individual physical processes, such as the formulation of the change in the snow albedo in response to surface melting and temperature change (see **Error! Reference source not found.**) [18].

It is important to note that in this master thesis, no model is developed or verified. The main focus as it will be stated specifically in the objective section is the evaluation of a certain atmospheric variable (temperature) over the chosen region.

1.4 Energy consumption in buildings

Global warming and climate change are the contemporary threats to ecosystem services and biodiversity that has a huge impact on the environment, livelihood of communities and economies across the world. It is well recognized that world energy consumption is divided into three major economic sectors [19].

- Buildings
- Transportation
- Industrial

Other sectors such as agriculture and service sectors are other major economic sectors with relatively high energy consumption.

Buildings account today for about 40% of final energy consumption worldwide and they are responsible for about one-third overall CO_2 emissions (36% in Europe, 39% in the USA, about 20% in China).

Especially in urban structures, the building energy consumption is typically twice as high as transport. The energy saving potential is large in the short-term (up to 2020), saving 20% is expected within the European Union and in the long term (up to 2050), buildings are supposed to be climate neutral.

An analysis of the final end use of energy in the EU-28 in 2014 shows three dominant categories: namely, transport (33.2 %), industry (25.9 %) and households (24.8 %) — see Figure 1-7 [20] .

The improvement of the building energy efficiency can be economically worthwhile, as shown by a study of the IPCC, between 12% and 25% CO_2 emissions caused by heating and cooling and between 13% and 52% CO_2 emissions caused by electric lightning and equipment can be reduced economically until 2020 [21]. Most of this energy is for the provision of lightning, heating, cooling and air conditioning [22].

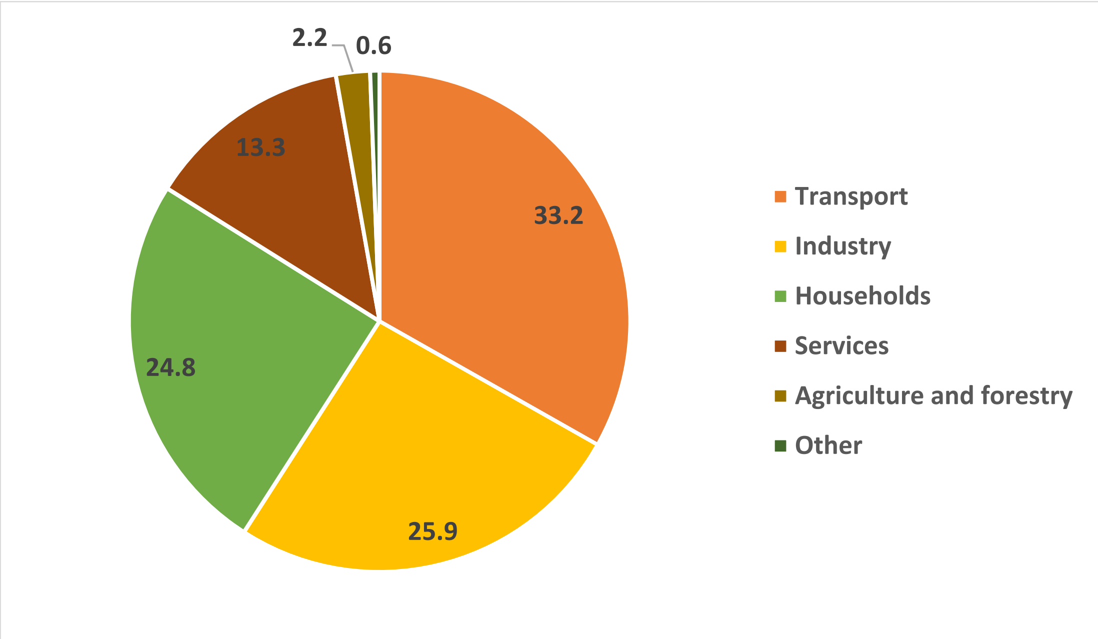

Figure 1-7: Final energy consumption, EU-28, 2014 (% of total, based on tonnes of oil equivalent), Source: [20]

By 2020, the EU aims to reduce its greenhouse gas emissions by at least 20%, increase the share of renewable energy at least 20% of consumption, and achieve energy savings of 20% or more.

Directive 2010/31/EU is the result of the Energy 2020 strategy. The objective of this Directive is to promote the improvement of the energy performance of buildings within the Union, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness.

The Catalan Strategy for the Energy Renovation of Buildings was elaborated in 2013 and has an aim of completion by 2020. Its main goal is to achieve a 14.4% reduction in energy consumption by buildings from 2012 levels and a 2.6 million-ton reduction of CO_2 emissions through the renovation of existing private and public buildings. In presenting this plan, the Catalan Government stressed the use of renewable energies, especially in private homes, and called for the energetic renovation of the 1.5 million buildings built in the territory before 1980 at an estimated cost of €8 billion [23].

The Energy Plan 2006-2015, developed by the Catalan government through the Catalan Energy Institute (ICAEN), has made a commitment to position itself at the top of the European energy sector in the 21st century.
The plan will develop a diversification strategy regarding energy sources by promoting renewable energy, improving efficiency and energy saving, creating the energy infrastructure necessary to support research and development, and technological innovation in this field.

In 2002, Barcelona started its Energy Improvement Plan (PMEB), which became the first structured approach to the sector in the city of Barcelona. In 2011, the city council approved a new plan called Barcelona Energy, Climate Change and Air Quality Plan 2011-2020 (PECQ).

This plan brings continuity to previous strategies in terms of global strategic planning in the energy and climate change sectors, but also incorporating air quality issues from a local perspective.

The reasons to invest in the energy, mobility and environmental sectors in Barcelona and Catalonia is that Barcelona is towards a new city model with sustainability and energy-saving efficiencies.
Major operators in Catalonia have commitments to renewable energies. Barcelona has a LIVE Platform, which is a benchmark in electric mobility. Energy Park is a strategic project for the future of the sector, the environmental forum platform, urban ecology is a key factor in Barcelona smart city [24].
Many activities are ongoing in Barcelona and Catalonia, which makes it very interesting and also crucial to study different aspects this movement toward sustainability and provide and implement intelligent solutions.

1.5 Building energy management systems (BEMS)

Building Energy Management Systems (BEMS) are integrated, computerised systems for monitoring and controlling energy-related building services plant and equipment such as heating, ventilation and air conditioning (HVAC) systems, lighting, power systems.

Energy management is the best solution for the direct and immediate reduction of energy consumption. The main objectives of energy management are resource conservation, climate protection, and cost saving.

The central task of the energy of energy management is to reduce costs for the provision of energy in buildings and facilities without compromising work processes. The simplest way to introduce energy management is the effective use of energy to maximize profit be a minimizing way to introduce energy management could save up 70% of the energy consumption in a typical building or plant.

As it said before, today, buildings are responsible for more than 40% of global energy used, and as one-third of global greenhouse gas emissions, both in developed and developing countries. The main source of greenhouse gas emissions from buildings is energy consumption, but buildings are also major emitters of other non-CO_2 greenhouse emissions such as halocarbons. The five major policy objectives for reducing greenhouse gas emissions from buildings are [22]:

1. Increase the energy efficiency of new and existing buildings (both the physical envelope and the operational aspects such as energy systems for heating, ventilation, and other appliances)
2. Increase the energy efficiency of appliances (white goods, entertainment, personal computers and telecommunication equipment)
3. Encourage energy and distribution companies to support emission reduction in the building sector.
4. Change attitudes and behaviours
5. Substitute fossil fuels with renewable energies.

Having said all the above, study the evolution of daily mean temperature in specific regions below Climate change scenarios and analysis of the impact on energy consumption in buildings could have significant impacts on the mentioned policies implementation.

Currently, space heating and cooling together with water heating is estimated to account for nearly 60% of global energy consumption in buildings. They, therefore, represent the largest opportunity to reduce building's energy consumption, improve energy security and reduce CO_2 emissions, particularly because space and water heating provision in some countries is dominated by fossil fuels. Meanwhile, cooling demand is growing rapidly in countries with highly carbon-intensive electricity systems. All occupied buildings require a supply of outdoor conditions. Depending on outdoor conditions, the air may need to be heated or cooled before it is distributed into the occupied space.

Moderate and controlled use of energy would be possible through an energy plan, which is adapted to the characteristics and status of the region's climate. Proper and optimum use/implementation of insulation, cooling and heating systems, lightning, appliances and consumer products, etc. would be possible through such a plan.

Energy efficiency means using less energy for the same or even increased output. It is increasingly being recognized as one of the most important and cost-effective solutions for reducing greenhouse gas emissions produced as part of industrial processes, including in the iron and steel sector.

An energy management system (EnMS) is a systematic process for continually improving energy performance and maximising energy savings. The principal of an EnMS is to engage and encourage staff at all levels of an organization to manage energy use an on-going basis. The basic EnMS process is based on the Plan-Do-Check-Act continual improvement framework [25]:

- Plan: conduct an energy review and establish the baseline, benchmark against similar sites, set objectives and targets, develop resources, and action plans necessary to deliver results in accordance with the organization's energy policy.
- Do: Implement the action plans.
- Check: Monitor and measure processes review the level of target achievement and the effectiveness of the EnMS against the objective of the energy policy.
- Act: Recognize achievements, take action to continually improve energy performance and the EnMS, derive new objectives.

This Plan-Do-Check-Act framework provides a procedure for companies to:

- Develop a policy for more efficient use of energy
- Fix targets and objectives to meet the policy
- Use data to better understand and make decisions concerning energy use and consumption
- Measure the results
- Review the effectiveness of the policy
- Continually improve energy management

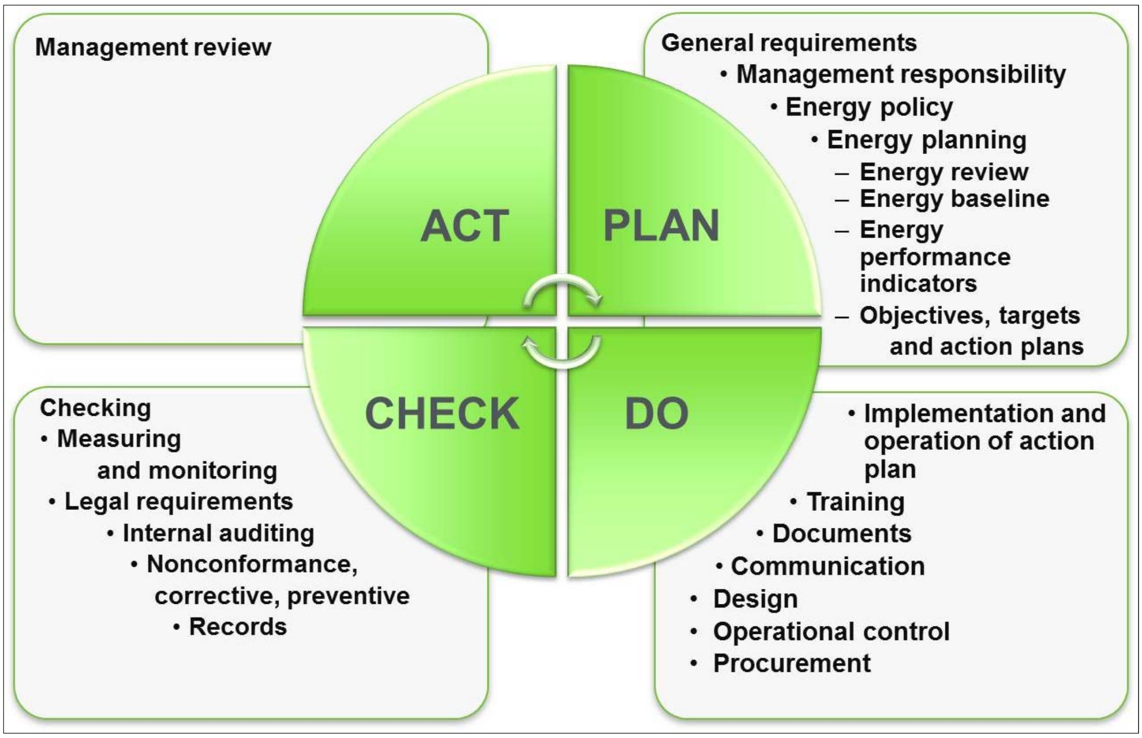

Figure 1-8: Basic EnMS process, Source: [26]

2 Objective

The aim of this study is to assess the temperature trend for Catalonia and Barcelona. That is analysing the annual and seasonal mean temperature from the past (1981-2005) and the future (2031-2050) below climate change scenarios.

It is of interest to define the appropriate methodology for calculating the CDD, HDD from data of a climate model. In addition, an analysis of the selected indicators for the first part of the 21st century will be presented and recommendations for energy managers will be provided.

3 Case of study

3.1 Geography of Catalonia and Barcelona

Catalonia is an autonomous region of north-eastern Spain that extends north to the French border and is divided into four provinces: Barcelona, Tarragona, Girona, and Lleida. Figure 3-1 shows these main orographic features [27].

There are two mountain ranges with average heights of around 500 m.a.s.l[3] and 1500 m.a.s.l, located parallel to the coastline, and the Pyrenees, with summits above 3000 m.a.s.l.

These orographic factors, together with the influence of the Mediterranean Sea and associated Mediterranean air mass, as well as the Atlantic influence on the north-western side of the region, produces high climatic and meteorological contrasts between different areas.

In Catalonia, in general, the maximum temperature variation occurs in summer and the minimum variation in winter, while autumn and spring are intermediate seasons (see Figure 3-2)[28].

Figure 3-1: Main orographic features of Catalonia. Source: [29]

[3] Metres above sea level

Barcelona is located in the north-eastern Spain and on the shores of the Mediterranean, is one of the principal European cities and centres of a vast metropolitan region of more than 160 towns. Barcelona is the capital of Catalonia. Most of the population lives along or near the coast. The coastline (580 km) is rocky with cliffs in the north and becomes much flatter in the south. Catalan landscape is diverse: there are large inland valleys and plains, and High Mountain peaks in the Pyrenees that reach 3,000 meters.

Barcelona exhibits a Mediterranean Climate with mild winters and hot summer. The average daily winter temperature reaches in winter a minimum of 4°C and a maximum of 13.4 °C (January) and in the peak of the summer (July and August) a minimum of 19.4 °C and maximum 28 °C. Rain occurs mainly in late summer and autumn, with very low precipitation in June and July (see Figure 3-3) [24].

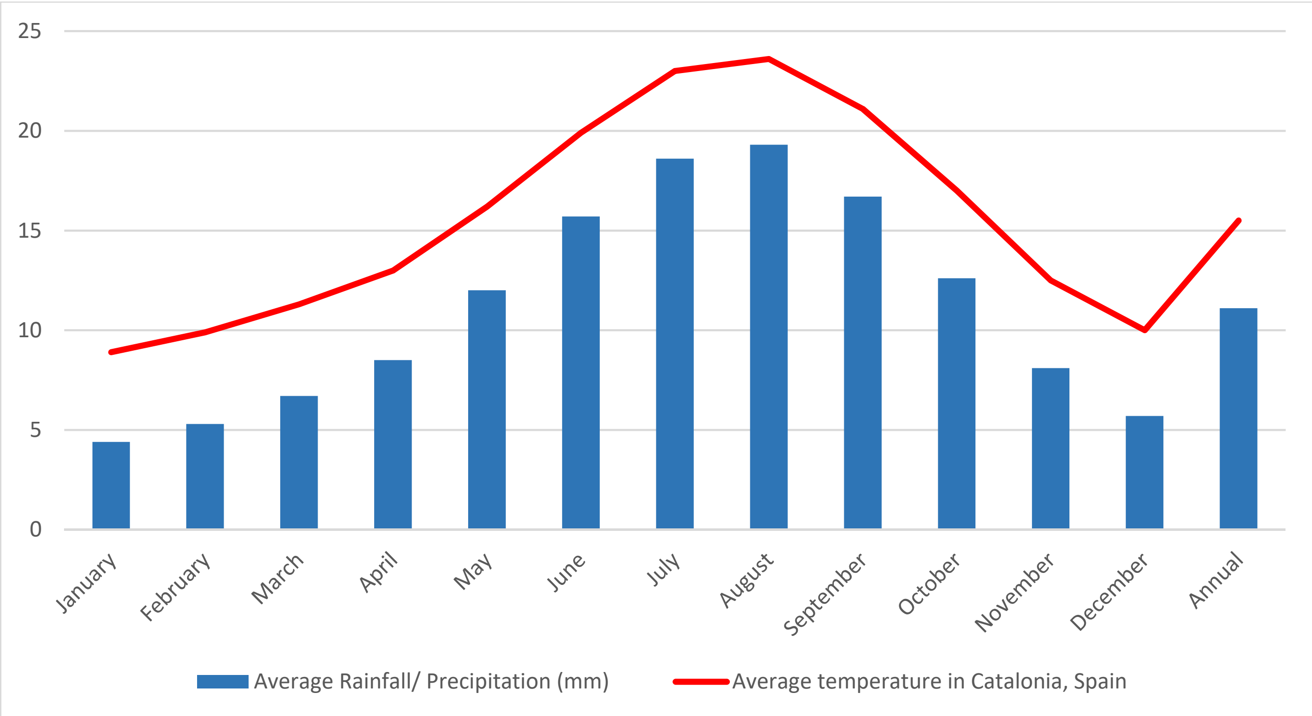

Figure 3-2 Graphical representation of Catalonia's climatological data, precipitation (blue) and temperature (red) changes along the year, source: [30]

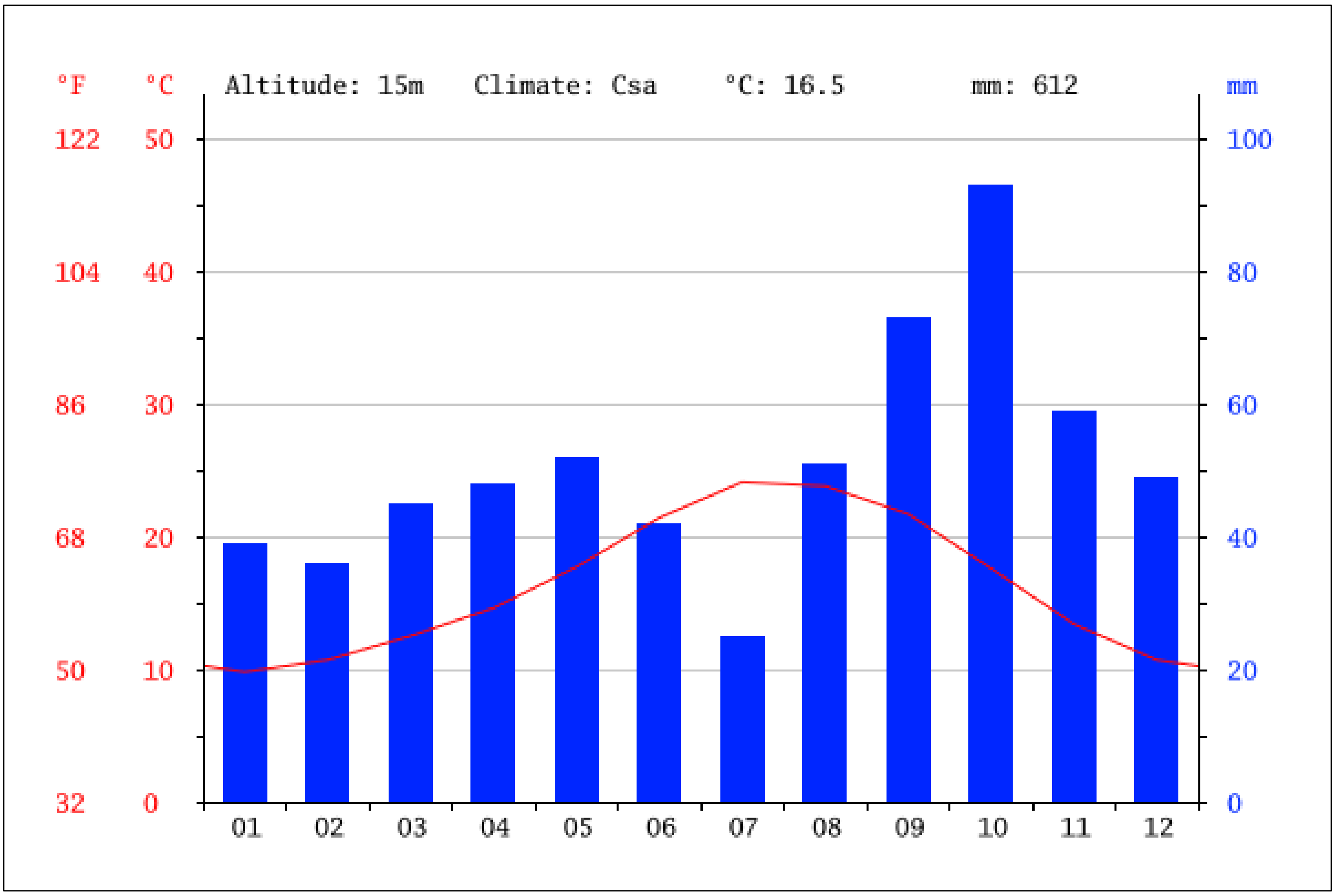

Figure 3-3 Graphical representation of Barcelona's climatological data, precipitation (blue) and temperature (red) changes along the year, source:[30]

Tabla.3.1 shows the population, surface area (Km2) and density (inhab/Km2) of Catalonia and Barcelona in 2015.

Table 3-1: Population, area (km²), density (inhab/km²) of Catalonia and Barcelona. Source: [31]

2015	Population	Surface area (km^2)	Density ($inhab/km^2$)
Catalonia	**7,508,106**	**32,108.0**	**233.8**
Barcelona	**5,523,922**	**7,726.4**	**714.9**

Figure 3-4 shows the monthly maximum temperature of Barcelona from 1950 to 2015. As it could be seen, the maximum temperature is higher than 23 °C, which is higher than the comfort temperature for HDD (22 °C) in summer (July). In addition, the minimum temperature is less than 7 °C, which is lower than the comfort temperature for CDD (18 °C) for winter (January).

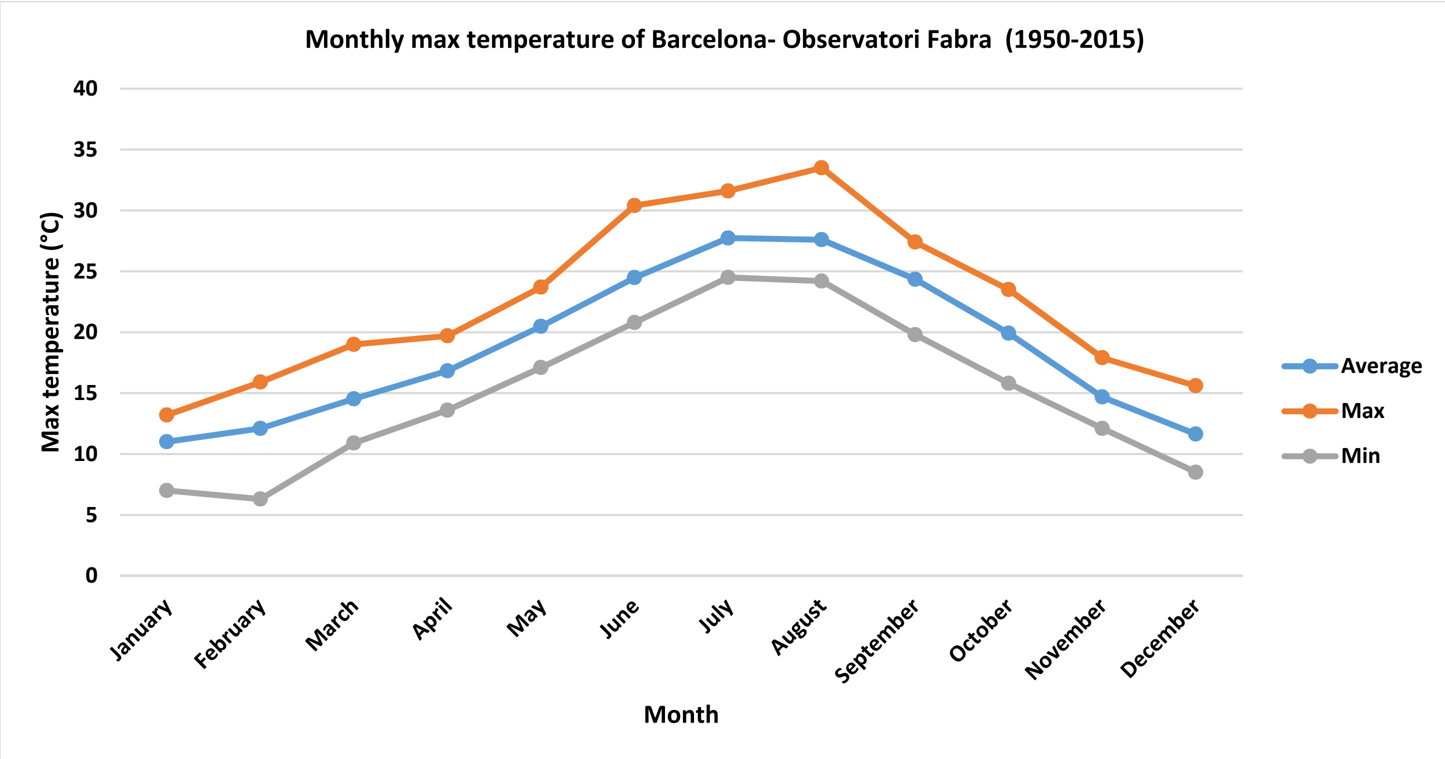

Figure 3-4: Maximum temperature of Barcelona-Observatory Fabra From 1950-2015. Source: [32]

According to the context of the United Nations Climate Change Conference, the Meteorological Service of Catalonia has conducted a preliminary study, with data from January to November, to evaluate the state of the climate in Catalonia in 2015.

The detailed examination of 15 monthly average temperature series for the period from 1950 to 2015 (see Figure 3-5) shows that 2015 is likely to be the fourth hottest year since 1950 and most probably since records began. Catalonia from January to November was 15.2 °C, some 1.5 °C higher than the climate average obtained for the 1961-1990 control period.

An analysis of temperatures average over five-year periods produces a more precise view of the long-term trend. Therefore, in Catalonia, the 2011-2015 quinquennium has clearly been the hottest, with a deviation of 1.37 °C with respect to the climate average.

It is also worth pointing out that since 1994, the average annual temperature has always been higher than the average for the 1961-1990 period. At the global level, the WMO[4] estimates that 2015 will probably be the hottest year since 1850, due to a combination of human-induced global warming and the extreme El Niño event currently taking place [33].

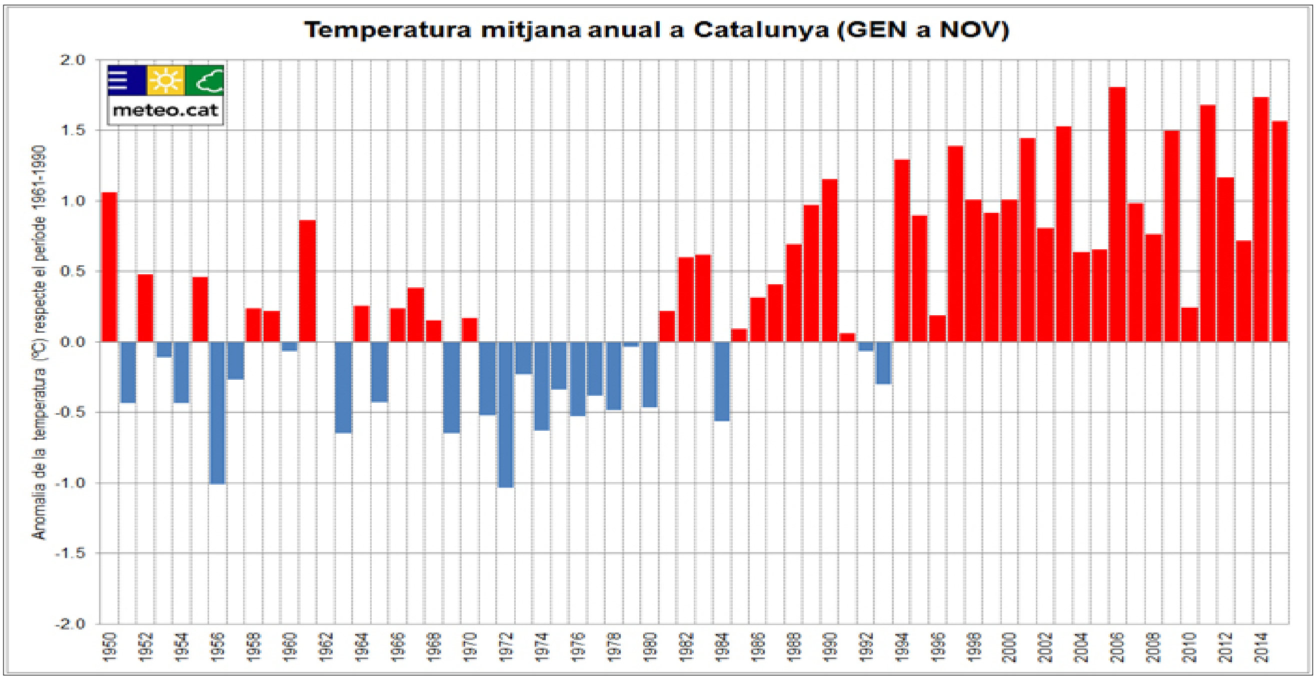

Figure 3-5: Annual anomaly temperature of Catalonia, from January to November (1950-2015), Source: [33]

3.2 Energy sector in Catalonia

The series for electricity invoicing in Catalonia is built by the aggregation of invoicing in KWh at the all-inclusive rate (regular market) and access/toll rate (free market) of the main electricity utility operating in Catalonia (FECSA-ENDESA), carried out by the Catalan Energy Institute and the Ministry of Economy and Finance (see Table 3-2).

Since January 2009 the new classification of economic activities (CCEA, 2009) has been used. It does not coincide in some cases with the sector groupings in the previous classification, which means the series are interrupted. Up until December 2008, electricity invoicing in Catalonia was broken down into the following sectors:

- Industry: manufacturing industry and energy sector.
- Tertiary: services, public administration, and transport.
- Domestic

[4] World Meteorological Organization

- Other: primary, construction, and public works, unclassified and sales to other electricity distribution companies.

Data from January 2009 on are broken down as follows:

- Industry: manufacturing industry and energy sector (except ship breaking and recycling, which move to Tertiary)
- Tertiary: services, public administration, transport, recycling, and ship breaking (previously in Industry) and sales to other electricity distribution companies (which previously was in other sectors).
- Domestic
- Other: primary, construction and public works, real estate development (previously in Services) and unclassified.

As it can be seen in the table, in Catalonia, the industry has the highest rate of invoicing followed by tertiary and domestic sectors. The enhanced energy plans based on the evolution of the climate changes can target these sectors for energy consumption efficiency.

Table 3-2: Electricity invoicing by sectors in Catalonia, Units: GWh, July 2014-June 2016. Source: Catalan Energy Institute (IDESCAT).

		Year-over-Year variation		
	Value	**Absolute**	**% month**	**% accumulated**
Industry	**1,323.9**	**-24.0**	**-1.8**	**1.1**
Tertiary sector	**1,084.0**	**-44.2**	**-3.9**	**-2.7**
Domestic sector	**791.1**	**47.4**	**6.4**	**-0.6**
Other	**50.5**	**1.5**	**3.0**	**2.0**
Total	**3,249.5**	**-19.3**	**-0.6**	**-0.6**

3.3 Energy Balance in Catalonia

In Catalonia, 24,297 ktoe (thousands of tonnes of oil equivalent) were consumed in 2009 (most recent available data) in the form of primary energy, i.e. the energy found in nature before it is transformed for use (Figure 3-6). 25% percent of this energy was produced in Catalonia, and the remaining 75% was imported from other regions.

82% percent of the primary energy produced in Catalonia was nuclear, while renewable energy, in the second place, represented 14% (Figure 3-7). Within this latter group, hydroelectric power was the main source, with 44%, followed by, in order of importance, renewable waste, agricultural and forestry biomass, wind power, biofuels, and lastly, biogas and solar power, with 5% each (Figure 3-8).

The sources of primary energy consumed in 2009 were, in order of consumption, oil (47%), natural gas (25%), nuclear energy (20%), renewable energy (4%) and other energy (4%).

With respect to the final energy, i.e. that which is used directly by consumers, 14,548 ktoe were consumed by energy end-users in Catalonia in 2009. This consumption was made up of petroleum products (49%), natural gas (21%), electric energy products (27%) and renewable energy products (2%).

In terms of the sector, the energy consumption associated with the transport sector is 41%, followed by that of the industrial sector (27%). These were followed by the domestic sector (16%), the service sector (12%) and the primary sector (4%).

The evolution of energy consumption between 2006 and 2009 (the last year for which data are available) shows that, following the constant rise since 1990 and the peak of consumption reached at 2005, the trend reversed.

Thus, consumption of primary energy and the final energy fell by 8% between 2006 and 2009. The major cause of this reduction was the economic recession. However, indices such as per capita consumption (**Error! Reference source not found.**) and energy intensity (the amount of energy consumed per unit of wealth created) also showed that energy consumption was slightly out of synch with respect to the population and the level of wealth generated since 2003, which would indicate improved efficiency in the use of energy [34].

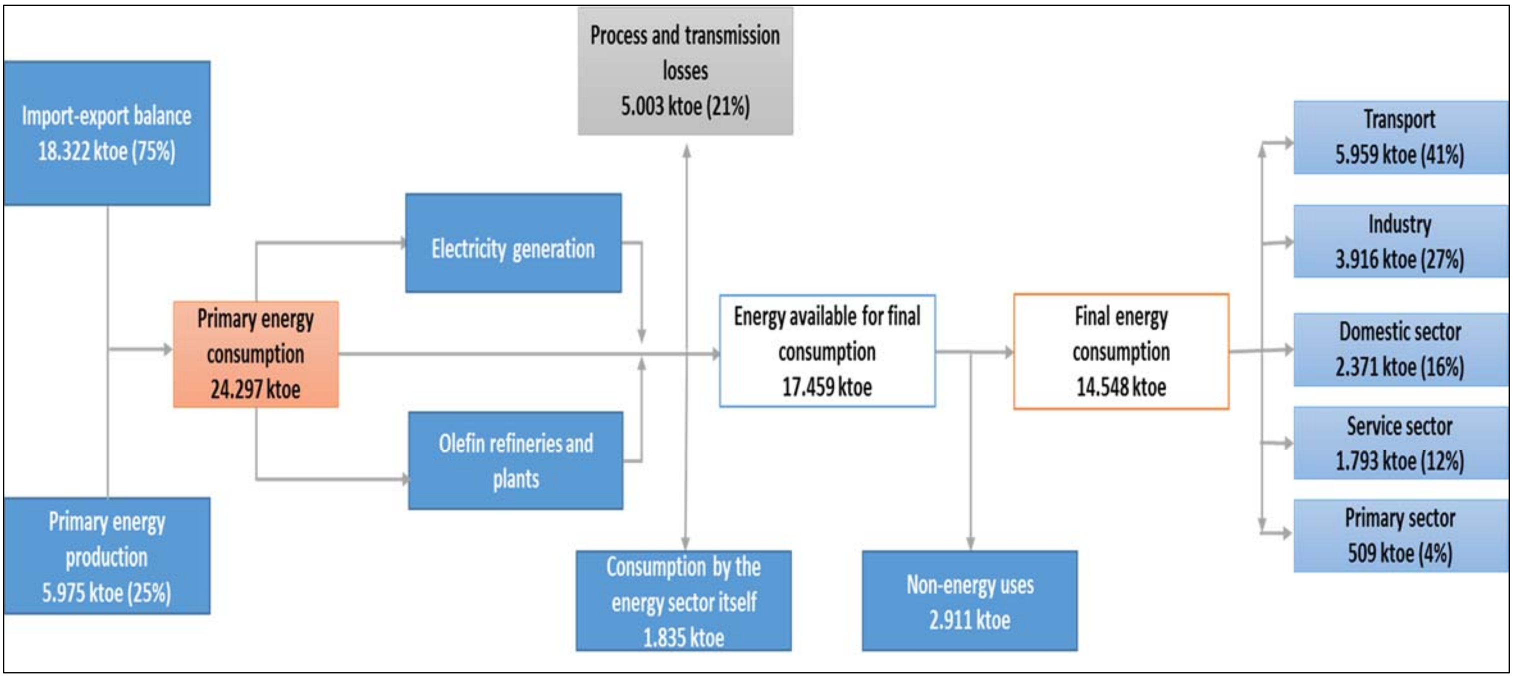

Figure 3-6: Simplified diagram of Catalonia's energy balance. 2009. Source: [34]

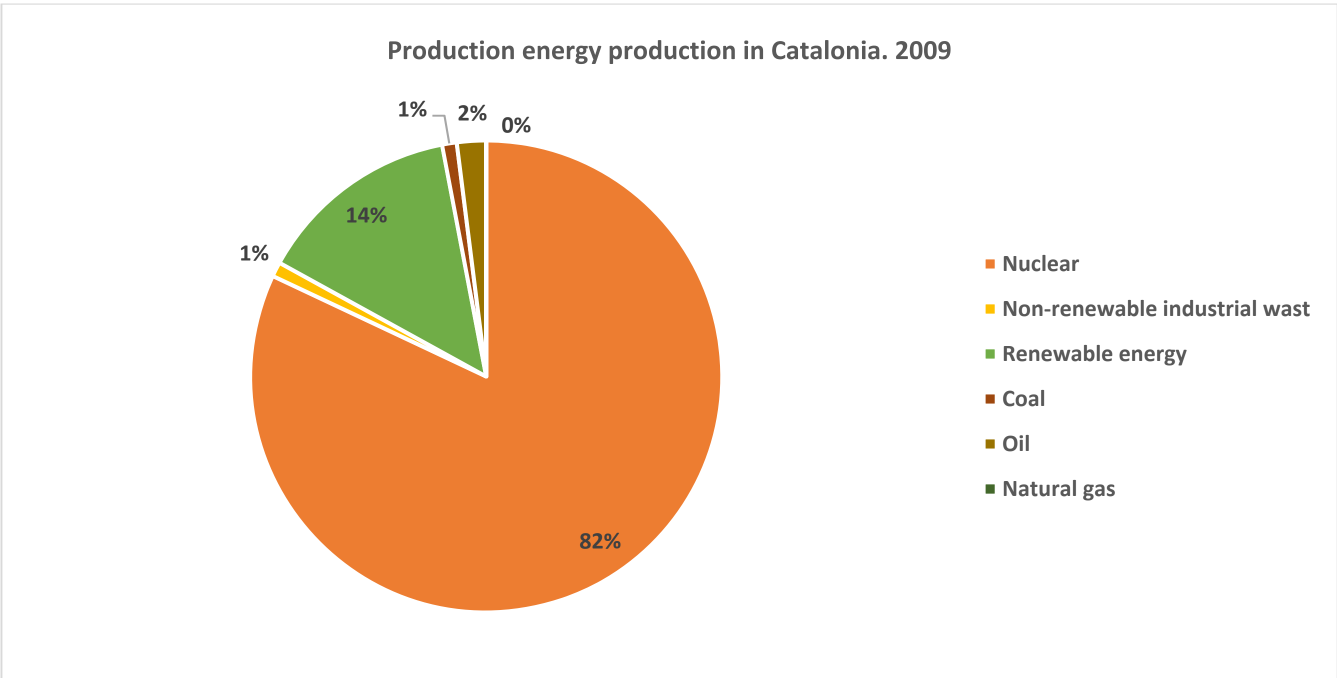

Figure 3-7: Primary energy production in Catalonia. 2009. Source: [35]

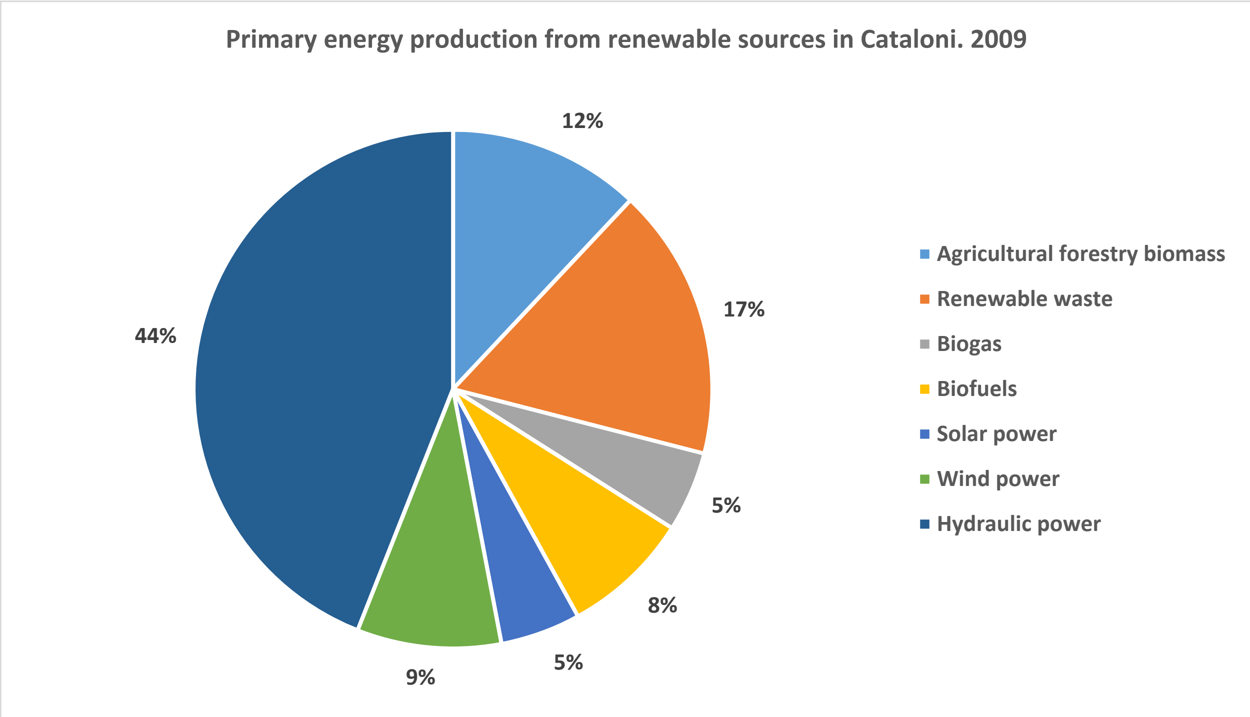

Figure 3-8: Primary energy production from renewable sources in Catalonia.2009. Source: [35]

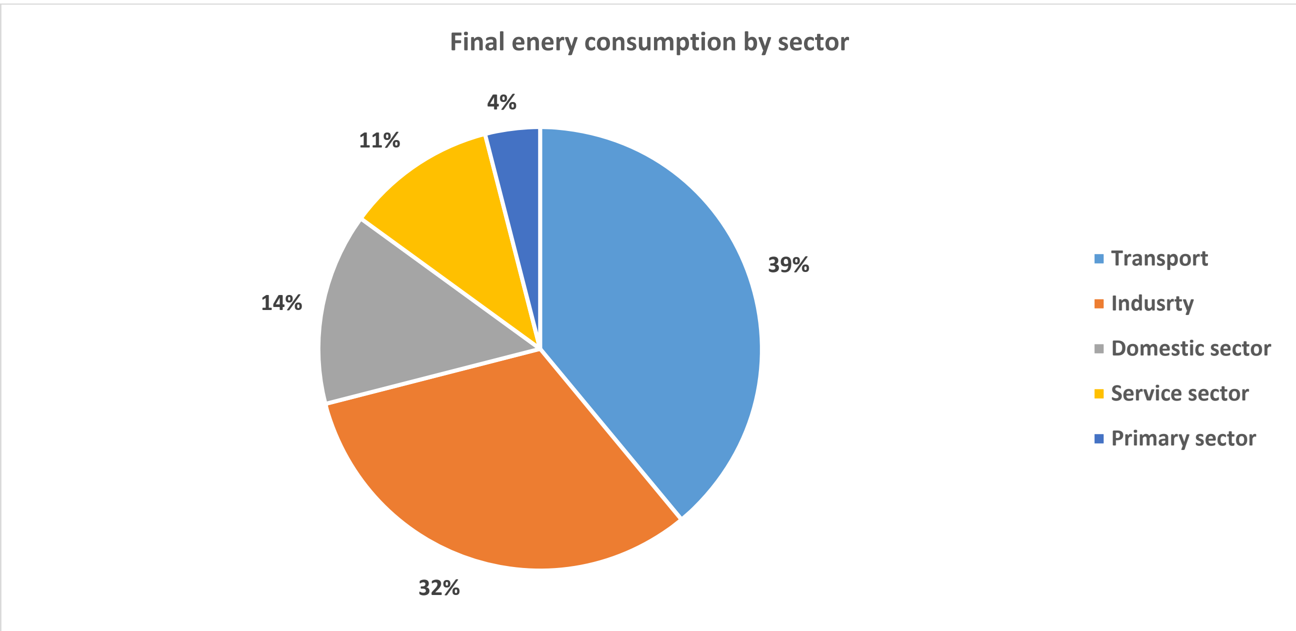

Figure 3-9: Final consumption by sector in Catalonia. 2009. Source: [35]

4 Methodology

4.1 Climate model data treatment and processing

In this study, the main goal is to predict the daily mean temperature of Catalonia and Barcelona provided by different regional climate models and it centred in the first part of the 21st century.

The model used for this study is the non-hydrostatic regional climate model COSMO-CLM[5]. The CCLM model is a versatile limited-area atmospheric modelling system, including a whole suite of model parameterization. It is based on the non-hydrostatic compressible atmospheric equations, uses the split-explicit time stepping scheme, and is suited for application with a horizontal grid spacing from about 100 m to 100 km. The CCLM has heavily been used for regional climate studies using real case and idealized configurations. In this study is called CLM model [36].

Another model, which has been used in this study, is the Max Planck Institute for Meteorology (MPI) model. MPI model is based on a coupled ocean-atmosphere GCM. It consists of the atmosphere model ECHAM5 with spectral resolution of T63 (1.875˚× 1.875˚) and 31 vertical levels as well as the MPI ocean model (MPI-OM) with an average horizontal grid spacing of 1.5° and 40 vertical levels and in this study is called MPI model. [37].

All this information is getting from EURO-CORDEX. EURO-CORDEX is the European branch of the international CORDEX initiative, which is a program sponsored by the World Climate Research Program (WCRP) to organize an internationally coordinated framework to produce improved regional climate change projections for all land regions worldwide [38].

As part of the global CORDEX framework, the EURO-CORDEX initiative provides regional climate projections for Europe at 50 km (EUR-44) and 12.5 km (EUR-11) resolution, thereby complementing coarser resolution data sets of former activities like, e.g., PRUDENCE and ENSEMBLES.

In this study, it used the RCP4.5 because it represents a medium mitigation scenario, while RCP2.6 represents a more aggressive mitigation scenario which aims to keep global warming below 2°C above pre-industrial temperatures and RCP4.5 has a greater rate of rising earlier in the century than RCP6.0 [39].

In this study, we used Climate Data Operators (CDO). A Climate Data Operators software is a collection of many operators for standard processing of climate and forecast model output. The operators include simple statistical and arithmetic

[5] Climate Limited-area Modelling

information, data selection and subsampling tools and spatial interpolation. CDO was developed to have the same set of processing functions for GRIB and netCDF datasets [40].

The downscale data is set in the historic baseline period from 1981 to 2005 and future baseline time period from 2031 to 2050. The data are included all the Europe, so according to this study the data should be extracted for Catalonia and Barcelona with their longitude and latitude and merge all the data that extracted, corresponding to the historical and the future periods of Catalonia and Barcelona.

The applied longitude of Catalonia is 3°19'59,94" 0°9'41,69" and the latitude is 42°51'45,97" 40°31'27,56" (source: Institute d'Estatistica de Catalunya).

The applied longitude for Barcelona is 2°46'45,14" 1°21'42,98" and the latitude is 42°19'27,72" 41°11'38,00" (source: Institute d'Estatistica de Catalunya).

Catalonia is characterized by complex topography that has a considerable impact on the region's climatology and atmospheric circulation patterns. This is the reason, which makes it important to study the evolution of different atmospheric variables (in our case the mean temperature) and assess the changes and their impact on different sectors and aspects.

Moreover, Barcelona as the capital of Catalonia and one of the most populated cities of it, with a high concentration of industrial sites, higher levels of greenhouse gas emissions and of course high levels of energy consumption. As said previously, our study could be of interest for decision-making in different sectors- active in this region.

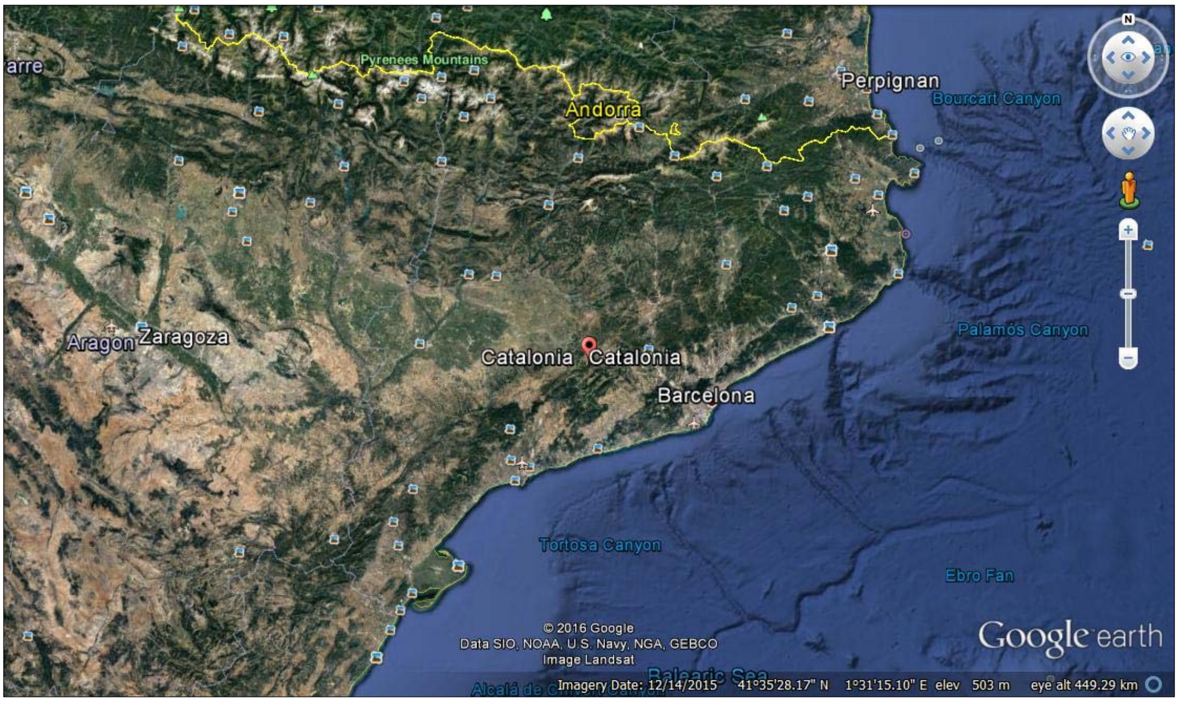

Figure 4-1: Map of Catalonia, Source: Google Earth

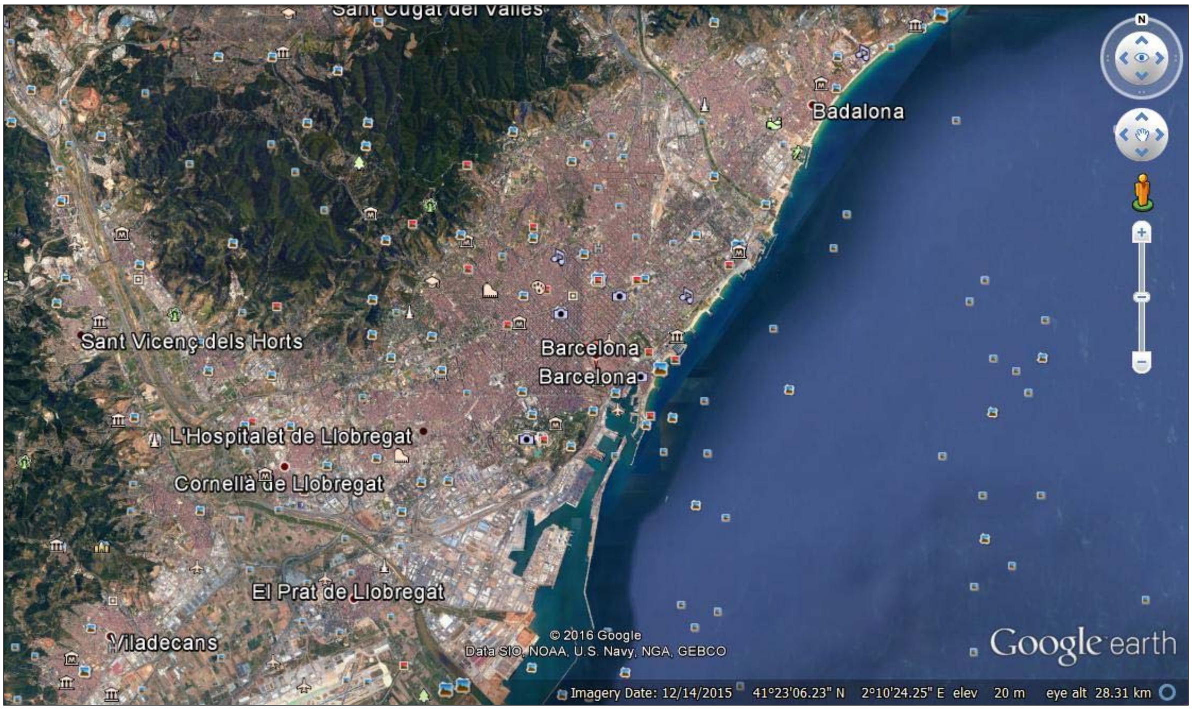

Figure 4-2: Map of Barcelona, Source: Google Earth

4.2 Observations used to evaluate the models

In order to evaluate the models and having a reference, we have used the observation data from ECA&D EOBS (European Climate Assessment & Dataset). The ECA dataset contains series of daily observation [41].

The data contains the daily mean temperature from 1981 to 2005 and future data from 2031 to 2050 for Catalonia and Barcelona. We calculated the seasonal average of CDD and HDD and the annual average anomaly of CDD and HDD with this data, to compare the observation results with the climate models. That is to compare different datasets and identify which model shows better, more realistic results.

4.3 Calculating of the HDD and CDD

Heating Degree Day (HDD) and Cooling Degree Day (CDD) are quantitative indices being designed to reflect the demand for energy requirements to heat or cool a building.

These indices are derived from daily temperature observations. Generally, a degree-day shows the value that contains the adding temperature of the environment.

It gives the value of quantity and duration when the air temperature becomes lower or higher than a determined threshold value, which is known as the basic temperature. Base temperature for CDD and HDD are:

$$\boldsymbol{CDD} = (\boldsymbol{T_{base}} - \boldsymbol{T_i}) +$$

$$\boldsymbol{HDD} = (\boldsymbol{T_i} - \boldsymbol{T_{base}}) +$$

Where T_i is the daily mean temperature and T_{base} is the base temperature, and the plus sign means that only positive values will be used, and all negative values are treated as zero [42].

For calculating Cooling degree-days, the comfort temperature should be subtracted, which is 295 Kelvin (22°C) from the daily mean temperature and select the positive values. For calculating Heating degree days, the daily mean temperature should be subtracted from the base temperature which is 291 Kelvin (18 °C) and selects the positive values [43].

4.4 Calculating anomaly

The term of anomaly means a departure from a reference value or long-term average.

In our study, a positive anomaly indicates that the observed values for the CDD/HDD were higher (warmer) than the reference value, while a negative anomaly indicates that the observed CDD/HDD was cooler than the reference value [44].

For calculating anomaly of HDD/CDD, first, the mean variable from historical and future period should be calculated and then the mean value should be subtracted from both historical and future data.

In addition to the annual average calculations and analysis, a seasonal study was performed as well (summer and winter months).

5 Result

This part includes the results of the calculations and analysis of the evolution of mean CDD and HDD in the selected region.

Section 5.1 presents the model evaluation against observations (historical data). Results from both annual and seasonal analysis are stated in the section.

Section 5.2 is all about the outcomes of the analysis for future data.

5.1 Model evaluation

In this section, the result of the model evaluations and comparisons is presented. The study is done for the period of 1981 to 2005 in Catalonia and Barcelona and we discussed that which models are shown the better anomaly for HDD and CDD respecting to the average.

5.1.1 Annual average of anomaly for cooling and heating degree days in Catalonia and Barcelona

Figure 5-1 represents the annual average of an anomaly for cooling degree-days in Catalonia from 1981 to 2005 from two climate models (CLM and MPI) and the observations data.

As it could be seen, anomaly shows the positive value, which means that the CDD increased every year, with respect to the average of all the period in the MPI model and the observations. However, the CLM model shows the opposite and the CDD decrease each year with respect to the all-time- average.

It can be concluded that MPI model better shows anomaly variations of CDD.

However, it should be considered that since the calculated R-square of the trend line is not strong enough and it has a very low value.

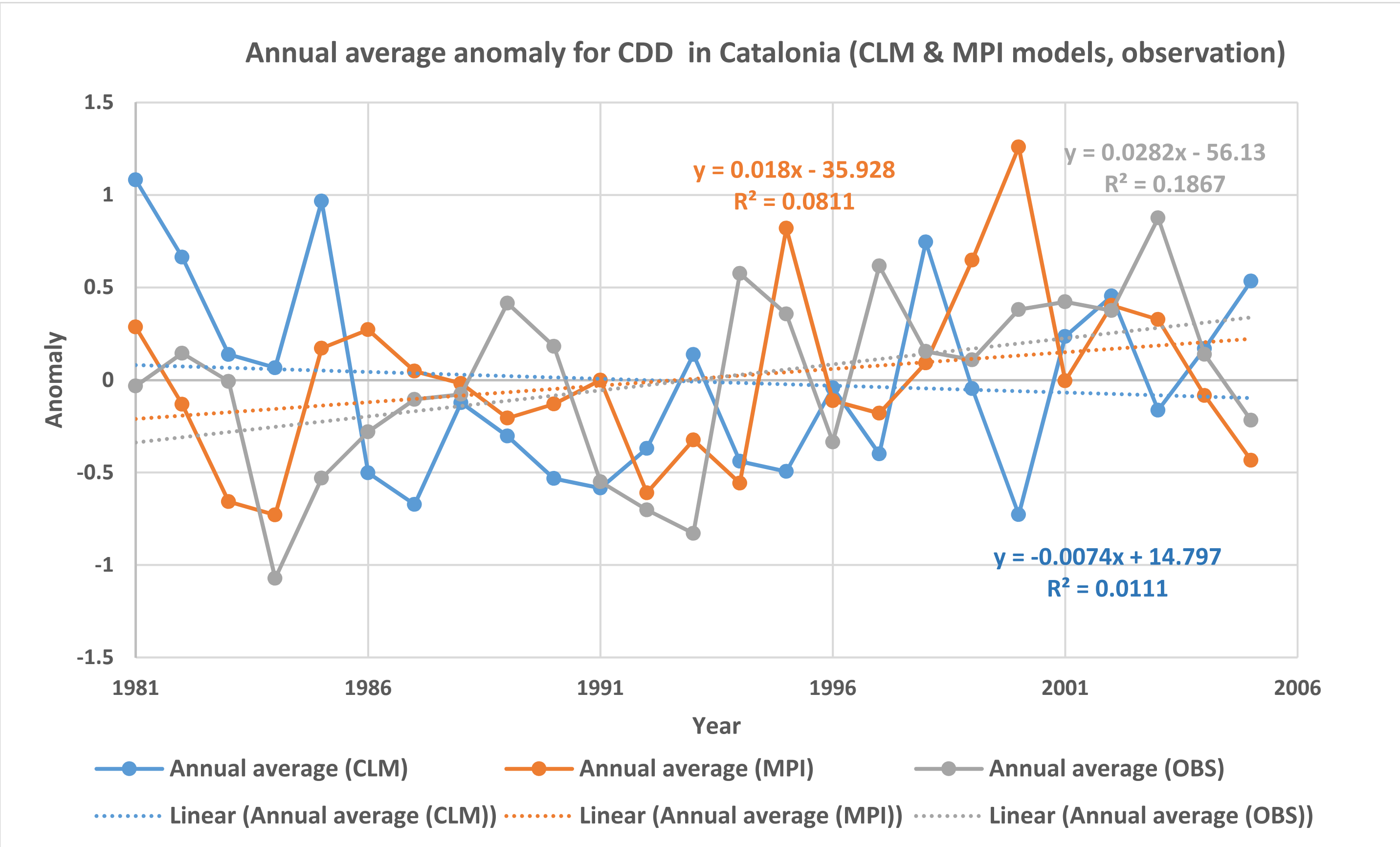

Figure 5-1: Annually average of anomaly for CDD in Catalonia, CLM, MPI models and observation, 1981-2005

Figure 5-2 shows the annual average anomaly of the heating degree-days in Catalonia from 1981 to 2005, using two climate models (CLM and MPI) and observations.

As it could be seen, anomaly for heating degree-days -applying the CLM model shows a positive value, which means that the HDD increased every year, with respect to the average of all the period.

The MPI model and observation analysis however, show the opposite result and the HDD in each year with respect to the all-time- average.

It can be concluded that MPI model better shows anomaly variations of HDD.

However, it should be considered that since the calculated R-square of the trend line is very low, so we cannot be so confident that the model shows better anomaly variation.

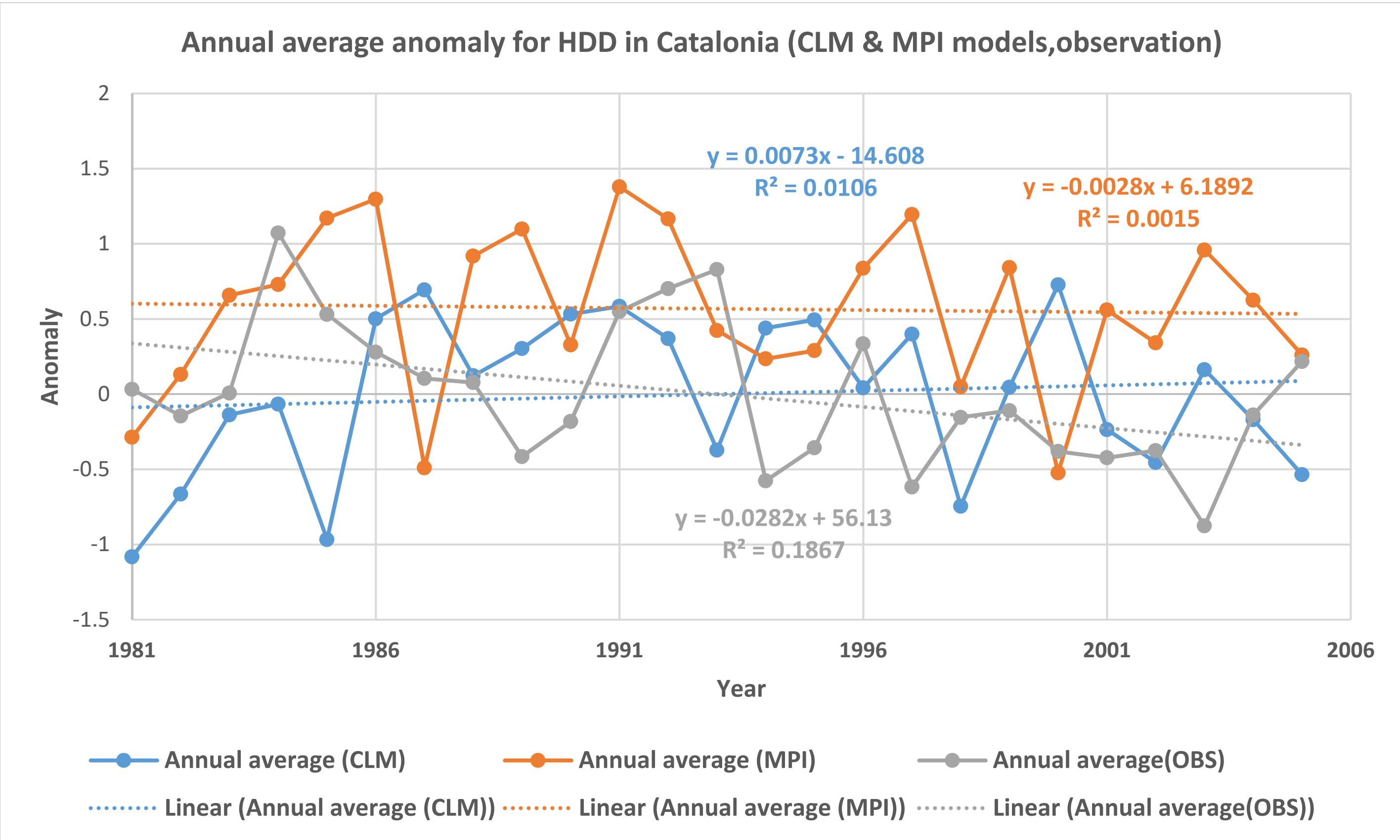

Figure 5-2: Annually average anomaly for heating degree-days in Catalonia, CLM & MPI models, and observation, 1981-2005

Figure 5-3 shows the annual average anomaly for cooling degree-days in Barcelona from 1981 to 2005 from two climate models and observation.

As it could be seen, the anomaly of CDD was increasing for both climate models and observation, which means that the CDD increased every year, with respect to the average of all the period.

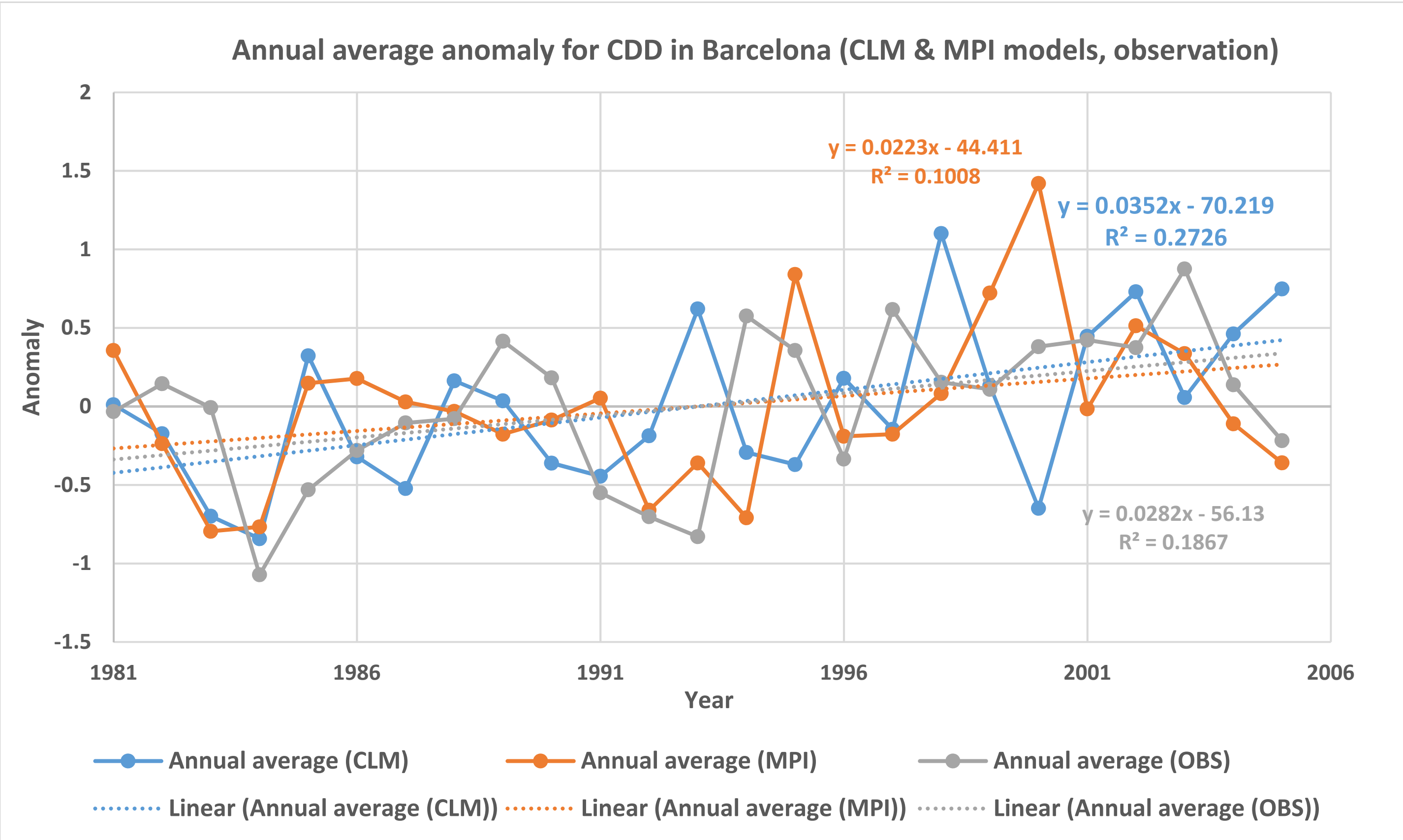

Figure 5-3: Annually average anomaly for cooling degree-days in Barcelona, CLM & MPI model and observation, 1981-2005

Figure 5-4 shows the annual average of anomaly for heating degree-days in Barcelona from 1981 to 2005 applying two climate models (CLM and MPI) and observation.

The MPI and CLM model analysis show a decrease in HDD of Barcelona while the observations point out to an increase in heating degree-days. As it could be seen, the CLM and MPI models have strong sharp trends.

It can be seen that CLM and MPI models cannot be fully trusted since none of the models are not really close to the observations.

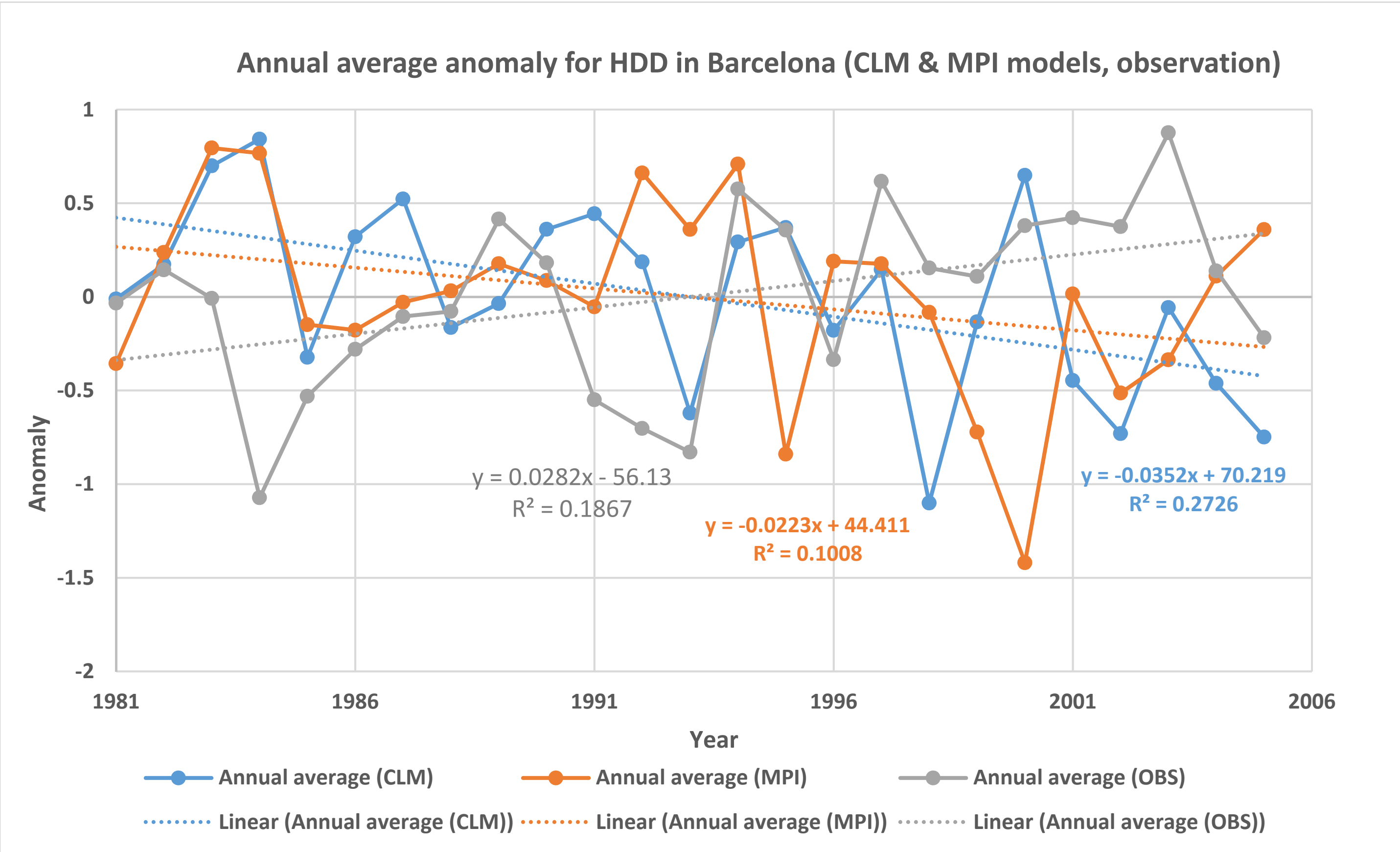

Figure 5-4: Annually average anomaly for heating degree-days in Barcelona, CLM, MPI and observation model, 1981-2005

Comparing the results of this section of the analysis, the calculations of the anomaly of CDD shows an increase in cooling degree-days and a decrease in HDD. Although the observations for heating degree-days is not consistent with the models and shows an increase in heating degree-days.

On the other hand, the result for Catalonia is not decisive enough. In CDD calculations, the observation and the MPI model show an increase while CLM model points to a decrease. The HDD similarly is increasing according to the model results but decreasing looking at the observations.

Table 5-1 Obtained results for HDD and CDD status for Catalonia and Barcelona, Annual average for anomaly

	Catalonia			Barcelona		
	Observation	CLM	MPI	Observation	CLM	MPI
CDD	Increase R^2= 0.18	Decrease R^2= 0.01	Increase R^2= 0.08	Increase R^2= 0.1	Increase R^2= 0.2	Increase R^2= 0.1
HDD	Decrease R^2= 0.02	Increase R^2= 0.01	Increase R^2= 0.001	Increase R^2= 0.1	Decrease R^2= 0.2	Decrease R^2= 0.1

5.1.2 Average of cooling and heating degree days (July-January) in Catalonia and Barcelona

Figure 5-5 shows the average of cooling degree-days in Catalonia in July from 1981 to 2005, relating to two climate models (CLM and MPI) and observation.

As represented in the figure, the average of cooling degree-days in July was increasing in MPI model and observation while decreasing applying the CLM model. It could be seen that the MPI model have a strong sharp trend.

On the other hand, MPI model better reflects the variations of CDD in July, since the calculated R-square of the trend line is very low.

Error! Reference source not found. shows the bias of CLM, MPI models with observation, it could be seen that the CLM model is closer to the observation; we could say that it shows a better average of CDD in July.

Table 5-2: The calculated bias between CLM, MPI model and observation, Catalonia (average of CDD in July)

	Average of CDD in July
CLM	1.74
MPI	2.36
OBS	2.19
Bias (CLM-OBS)	-0.4
Bias (MPI-OBS)	0.1

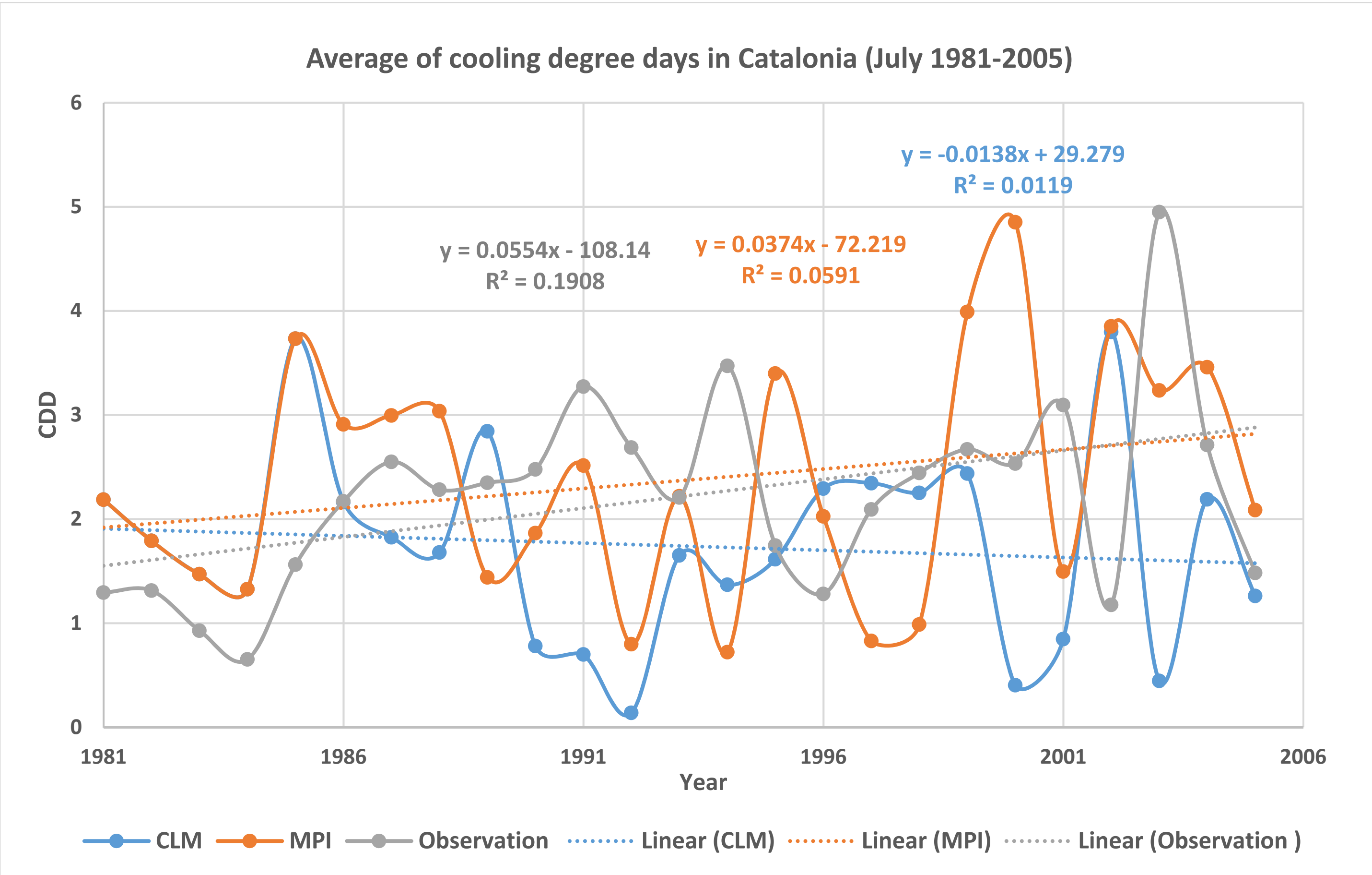

Figure 5-5: Average of cooling degree days in Catalonia, CLM & MPI models, and observation, July (1981-2005)

Figure 5-6 shows the average heating degree-days in Catalonia in January from 1981 to 2005 from two climate models (CLM & MPI) and observation.

As depicted in the figure, the heating degree-day decreased based on the observations and CLM model. The MPI model, however, shows an increase in HDD of Catalonia in winter. According to the figure, it can be seen that CLM model better shows the variation of HDD in January, but similar to the previous cases, the obtained R-square is not very strong.

Table 5-3, shows the bias of CLM, MPI models from observation. As it can be seen, the MPI model results in average HDD calculations has less bias from observations in comparison with CLM results.

Table 5-3: the calculated bias of CLM, MPI models from observation, Catalonia (average of HDD in January)

	Average of HDD in January
CLM	**9.76**
MPI	**9.08**
OBS	**11.12**
Bias (CLM-OBS)	**-1.03**
Bias (MPI-OBS)	**-2.03**

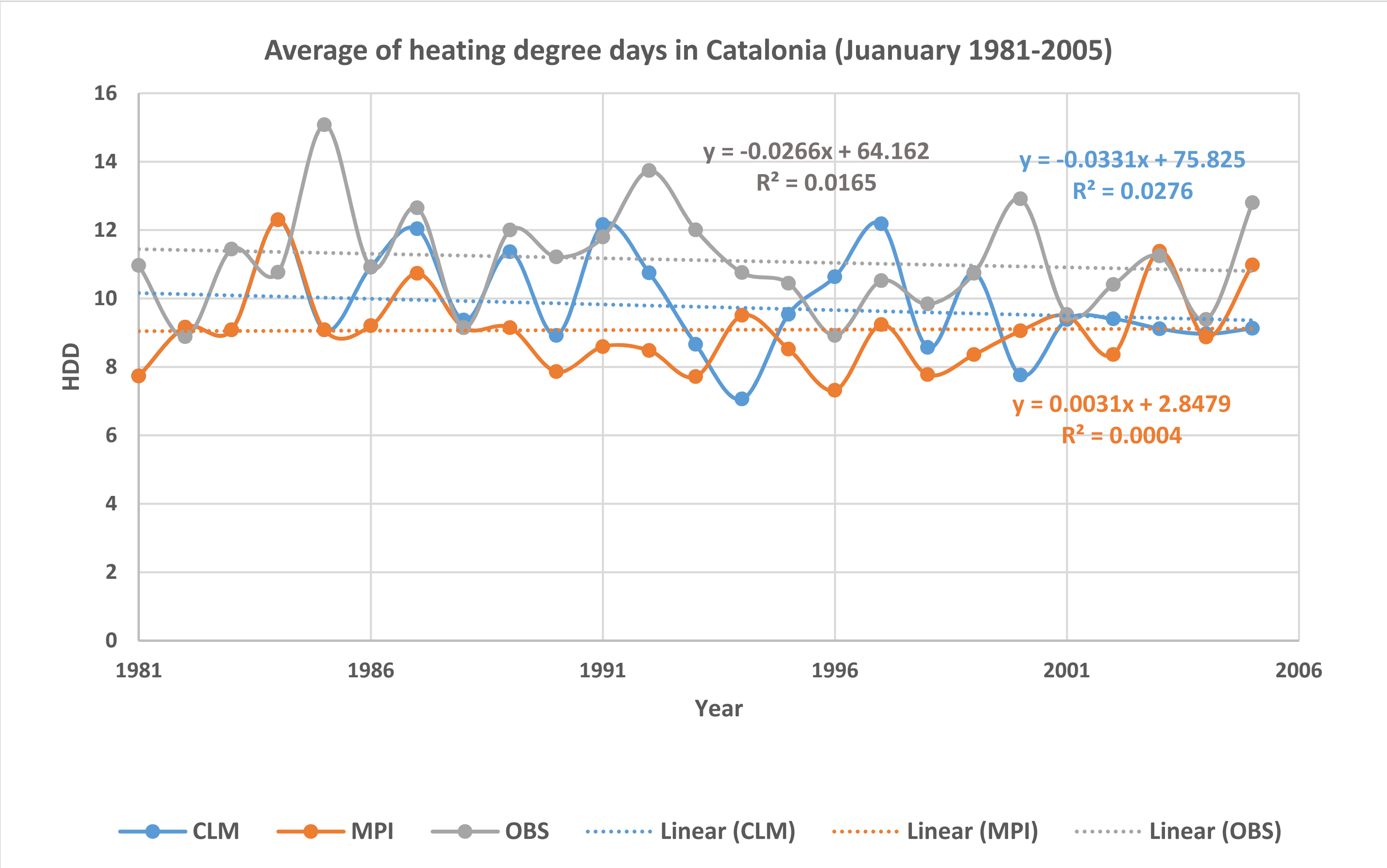

Figure 5-6: Average of heating degree days in Catalonia, CLM & MPI, and Observation, January (1981-2005)

Figure 5-7 shows the average of cooling degree-days in Barcelona in July from 1981 to 2005 from CLM & MPI models and observation.

As it is shown in the figure, observation and both MPI and CLM model show an increase in CDD of Barcelona.

Both models show increasing CDD in July in accordance with the observations but it should be considered that the calculated R-square is very low.

According to the Table 5-4, it could be seen that the CLM model shows a better average of CDD in July in Barcelona and less biased.

Table 5-4: The calculated bias between CLM, MPI model and observation, Barcelona (average of CDD in July)

	Average of CDD in July
CLM	1.06
MPI	1.52
OBS	2.19
Bias (CLM-OBS)	-1.1
Bias (MPI-OBS)	-0.6

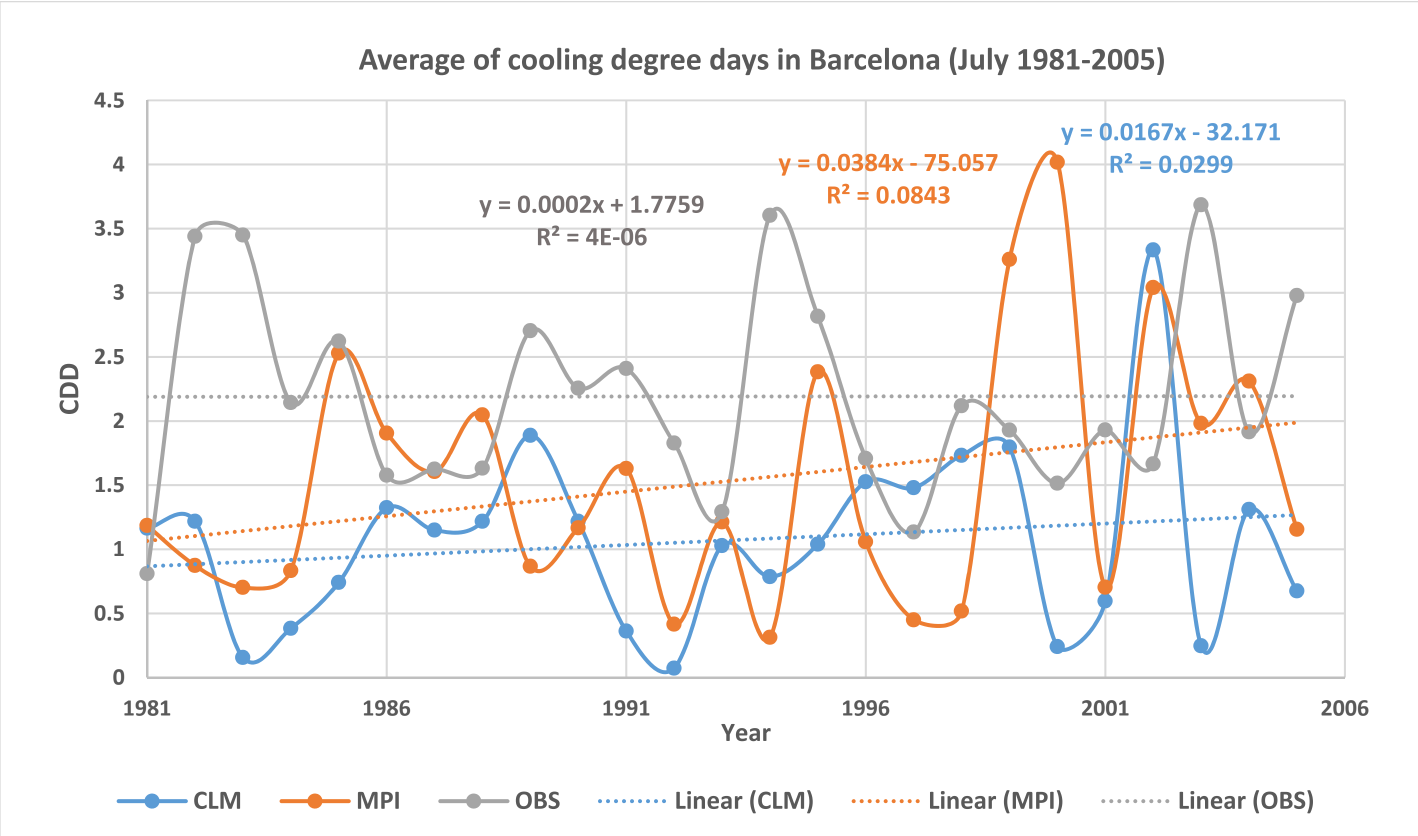

Figure 5-7: Seasonally average of cooling degree days in Barcelona, CLM & MPI models and observation, July (1981-2005)

Figure 5-8 representing the average heating degree-days in Barcelona in January from 1981 to 2005.

The observation and CLM model results illustrate a decrease in heating degree-days during winter while the MPI model shows an increase in HDD of winter in Barcelona.

It can be concluded that CLM model better shows variations of HDD in January but it should be considered that since the calculated R-square of the trend line is very low.

According to the Figure 5-8, it could be seen that the CLM model shows a better average of HDD in January in Barcelona.

Table 5-5: shows the bias between CLM, MPI models, and observation (average of HDD in January)

	Average of HDD in January
CLM	**12.3**
MPI	**11.8**
OBS	**11.1**
Bias (CLM-OBS)	**1.1**
Bias (MPI-OBS)	**0.7**

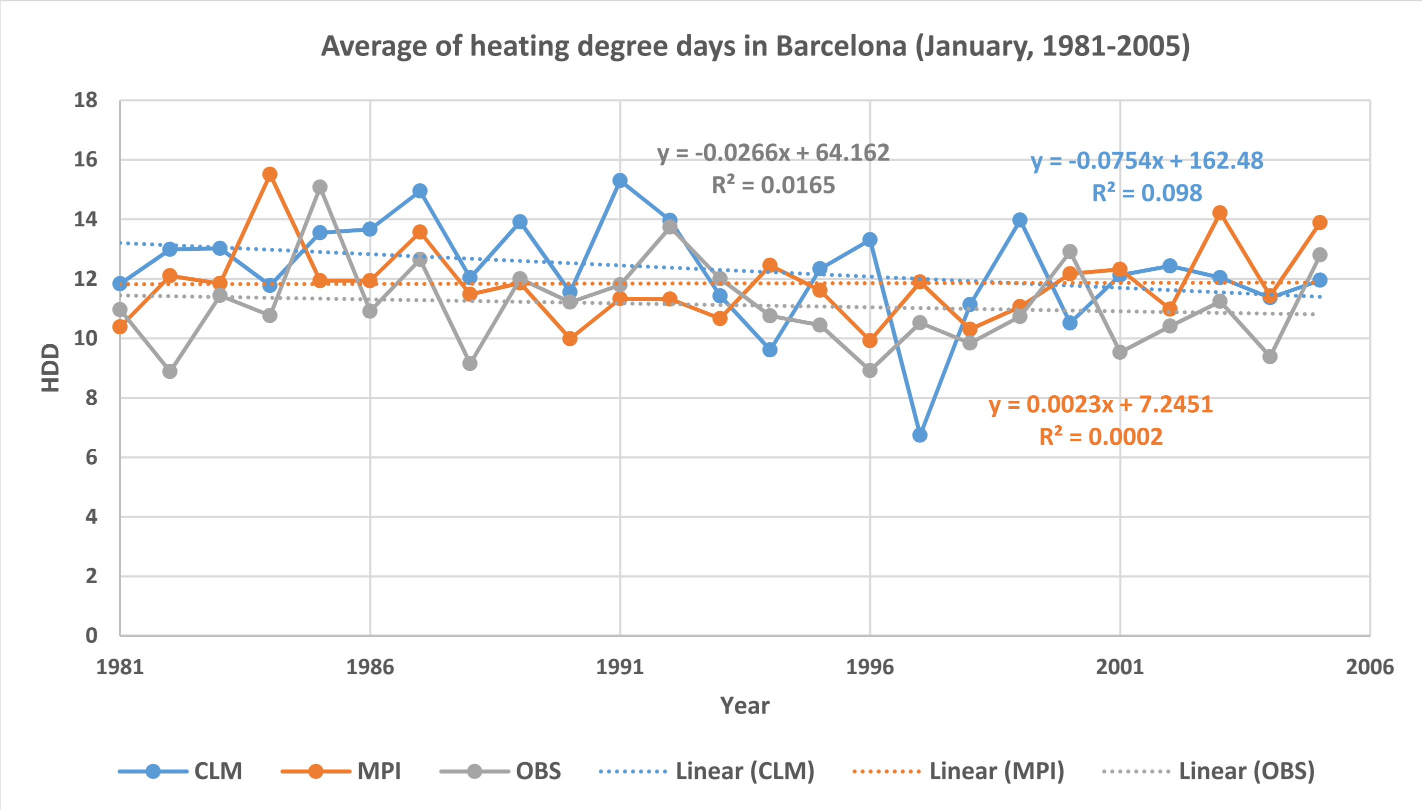

Figure 5-8: Average of heating degree days in Barcelona, CLM & MPI models and observation, January (1981-2005)

5.2 Analysis of future trends

5.2.1 Annual average of anomaly for cooling and heating degree days in Catalonia and Barcelona

Figure 5-9 shows the annual average of anomaly for cooling degree-days in Catalonia according to climate models (CLM and MPI) from 2031 to 2050.

The results show that the cooling degree-days, is increasing according to the CLM model but in the case of MPI model, it shows a decrease. However, this decrement does not have a strong sharp trend and between 2037 up to 2039, it is almost constant.

In addition, the results from both models show anomalous years with sharp rise or fall in the calculated average. In MPI model in 2042, there is a peak and a sharp fall in the anomaly. The same could be observed in the behaviour of CLM model in 2037.

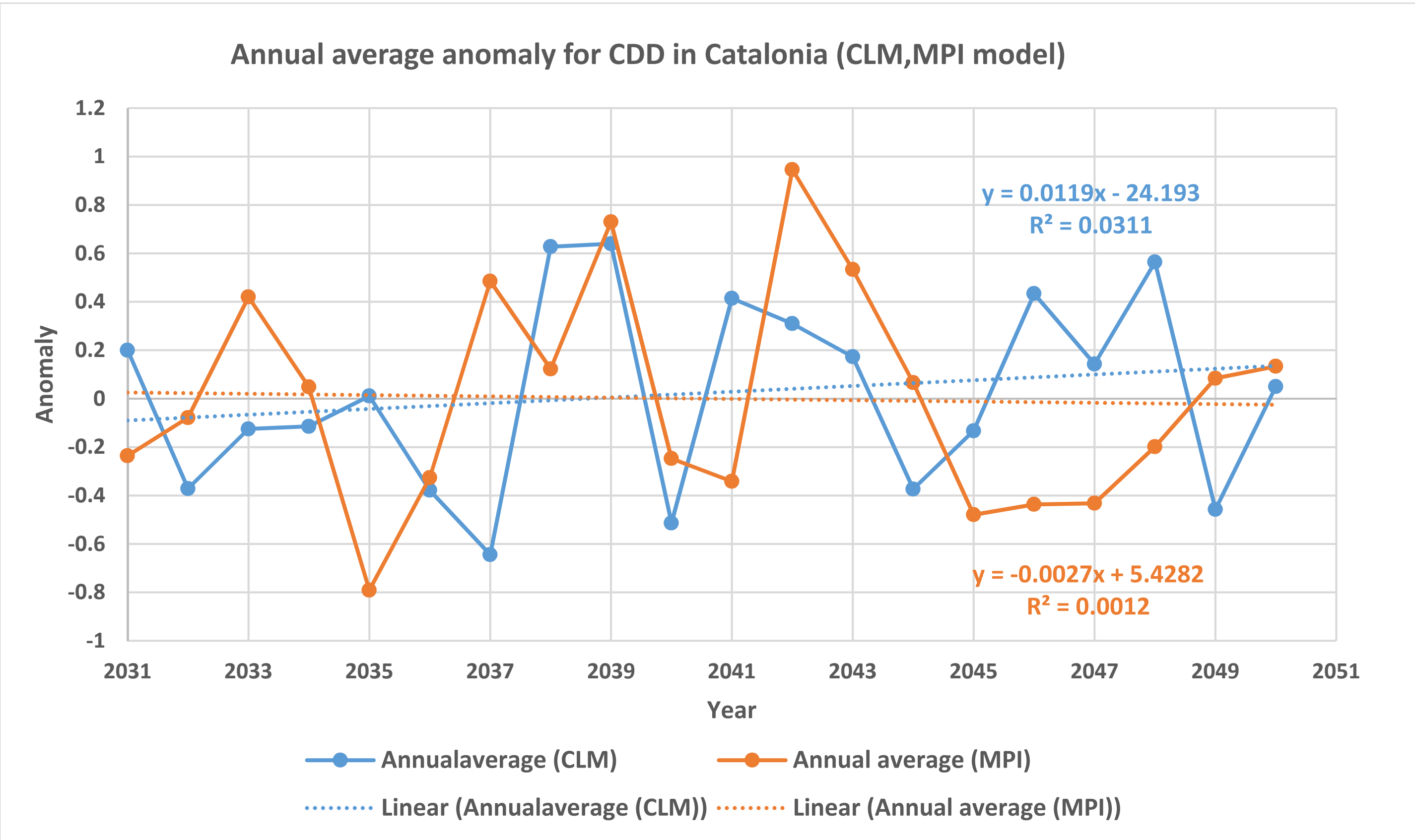

Figure 5-9: Annually average of anomaly for cooling degree-days in Catalonia, CLM & MPI model, 2031-2050

Figure 5-9 shows the annual average of anomaly for heating degree-days in Catalonia according to CLM, MPI models.

As expected, some anomalous behaviour could be seen in the results. The CLM model shows a decrease in the annual average of anomaly for HDD while this is an increment for MPI model. That is in accordance with the CDD calculations.

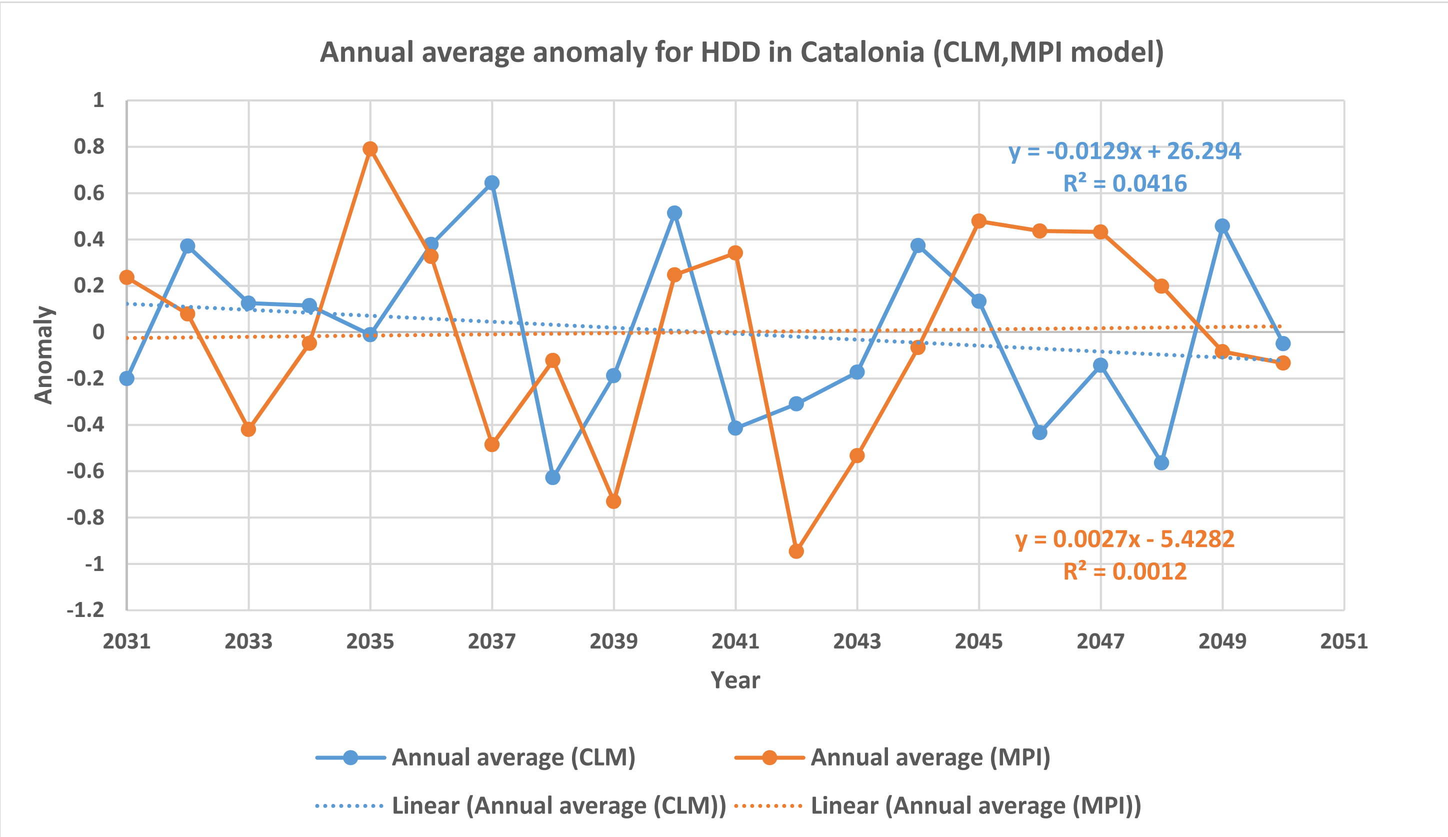

Figure 5-10: Annually average of anomaly for heating degree days in Catalonia, CLM and MPI model, 2031-2050

Figure 5-11 shows the annual average of anomaly for cooling degree-days in Barcelona from 2031 to 2050.

According to Figure 5-11, the anomaly for cooling degree-days is increasing in both models. The trend here in the case of Barcelona is stronger and clearer than the Catalonia case as a whole.

However, the sharp rise of anomaly in 2036 in MPI model can be seen in the figure as an anomalous year.

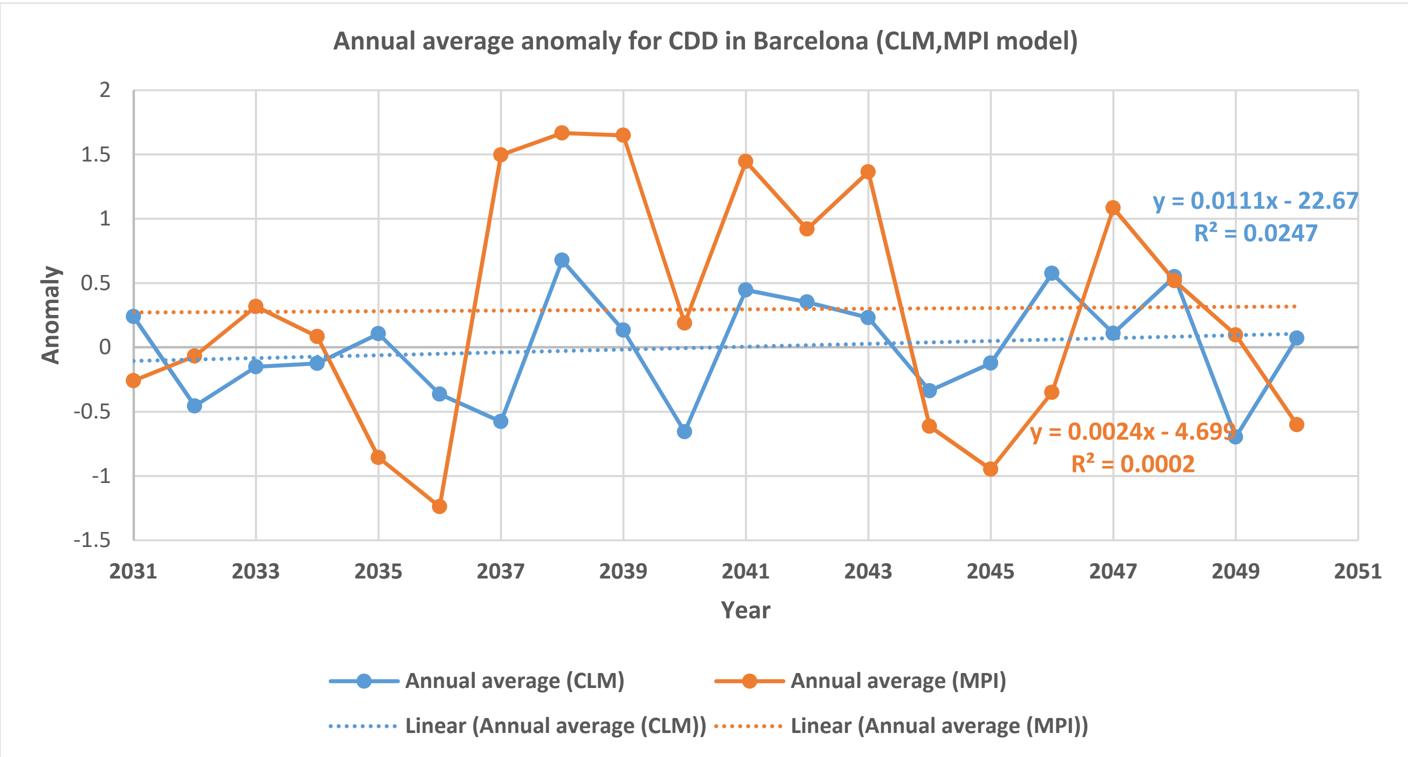

Figure 5-11: Annually average of anomaly for cooling degree days in Barcelona, CLM and MPI model, 2031-2050

Figure 5-12 show the annual average anomaly for heating degree-days in Barcelona from 2031 to 2050 from to climate model (CLM & MPI).

Both models show a decrease in the anomaly of HDD in Barcelona. Generally, MPI model behaves sharper than the CLM model and the variations are bigger than the CLM case.

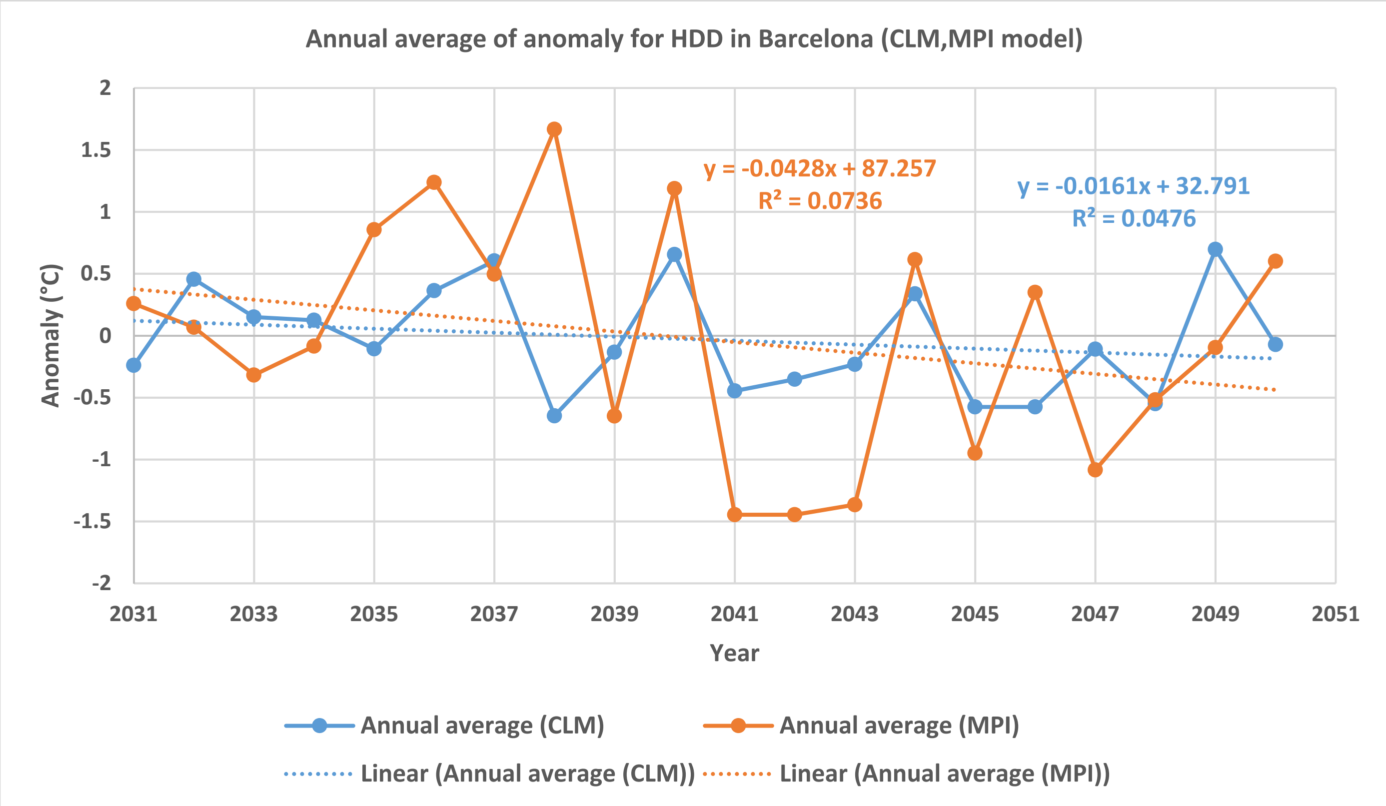

Figure 5-12: Annually average of anomaly of heating degree days in Barcelona, CLM and MPI model, 2031-2050

Comparing the decrease in HDD and increase in CDD in the previous graphs for Barcelona, it could be concluded that the decrease in HDD is stronger than the increase of CDD.

Comparing the results of this section of the analysis, the calculations of the anomaly of CDD shows an increase in cooling degree-days and a decrease in HDD for both Catalonia and Barcelona.

As Table 5-6 shows, both models show an increase of CDD and a decrease of HDD in Barcelona. In case of Catalonia, they show opposite results and it is difficult to make a conclusion.

Table 5-6: future Obtained results for future HDD and CDD status for Catalonia and Barcelona, Annual average for CDD & HDD

	Catalonia		Barcelona	
	CLM	MPI	CLM	MPI
CDD	Increase R^2= 0.03	Decrease R^2= 0.001	Increase R^2= 0.02	Increase R^2= 0.0002
HDD	Decrease R^2= 0.04	Increase R^2= 0.001	Decrease R^2= 0.04	Decrease R^2= 0.07

5.2.2 Average of cooling and heating degree days (July-January) in Catalonia and Barcelona

Figure 5-12 shows the average of cooling degree-days in Catalonia in July from 2031 to 2050 from two climate models (CLM, MPI).

As represented in the figure, the average of cooling degree-days in July will be increasing in CLM model while decreasing applying the MPI model.

MPI model behave sharper than the CLM model and the variations are bigger than the CLM case.

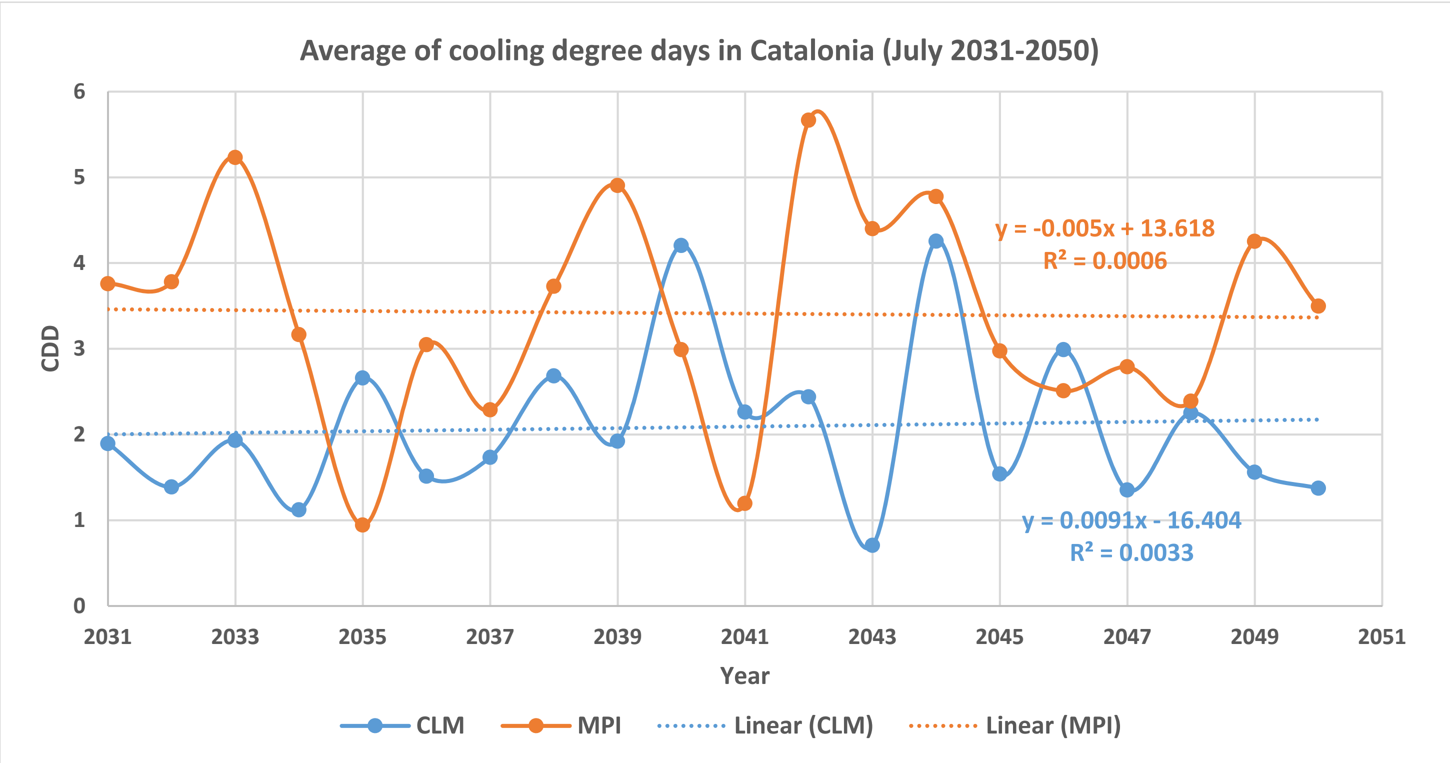

Figure 5-13: Average of cooling degree days in Catalonia, CLM, MPI model, July (2031-2050)

Figure 5-13 shows the average heating degree-days in Catalonia in January from 2031 to 2050, from two climate models (CLM, MPI).

As it can be seen, the heating degree-days will be increased for both models in Catalonia over winter.

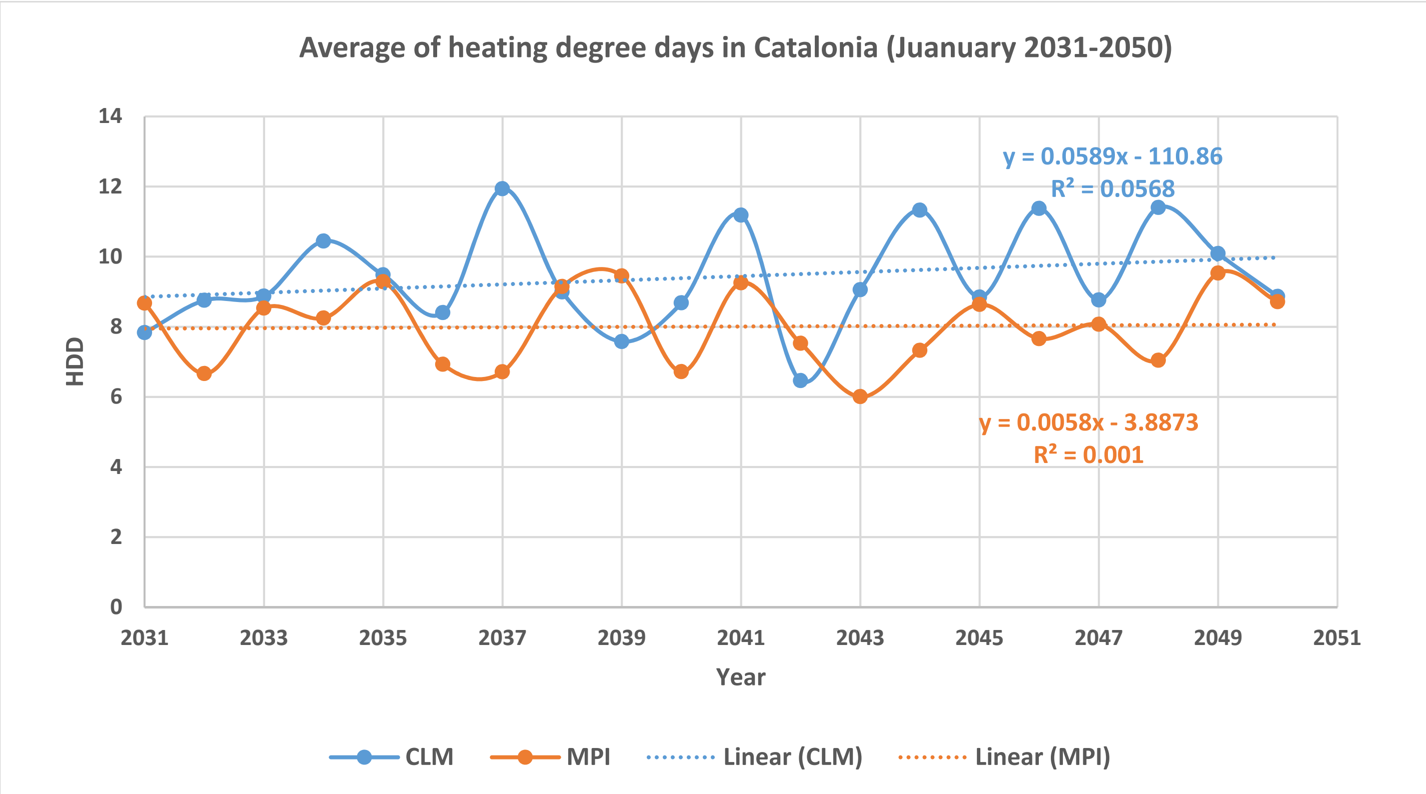

Figure 5-14: Average of heating degree days in Catalonia, CLM and MPI model, January (2031-2050)

Figure 5-15 shows the average of cooling degree-days in Barcelona in July (summer) from 2031 to 2050.

The figure presented that cooling degree-days in Barcelona according to climate models will be increased in summer.

As it could be seen, the MPI model shows the bigger variation than CLM model.

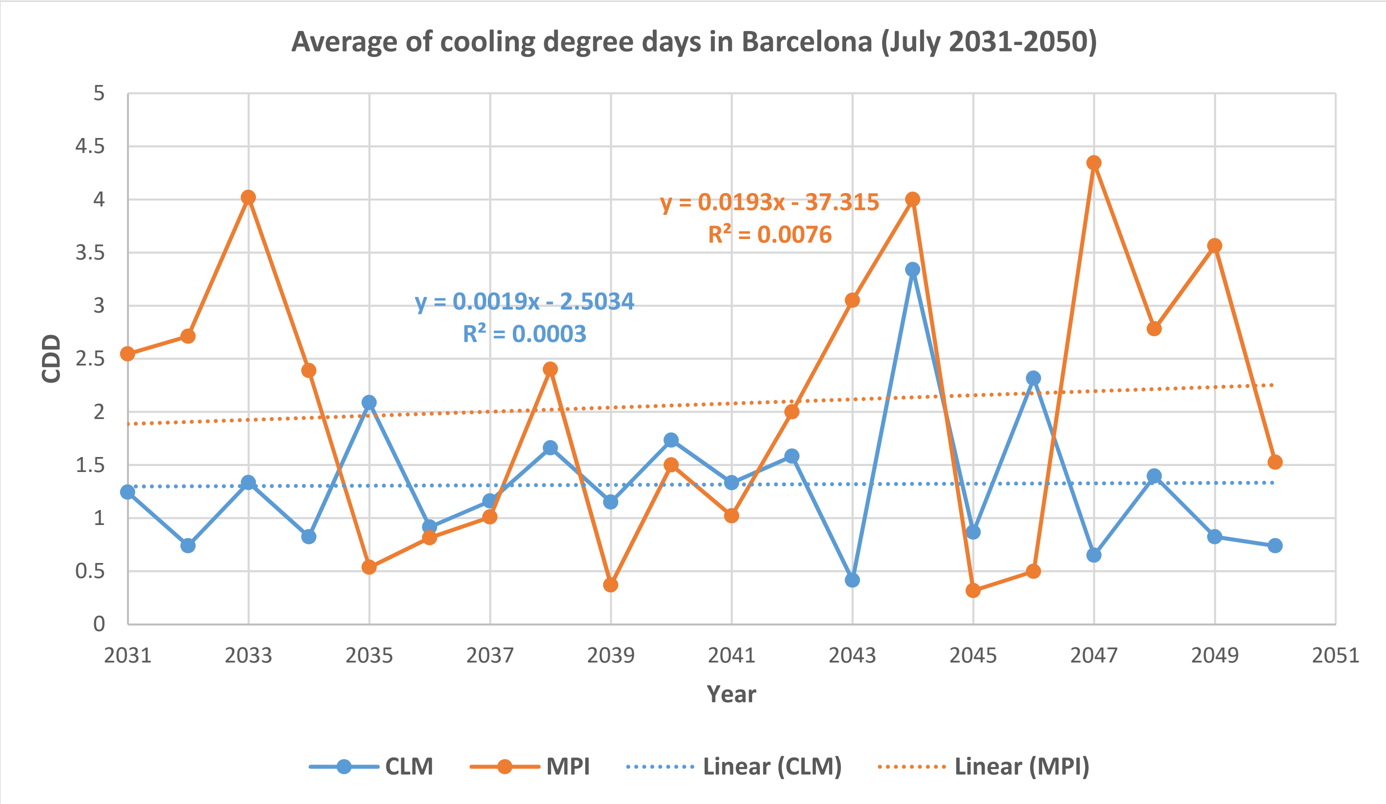

Figure 5-15: Average of cooling degree-days in Barcelona in July 2031-2050, CLM and MPI model

Figure 5-16 shows the average of heating degree-days in Barcelona in January from 2031 to 2050. As it could be seen, the average of heating degree-days for CLM shows that HDD will be increased in January, while MPI model shows that the HDD will be decreased.

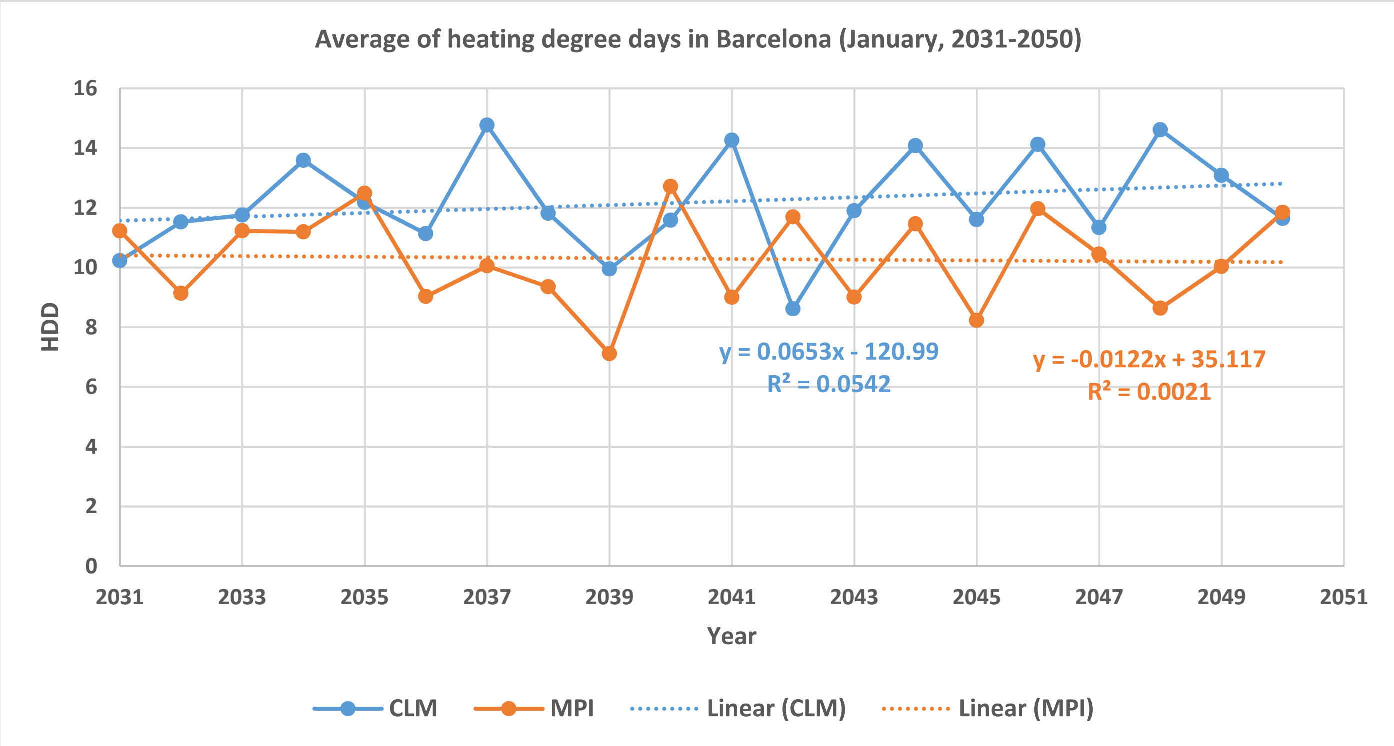

Figure 5-16: Average of heating degree-days in Barcelona, January 2031-2050, CLM and MPI model

Table 5-7, shows the future seasonal average of CDD and HDD in Catalonia and Barcelona

Table 5-7: Average of cooling degree-days (July) and heating degree-days (January) in Barcelona and Catalonia (2031-2050)

Average	Catalonia		Barcelona	
	CLM	MPI	CLM	MPI
CDD (July)	2.08	3.41	1.3	2.06
HDD (January)	9.41	8	12.18	10.29

6 Conclusion

In this thesis, both seasonal and annual analysis was studied. Although in the final model of both approaches, the obtained results from the models are different from the observation results and not accurately fitted, it could be said that the seasonal analysis is more useful for energy management and provide a rough estimate of seasonal heating requirements. In the course of the heating season, for instance, the number of HDD for two different cities or regions will provide necessary information for calculating the required energy to heat the buildings with similar structure and insulation. This information is hardly retrievable from an annual analysis.

Degree-days is an important climatic design indicator and is widely used in the design and operation of energy-efficient buildings. The calculation of degree-days has always been a topic of focus by researchers. Attempts have been made in the past to calculate degree-days from datasets of reduced temporal resolution, the lowest being the daily mean temperature. This research went further and investigated the relationship between an annual anomaly and seasonal heating and cooling degree-days in Catalonia and Barcelona.

The result of future analysis shows that Barcelona will experience less heating degree-days and more cooling degree-days in the considered period (annual analysis). The same cannot be said for Catalonia case since each model shows a different trend and it is difficult to make a conclusion.

The historical analysis shows that during the period of study, Barcelona's annual average of CDD has been increased while HDD has been decreased. For Catalonia, the annual HDD has decreased and the CDD has increased.

In seasonal evaluation of historical data, Barcelona's CDD has increased and the HDD has decreased. For Catalonia, the same results were obtained. The increasing trend of average CDD/HDD it can be said that the requirements for cooling the building is rising and it seems much larger than heating requirements.

Calculations using HDD have several problems. Heat requirements are not linear with temperature [45] and heavily insulated buildings have a lower balance point. The amount of heating and cooling required depends on several factors besides outdoor temperature: How well insulated a particular building is, the amount of solar radiation reaching the interior of a house, the number of electrical appliances running (e.g. computers raise their surrounding temperature), the population, the amount of the wind outside, and what temperature the occupants find comfortable. Another important factor is the amount of relative humidity indoors; this is important in determining how comfortable an individual will be. Other variables such as precipitation, cloud cover, heat index, building albedo, and snow cover can also alter a building's thermal response (These factors does not consider in this study).

Degree-day-based monitoring is an important part of many energy management programs, but degree-days are commonly used in ways that can lead to inaccurate, misleading results. When using or applying the degree-day-based methods, it is important to have an understanding of the sources of inaccuracy, and a sense for the reliability of the figures on which the decisions are made. Otherwise, the energy plan may chase excess consumption that does not really exist, or may highlight improvements that have not really be made.

On the positive side, any monitoring, however inaccurate, could still result in energy savings: it is usually possible to find energy wastage if being looked for and anything that builds energy awareness is generally good (from a social point of view). However, separating the real indicators from the wrong estimations will help the energy management plans to be more efficient in time, budget and results and will help in achieving significantly greater energy savings.

7 References

[1] U.S. Department of commerce / National Oceanic Research Laboratory (NOAA), “Earth System Research Laboratory.” [Online]. Available: http://www.esrl.noaa.gov/research/themes/water/.

[2] F. Breu, S. Guggenbichler, and J. Wollmann, “Climate Change 2013: The Physical Science Basis. Contribution,” *IPCC*, pp. 1–29, 2013.

[3] L. Treut, R. Somerville, U. Cubasch, Y. Ding, C. Mauritzen, A. Mokssit, T. Peterson, M. Prather, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and U. Kingdom, “Historical Overview of Climate Change Science,” 2007.

[4] “Intergovernmental Panel on Climate Change.” [Online]. Available: https://www.ipcc.ch/publications_and_data/ar4/wg1/en/faq-1-1.html.

[5] United Nations Framework Convention on Climate change, “Climate Change: Impacts, Vulnerabilities and Adaptation in Developing Countries.”

[6] “US Environmental Protection Agency (EPA).” [Online]. Available: https://www.epa.gov/climate-indicators/greenhouse-gases.

[7] “United States Environmental Protection Agency.” [Online]. Available: https://www3.epa.gov/climatechange/science/causes.html.

[8] “Intergovernmental panel on climate change.” [Online]. Available: http://www.ipcc.ch/ipccreports/tar/vol4/index.php?idp=204.

[9] D. A. Randall and R. A. Wood, “Climate Models and Their Evaluation.” [Online]. Available: https://ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter8.pdf.

[10] “world Meteorological Organization.” [Online]. Available: https://www.wmo.int/pages/index_en.html.

[11] L. M. Druyan, “Climate Models.”

[12] “Word Meteorological Organization.” [Online]. Available: https://www.wmo.int/pages/themes/climate/climate_models.php.

[13] “SMHI.” [Online]. Available: http://www.smhi.se/en/climate/climate-scenarios/haag_en.html.

[14] G. P. Wayne, “The Beginner’s Guide to Representative Concentration Pathways (RCPs),” 2013.

[15] D. P. Van Vuuren, J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G. C.Hurtt, T. Kram, V. Krey, J.-F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S. J. Smith, and S. K. Rose, “The representative concentration pathways : an overview,” 2011.

[16] J. Weyant, C. Azar, M. Kainuma, J. Kejun, N. Nakienovie, P. R. Shukla, E. La Rovere, and G. Yohe, “Report of 2.6 versus 2.9 Watts&m2 RCPP Evaluation Panel,” 2009.

[17] A. Foley, “Uncertainty in regional climate modelling: A review,” 2010. [Online]. Available: http://www.wou.edu/~vanstem/490.S12/Uncertainty in Climate Modelling.pdf.

[18] Universite catholique de Louvain, “Introduction to climate dynamics and climate modelling,” 2008. [Online]. Available: http://www.elic.ucl.ac.be/textbook/chapter3_node22.xml.

[19] “Building Energy Consumption and Carbon dioxide Emissions: Threat to Climate Change,” *J. Earth Sci. Clim. Change*, 2015.

[20] “Eurostat.” [Online]. Available: http://ec.europa.eu/eurostat/data/database.

[21] U. Eicker, “Energy consumption of buildings,” 2014.

[22] United Nations Environment Programme, “Buildings and Climate Change (Summary for Decision-Makers),” 2009.

[23] “Catalan news agency,” 2015. [Online]. Available: http://www.catalannewsagency.com/society-science/item/avoiding-extreme-climate-change-demands-clean-energy-but-catalonia-has-limited-powers-to-act.

[24] Ajuntament de Barcelona, “Energy , Mobility and Environmental Sectors in Barcelona,” 2012.

[25] “An introduction to energy management systems: energy savings and increased industrial productivity for the iron and steel sector,” 2015. [Online]. Available: https://www.oecd.org/sti/ind/DSTI-SU-SC(2014)14-FINAL-ENG.pdf.

[26] “Clean Energy Ministerial (Accelerating the Global Clean Energy Transition).” [Online]. Available: http://www.cleanenergyministerial.org/.

[27] P. Laroche, *Lightning: Principles, Instruments, and Applications*. 2008.

[28] A. Barrera-Escoda and M. C. Llasat, “Evolving flood patterns in a Mediterranean region (1301-2012) and climatic factors - The case of Catalonia,” 2015.

[29] “Free World Maps.” [Online]. Available: http://www.freeworldmaps.net/europe/spain/catalonia.html.

[30] “Institute d’Estatistica de Catalonia (Idescat).” [Online]. Available: http://www.idescat.cat/economia/inec?tc=7&id=0103&dt=201605&lang=en.

[31] "Generalitat de Catalunya (Institut d'Estatistica de Catalunya)." [Online]. Available: http://www.idescat.cat/pub/?id=aec&n=249&lang=en.

[32] Generalitat de Catalunya, "Servei Meteorologic de Catalunya." [Online]. Available: http://www.meteo.cat/wpweb/climatologia/serveis-i-dades-climatiques/series-climatiques-historiques/.

[33] Generalitat de Catalonia, "2015, the 4th hottest year in Catalonia since records began." [Online]. Available: http://web.gencat.cat/en/actualitat/detall/El-2015-el-4t-any-mes-calid-a-Catalunya-des-de-que-hi-ha-registres.

[34] Generalitat de Catalunya (Ministry of Territory and Sustainability, "Executive Summary report on the environment in Catalonia."

[35] Institute Català d'Energia, "Balanç energètic de Catalunya." [Online]. Available: http://icaen.gencat.cat/ca/pice_serveis/pice_estadistiques_energetiques/pice_resultats/pice_estadistiques_energetiques_anuals_de_catalunya/pice_balanc_energetic/.

[36] O. Bellprat, S. Kotlarski, D. Lüthi, and C. Schär, "Objective calibration of regional climate models," 2012. [Online]. Available: http://onlinelibrary.wiley.com/doi/10.1029/2012JD018262/full.

[37] P. Friedlingstein, P. Cox, R. Betts, L. Bopp, W. von Bloh, V. Brovkin, P. Cadule, S. Doney, M. Eby, I. Fung, G. Bala, J. John, C. Jones, F. Joos, T. Kato, M. Kawamiya, W. Knorr, K. Lindsay, H. D. Matthews, T. Raddatz, P. Rayner, C. Reick, E. Roeckner, K.-G. Schnitzler, R. Schnur, K. Strassmann, A. J. Weaver, C. Yoshikawa, and N. Zeng, "Climate–Carbon Cycle Feedback Analysis: Results from the C 4 MIP Model Intercomparison," *J. Clim.*, vol. 19, no. 14, pp. 3337–3353, 2006.

[38] "EURO-CORDEX." [Online]. Available: http://www.euro-cordex.net/060374/index.php.en.

[39] IPCC Fifth Assessment Synthesis Report, "Summary for policy makers."

[40] U. Schulzweida, L. Kornblueh, and R. Quast, "CDO User ' s Guide," 2009.

[41] "European Climate Assessment & Dataset (ECA&D)." [Online]. Available: http://eca.knmi.nl/dailydata/index.php.

[42] R. E. Benestad, "Heating degree days , Cooling degree days and precipitation in Europe," 2008.

[43] "Climate Data Operator." [Online]. Available: https://code.zmaw.de/boards/1/topics/2484?r=2485#message-2485.

[44] "National Centers for Environmental Information (NOAA)." [Online].

Available: https://shortly.im/YSTqr.

[45] E. Valor, V. Meneu, and V. Caselles, “Daily air temperature and electricity load in Spain,” *J. Appl. Meteorol.*, vol. 40(8): 141, 2001.