POLITECNICO DI TORINO

Master of science program in
ENVIRONMENTAL AND LAND ENGINEERING

Master of science Thesis

Data analysis of key parameters to study the impacts of climate change on infrastructures

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"Dedicated to my parents, the pillars of my strength, whose enduring support turned challenges into victories, their love an everlasting light by my side."

Abstract

The Earth's climate system is undeniably complex, necessitating an in-depth study of its changes over time. This research is fundamental for identifying climate trends that form the basis for effective climate change mitigation and adaptation strategies, which are paramount for informed decision-making and risk management. According to IPCC, (2014) climate datasets reveal a global average warming of approximately 0.85 degrees Celsius (with a range of 0.65 to 1.06 degrees Celsius) between the years 1880 and 2012.

This thesis has been developed within the framework of the PNRR NODES (Nord-Ovest Digitale e Sostenibile, "Digital and Sustainable North-West") project, focusing on Northwestern Italy. In particular the Valle d'Aosta region has been chosen as the area where to build landslide risk maps accounting for climate change. As a first step this thesis has undertaken a comprehensive literature review of climate change, including its causes and impacts. It is crucial to acknowledge that while substantial work has been conducted on climate change at a global scale, examining climate change on a regional scale introduces unique challenges. Key climate system parameters, such as precipitation and temperature, exhibit distinct behaviours in different regions, influenced by factors like longitude, latitude, altitude, and land use. These parameters can vary significantly between regions, especially in areas characterized by complex topography, such as alpine regions like Valle d'Aosta, where altitude has a significant impact on the local climate.

However, studying climate change in Valle d'Aosta is a complex endeavour, as climate variables are profoundly influenced by the region's topography and exhibit local variations. Consequently, accessing reliable datasets for the study of climate variables in this region is of paramount importance. Most publicly accessible climate datasets have limitations when employed on such a small scale, often lacking the required spatial resolution. Furthermore, the scarcity of historical observation data presents another challenge in studying climate change in this region.

The choice of an appropriate dataset depends heavily on the region's climatic characteristics. While some reanalysis datasets align well with coarser reanalysis data in global and regional scales, the complex topography of Valle d'Aosta necessitates careful consideration in choosing the suitable reanalysis dataset. After thorough experimentation with various reanalysis datasets and a rigorous comparison with observed data, ERA5-LAND, with an approximate grid size of 9 km x9 km and a minimum temporal resolution of 1 hour, offering a wide range of climate variables, including temperature and total precipitation data from 1950 to the present, was selected. This dataset is an open-access source provided by the European Centre for Medium-range Weather Forecasts (ECMWF).

In Valle d'Aosta, there are 87 weather stations, which are unevenly distributed across the region and do not consistently provide data for extended periods. To address this limitation, reanalysis datasets come, offering historical data access and consistent information for remote and challenging locations like mountainous areas. Most reanalysis datasets operate on a global scale with horizontal resolutions unsuitable for regional climate change studies. Thus, selecting a compatible reanalysis dataset for regional analysis becomes essential.

With the aim of defining a possible methodological procedure, this Thesis focuses on a smaller area of the Valle d'Aosta ranging from Pont St. Martin to Gressoney-la-Trinité. Considering the diverse behaviour of climate variables based on their location-specific characteristics, it is crucial to validate the usability and reliability of these datasets before implementation. To validate this dataset, 13 weather stations in the previously mentioned area were chosen, and a reference period of 2014-2022 was selected due to its highest consistency in temporal and spatial data.

To validate the ERA5-LAND dataset and facilitate comparison, various statistical indicators were calculated for both in-situ parameters and simulated mean monthly temperature data for 13 weather stations during the reference period of 2014-2022. Among these stations, the Gressoney-Saint-Jean – Weissmatten station displayed strong reliability with a root mean square error (RMSE) of 0.39, indicating a high level of agreement with the ERA5-LAND dataset. Conversely, the Bard – Albard station exhibited the weakest agreement, with an RMSE of 6.73. This discrepancy is attributed to the challenges of implementing reanalysis datasets in regions strongly influenced by complex topography.

To address this challenge, further investigations identified a significant source of error associated with elevation biases. To ensure the usability of the dataset for periods lacking consistent observational data, an elevation bias correction based on the adiabatic lapse rate is considered.

A similar approach is applied to precipitation data. Since observational data is collected at specific points while reanalysis datasets provide precipitation amounts over a 9kmx9km grid, interpolation based on observed point data is conducted to enable meaningful comparisons. However, ERA5-LAND data shows discrepancies with observed precipitation data, likely due to the limitations of reanalysis models in accurately recording local precipitation events. In response, another dataset, the GPCC dataset, is chosen. This gauge-based dataset provides global spatial coverage and is used for periods with limited observational data. Comparisons between interpolated mean monthly precipitation from observed data and GPCC datasets reveal a moderate to good agreement over the Valle d'Aosta basin for (2011-2020) as reference period.

In summary, this study represents a fundamental step in the investigation of climate change in regions where observational data is scarce, historical data is unavailable, and environmental variables, such as precipitation and temperature, exhibit highly localized variations. These challenges are particularly prominent in areas characterized by significant altitude and complex topography.

This meticulous selection and validation of datasets ensure the credibility of research and its applicability to studying the climate change effects on landslides of Valle d'Aosta.

Contents

CHAPTER 1

Introduction

1.1 Climate of Earth

Climate is a region's mean long-term weather pattern over a period, usually 30 years. Climate and weather are distinct, weather can change quickly in some hours or with seasons. More precisely, climate is the average and variation of climatic variables over a period that can range from a few months up to millions of years. Temperature, humidity, atmospheric pressure, wind, and precipitation are a few of the meteorological factors that are frequently measured. In a broader context, climate refers to the interactions between the atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere, which together constitute the climate system. A location's latitude, longitude, topography, altitude, land use, and proximity to water bodies and their currents all have an impact on the climate there. (Gough et al., 2022; Earth's Climate Background Information. Lunar and Planetary Institute (LPI) https://www.lpi.usra.edu/education/explore/ice/background/iceEarth/)

1.1.1 Factors determining the climate of Earth

Under the influence of its internal dynamics and external factors that affect climate (called 'forcings'), the climate system evolves over time. Among the external forcings are natural phenomena such as volcanic eruptions and solar variations, as well as human-induced changes in atmospheric composition (Le Treut et al., 2007).

The climate system is powered by solar radiation. Radiation balance can be altered in three fundamental ways: 1) by changing the incoming solar radiation (e.g., by changing Earth's orbit or by changing the Sun); 2) by altering the fraction of solar radiation reflected (called "albedo"; e.g., by changing cloud cover, atmospheric particles, or vegetation); and 3) by altering the longwave radiation from Earth towards space (e.g., by changing greenhouse gas concentrations). As a result, climate responds directly and indirectly to such changes (Le Treut et al., 2007).

A third of the sunlight that reaches the top of the atmosphere is reflected into space. About two-thirds of this reflectivity is caused by clouds and aerosols in the atmosphere. The remaining one-third of sunlight is reflected by light-coloured areas of Earth's surface, primarily snow, ice, and deserts (Le Treut et al., 2007).

During major volcanic eruptions, material is ejected very high into the atmosphere. Before entering the troposphere and being delivered to the surface by precipitation, these aerosols often affect the climate for a year or two. Thus, large-scale volcanic eruptions have the potential to result in a reduction in the average global surface temperature of around 0.5 degrees Celsius, which may persist for months or even years. Some manmade aerosols considerably reflect sunlight as well (Le Treut et al., 2007).

The Earth's surface and atmosphere absorb the energy that is not reflected to space. This is equivalent to about 240 Watts per square meter (W m^{-2}). The Earth itself must emit, on average, the same amount of energy back into space to balance the incoming energy. The Earth accomplishes this by releasing longwave radiation into space. A surface would need to be about -19°C in temperature to release 240 W m^{-2}. This is far cooler than the actual Earth's surface temperatures (Le Treut et al., 2007).

The presence of greenhouse gases, which form a partial cover for the long wave radiation from the surface, is what makes Earth's surface so hot. This blanketing is referred to as the natural greenhouse effect. Water vapour and carbon dioxide are the major greenhouse gases. There is no such effect on the two most abundant components of the atmosphere, nitrogen, and oxygen (Le Treut et al., 2007).

1.2 Different climate types

A German climate scientist named Wladimir Koppen divided the world's climate into categories in the late 1800s and early 1900s. His categories were based on temperature, precipitation amounts, and times of year when precipitation occurs. Furthermore, the categories were influenced by a region's latitude - the imaginary lines used to measure our planet from north to south (What Are the Different Climate Types? https://scijinks.gov/climate-zones/).

The Earth's climate is divided into five main types by climate scientists:

- Tropical. The average temperature in this hot and humid region is more than 64°F (18°C) year-round, and there are more than 59 inches of precipitation a year.
- Dry. These climate zones are so dry because moisture evaporates rapidly from the air and there is very scarce precipitation.
- Temperate. Warm and humid summers and mild winters are typical of this zone.
- Continental. These regions have warm to cool summers and very cold winters. In the winter, this zone can experience snowstorms, strong winds, and very cold temperatures—sometimes falling below -22°F (-30°C)
- Polar. In the polar climate zones, it’s extremely cold. Even in summer, the temperatures here never go above 50°F (10°C) (What Are the Different Climate Types? https://scijinks.gov/climate-zones/).

1.3 An Introduction to climate change

The climate of the Earth has been changing over time. Eight cycles of ice ages and warmer periods have occurred in the last 800,000 years, with the end of the last ice age 11,700 years ago indicating the start of the modern era of climate and human civilization. Most of these changes in the climate are a result of small variations in the Earth's orbit, which alter the quantity of solar energy the earth receives. The current warming trend is different because it is clearly the result of human activities since the mid-1800s and is proceeding at a rate not seen over many recent millennia. It is undeniable that human activities have produced the atmospheric gases that have trapped more of the Sun's energy in the Earth system. This extra energy has warmed the atmosphere, ocean, and land, and widespread and rapid changes in the atmosphere, ocean, cryosphere, and biosphere have occurred (How Do We Know Climate Change Is Real? https://climate.nasa.gov/evidence/).

1.4 A brief history of climate change studies and policies

The basic physics of greenhouse warming has been understood for more than a century, (Houghton, 2009) and climatology has always been recognized as an important part of meteorology (Landsberg, 1945). During the 1950s, five important scientific, technological, and geopolitical developments converged to generate the global concern with climate issues (Zillman, 2009). These developments include considerable understanding of the large-scale circulation mechanisms of the atmosphere due to developments in atmospheric science; new geophysical observations; development of meteorological Earth-orbiting satellites; advances in digital computers; and the desire of countries to cooperate under the United Nations System to address important global problems (Zillman, 2009).

Climate change was mainly regarded at the turn of the 20th century as an obscure study of a hypothetical scientific phenomenon. The House of Commons [1]proclaimed a "climate emergency" in 2019, cementing its place as a major political issue. It may also be the most urgent long-term issue that governments around the world are dealing with (Hirst, 2020).

Climate change must be understood within the context of the rise of environmental issues on the global agenda. When the United Nations was created, environmental issues, much less climate change, were not a major concern. During its first 23 years, action on these issues was limited to operational activities, mostly through the World Meteorological Organization (WMO), and when they were mentioned, it was in the context of one of the most pressing concerns of the time: whether natural resources were adequate for the economic development of many UN members, or underdeveloped countries (Jackson, 2007).

The first UN body to address the depletion of resources and their usage was the UN Scientific Conference on the Conservation and Utilization of Resources (Lake Success, New York, 17 August to 6 September 1949). But rather than managing them for conservation, the focus was on how to manage them for economic and social development. Environmental issues did not receive meaningful consideration from any significant UN organs until 1968.On May 29, the Economic and Social Council became the first body to incorporate these concerns as a separate item on its agenda. It also voted to

[1]The House of Commons is the lower house of the Parliament of the United Kingdom. Like the upper house, the House of Lords, it meets in the Palace of Westminster in London, England. The House of Commons is an elected body consisting of 650 members known as members of Parliament.

host the inaugural United Nations Conference on the Human Environment, which was later supported by the General Assembly (Jackson, 2007).

Environmental issues made their worldwide and intergovernmental debut in the second half of the 20th century. The first global environmental conference was held in Stockholm, Sweden, in 1972. The development of global environmental politics was altered by this UN-organized summit. As a result, the United Nations Environment Programme (UNEP) was established, and agreements were made to coordinate international efforts to advance sustainability and protect the environment (Hirst, 2020).

The subject was primarily considered as a scientific issue rather than a serious political "problem". But from the time of this conference in 1972 until the second half of the 1980s, some policymakers paid attention as scientists raised alarms about the dangers presented by rising greenhouse gas emissions (GHGs). This was acknowledged in both the Toronto Conference on the Changing Climate in 1988 and the First World Climate Conference in 1979(Hirst, 2020).

1.4.1 Intergovernmental Panel on Climate Change

International agreement was reached in 1988 for the World Meteorological Organization (WMO) and UNEP to establish a joint intergovernmental assessment of the science, consequences, and available climate change response options. The Intergovernmental Panel on Climate Change (IPCC) was founded to do this assessment, and it has since produced five thorough assessments that have been put through stringent review procedures (Hirst, 2020).

The IPCC released its initial assessment report in 1990. The statement stated that "emissions resulting from human activities are substantially increasing the atmospheric concentrations of greenhouse gases." Vast requests for a global convention resulted from this. On May 9, 1992, the Convention was ratified and made available for signatures with 197 Parties, this first global climate change accord has almost universal membership. The Treaty's goal is to "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." (Hirst, 2020).

1.4.2 The first global agreement on climate change: UNFCCC

A Conference of Parties (COP) has been held every year since that time. This is the UNFCCC's decision-making body. Countries, or Parties, evaluate the Convention during COPs and make choices to advance its execution, considering items like national emission inventories. (Hirst, 2020).

1.4.3 The Kyoto Protocol

On December 11, 1997, the Kyoto Protocol was formally adopted. It took a while for ratification, and on February 16th, 2005, it became effective. The Kyoto Protocol has 192 Parties at this moment. The Kyoto Protocol executes the United Nations Framework Convention on Climate Change by requesting industrialized nations and economies in transition to set and achieve individual emission reduction targets for greenhouse gases (GHG). The Convention just asks these nations to develop mitigation-related policies and procedures and to report on a regular basis (Würth, K.(n.d.). What is the Kyoto Protocol? Https://unfccc.int/kyoto_protocol).

Negotiations on what would follow the Kyoto Protocol from 2020 onwards began at COP 13 in 2007. The failure to reach agreement in Copenhagen at COP 15 in 2009, meant the next major attempt didn't take place until Paris in 2015 at COP 21. The Paris Agreement sets out a global framework to avoid dangerous climate change by limiting global warming to well below 2°C and pursuing efforts to limit it to 1.5°C. It also aims to strengthen countries' ability to deal with the impacts of climate change and support them in their efforts. What was significant for the Agreement is that all Parties – industrialised and less developed – were required to submit comprehensive nationally determined contributions (NDCs). These were essentially national climate change plans. The Paris Agreement set countries a deadline of 2018 to develop and agree guidelines for bringing the agreement fully to life ahead of it coming into effect in 2020. (Hirst, 2020).

Table 1.1 Key dates in global climate change negotiations, 1972-2021 (Hirst, 2020).

Year	Convention
1995	IPCC Second Assessment report published
1995	The first meeting of the UNFCCC Conference of Parties (COP 1) takes place in Berlin, Germany
1997	After two years of formal negotiations, the Kyoto Protocol agreed is agreed at COP 3 in Kyoto, Japan
2001	IPCC Third Assessment Report (TAR) published
2005	Kyoto Protocol enters into force
2007	The IPCC's fourth assessment report (AR4) published
2009	Parties fail to reach agreement on a successor to the Kyoto Protocol at COP 15 in Copenhagen, Denmark
2014-2015	IPCC Fifth Assessment Report (AR5) published
2015	A successor agreement to the Kyoto Protocol (the 'Paris Agreement') is reached at COP 21 in Paris, France
2020	Paris Agreement takes legal effect
2021	Postponed COP 26 scheduled to take place in Glasgow with UK Government as hosts

1.5 Structure of the thesis

The first two chapters extensively delve into the climate system, climate change, and their characteristics. This thesis operates within the framework of the PNRR NODES (Nord-Ovest Digitale e Sostenibile, "Digital and Sustainable North-West") project, which seeks to create landslide hazard maps focusing on the influence of climate change on landslide occurrences.

It's important to note that the primary scope of this thesis is not a direct investigation into the impact of climate change on landslides and their subsequent effects on infrastructure. Rather, the focus lies in meticulously examining environmental parameters, notably temperature and precipitation data, which serve as foundational elements for subsequent climate change studies in the specific case study region. This thesis aims to provide essential inputs for researchers interested in studying climate change in the region, specifically its impact on landslide occurrences and their ramifications for infrastructure.

Due to the complex nature of the climate system and to provide a reasonable sequence of related contents to understand it, the first chapter of this thesis reviews brief information about earth climate system, its main mechanisms and components which form the climate system .furthermore, history of climate change policies is discussed. the aim of this chapter is to give the readers general information about the importance of studying climate change and its consequences.

In the next chapter climate change, its causes, impacts and its characteristics are discussed in detail. Studying the climate change is highly dependent on the area which the case study is located in, as the climate characteristics are highly dependent on the geography of the region, therefore it is essential before writing down the methodology chapter, give the reader a comprehensive image of the reason of the choosing of the climatological variables and the methodology which is going to be used in the 4^{th} chapter of this thesis , the case study of this thesis is occurred in Valle d'Aosta which has its unique characteristics ,it should be mentioned that to study the climate of a region and the environmental parameters under the study it is essential to have a precise understanding of the climate of that region , this leads to choosing the appropriate datasets , most related climate variables and eventually the methodology . Although there is a massive literature in climate change studies , the lack of data analysis studies specifically in a regional scale is seen , to overcome this issue we will be focused in climate change study of our region of interest , the importance to study the climate change of this region , available data , data collection , a brief literature review of the reanalysis datasets , and in chapter 4 the methodology to conduct data evaluation is explained , chapter 5 represent results of data analysis and remarkable findings of the thesis .

CHAPTER 2

Climate change: Characteristics, causes and consequences

2.1 Introduction

This chapter delves into an examination of the causes and impacts of climate change across different confines. Also, it provides a brief explication of greenhouse gas emigrations and their primary contributing factors. The chapter offers perceptivity into comprehending the significance of climate change studies and their vital part in advancing conduct for both mitigating and adapting to climate change. It is important that audience has a comprehensive image of climate change, its top causative factors, and implicit ramifications.

2.2 Climate change definition

Climate change is evident, and it is observed, Over the past century, Earth's climate has changed. Sea levels have risen, glaciers and ice sheets have decreased in size, and the atmosphere and oceans have warmed. Human activities are the main cause of greenhouse gas emissions. As greenhouse gases continue to increase, Earth's physical environment and ecosystems will undergo further changes ("The science of climate change: Questions and answers", Australian Academy of Science, Canberra, 2015 www.science.org.au/climatechange).

To have a clearer understanding of what is climate change and how it can impact in different aspects, it is necessary to discuss the term "Climate Change "more specifically and to know what is referred as climate change in scientific terms. There is a large literature on climate change. The most comprehensive reference and literature survey is provided by the Reports of the Intergovernmental Panel on Climate Change (IPCC). In this chapter of the thesis IPCC reports are used several times as the main reference.

IPCC defines Climate Change as following: "A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use "(IPCC, 2012: Glossary of terms. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation).

Since 1850, each of the last three decades has been successively warmer than the preceding decade. An assessment in the Northern Hemisphere indicates, since 1983 to 2012 may have been the warmest 30-year period in the last 1400 years. Multiple independently produced datasets show a global average warming of 0.85 [0.65 to 1.06] °C 2 between 1880 and 2012 as calculated by a linear trend (Figure 2.1) (IPCC, 2014: Climate Change 2014: Synthesis Report).

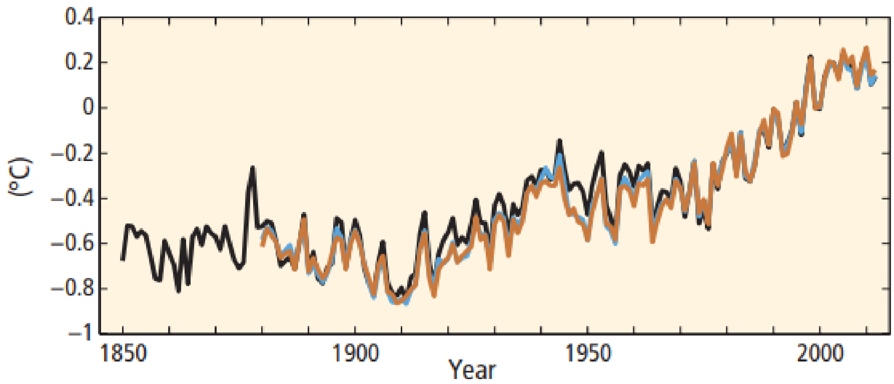


Figure 2.1 Globally averaged combined land and ocean surface temperature anomaly (IPCC, 2014: Climate Change 2014: Synthesis Report)

Greenhouse gases such can trap the emitted heat from the earth surface, and human activities increase the concentration of GHGs in the atmosphere. Since industrial revolution and mainly due to combustion of fossil fuels, CO2 concentration in the atmosphere has increased by 40 % and the average temperature of earth surface has increased by about 1 ° Celsius globally. Continuous emission of greenhouse gases, results in further climate change including global warming and significant changes in regional climate (National Research Council 2020. Climate Change: Evidence and Causes: Update 2020).

Natural causes such as sun's output variations and changes in the Earth's orbit around the sun, internal fluctuation in the climate system and volcanic eruptions are not adequate to result in recent changes in the climate system. Simulations in climate models show that if only natural causes influence the climate system, there would be slight increase in surface temperature or even a little cooling over the 20th century and into the 21st century, but when human influences are included in these simulations, changes in temperature have similar behaviour of the recent observed climate change (National Research Council 2020. Climate Change: Evidence and Causes: Update 2020).

2.2.1 Global warming

One of the most controversial issues of the world today is global warming. The term "global warming" describes how anthropogenic activities have impacted the climate system, particularly the burning of fossil fuels (coal, oil, and gas) and extensive deforestation. Specifically, after the industrial revolution global warming has increased substantially and are currently responsible for the release of about 7 billion tonnes of carbon dioxide as well as significant amounts of methane, nitrous oxide, and chlorofluorocarbons (CFCs) into the atmosphere each year. They are referred to as greenhouse gases. The greenhouse effect results from the presence of greenhouse gases in the atmosphere that absorb thermal radiation emitted by the Earth's surface and, consequently, act as a blanket over the planet by considering both the solar radiation that warms the Earth's surface and the thermal radiation that the Earth and its atmosphere emit into space, one may comprehend the fundamental idea behind global warming (Houghton, 2005).

These two radiation streams generally need to be in balance. The reason it is called the "greenhouse effect" is because the glass in a greenhouse has characteristics in common with greenhouse gases, "such as the ability to absorb infrared radiation while remaining transparent to the visible part of the spectrum"(Houghton, 2005). The basic radiation balance is changed if greenhouse gas concentrations rise because of human activity. The balance can be restored through an increase in the Earth's surface temperature (Houghton, 2005).

2.2.2 A simple model of greenhouse gases blanket effect

(Houghton, 2005) explained the blanket effect of greenhouse gases and named it "a simple model", in this model he considered a black surface at temperature T_s which receives radiation in the visible part of the spectrum of magnitude:

$$\sigma T_0^4 \tag{1}$$

where σ is Stefan's constant. If there is no blanketing effect $T_s = T_0$.

In this case, suppose there is an absorbing layer at temperature T_a above the surface, which is transparent to the incident visible light but absorbs a fraction of the infrared light from the underlying surface at all wavelengths. In addition to absorbing energy, surfaces that emit energy radiate energy of magnitude $k\sigma T_s{}^4$ both upwards and downwards. This formula can be determined from the radiative equilibrium of the layer:

$$T_a^4 = 0.5k\, T_s^4 \tag{2}$$

According to the radiative equilibrium of the surface, its temperature is given by:

$$T_s^4 \ = (1 - 0.5k) -1\, T_0^4 \tag{3}$$

For k = 0.5, $T_s^4 = 1.33\ T_0^4$. Therefore, a thin layer that absorbs half of the thermal radiation it encounters will raise the surface's absolute temperature by around 7.5%. This entails a rise of 20° C for a surface that was initially at 260° C. If the absorbing layer were to be introduced instantly, before the surface or layer had time to warm, there would be an immediate drop in outgoing radiation of $0.5k\sigma T_0^4$ at the top of the atmosphere (i.e., above the absorbing layer). This quantity is called the radiative forcing. A rough approximation of the influence of greenhouse gases in the atmosphere on the surface temperature and on the radiation that escapes from the top of the atmosphere is provided by this simple model with k = 0.5(Houghton, 2005).

To understand what is the basic science of the greenhouse effect and how it is related to climate change , it is essential to address following topics : climate variability evidenced by past records , sources and sinks of greenhouse gases , the concept of radiative forcing ,climate models and how well they simulate past and current climate , projections of climate change over the 21st century , impacts of climate change especially those on infrastructures ,international policy and action regarding climate change , mitigation of climate change and implications for technology and the future challenge .

2.3 Greenhouse effect

The primary energy source for the climate of Earth is the Sun. The bright surfaces like ice and clouds reflect some of the incoming sunlight back into space, while the remaining sunlight is absorbed by the surface and the atmosphere. Most of this solar energy is reemitted as heat (longwave or infrared radiation). The atmosphere in turn absorbs and re-radiates heat, some of which escapes to space (National Research Council 2020. Climate Change: Evidence and Causes: Update 2020).

The climate will be impacted by any changes to this equilibrium of incoming and outgoing energy. For instance, small changes to the Sun's energy will have a direct impact on this equilibrium. The average surface temperature of the Earth would be tens of degrees lower if all heat energy released from the surface went straight through the atmosphere and into space. The presence of greenhouse gases in the atmosphere, such as water vapor, carbon dioxide, methane, and nitrous oxide, causes the surface to be much warmer than this (Figure 2.2).

These gases absorb and radiate heat energy in all directions, including downward, maintaining the temperature of the Earth's surface and lower atmosphere. The evolution of life as we know it on our planet would not have been possible without the greenhouse effect. The atmosphere's ability to stop heat from escaping into space is increased by adding additional greenhouse gases to the atmosphere. Earth warms when energy leaving exceeds energy entering until a new balance is reached (National Research Council 2020. Climate Change: Evidence and Causes: Update 2020).

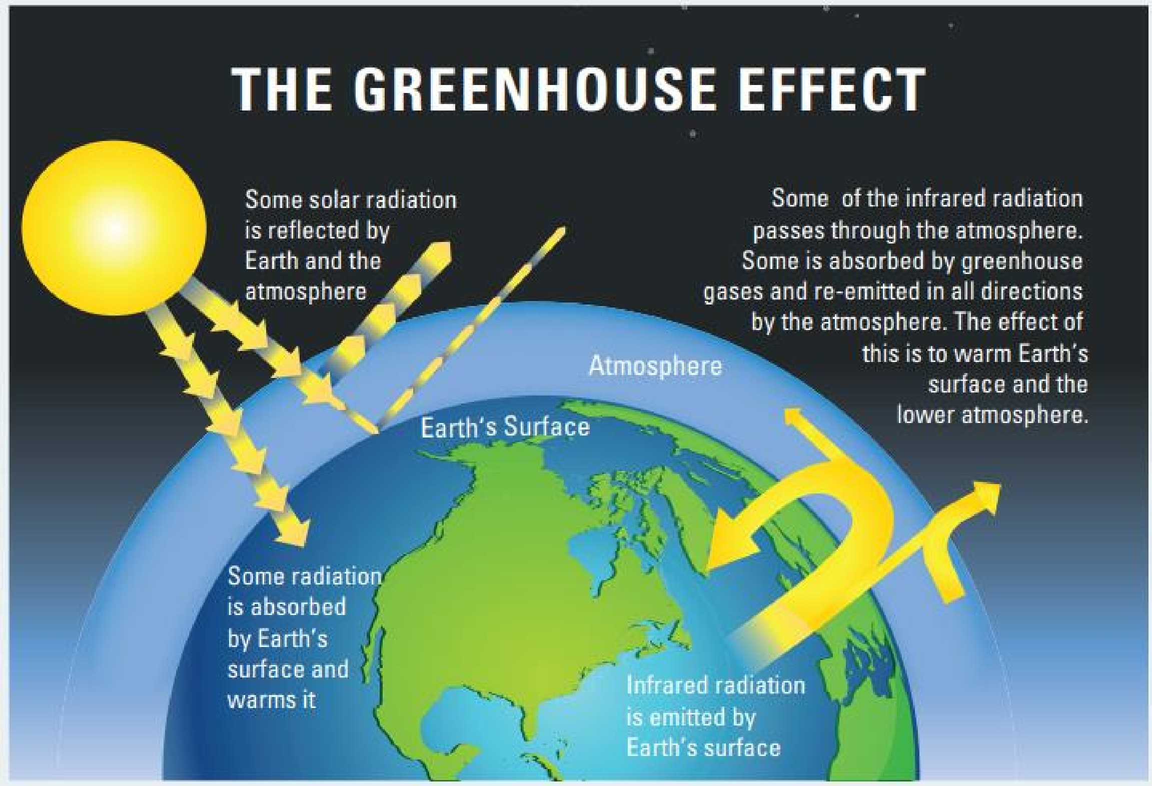


Figure 2.2 Greenhouse gases in the atmosphere, including water vapour, carbon dioxide, methane, and nitrous oxide, absorb heat energy and emit it in all directions (National Research Council 2020. Climate Change: Evidence and Causes: Update 2020).

2.3.1 The radiation balance of Earth and atmosphere

The energy entering and leaving the Earth system balance globally on average, with the incoming solar radiation balanced by thermal radiation leaving the atmosphere or the surface (Greenhouse Gases and Earth's Energy Balance retrieved from: https://resilience.earth.lsa.umich.edu/). The transfer of energy occurs through various processes such as infrared radiation, conduction of sensible heat, and evaporation of water whose latent heat is released later when the water condenses again. The incident solar radiation on a surface of one square meter directly facing the sun is about 1370 W, while the average over the whole Earth's surface is one quarter of this or 342 Wm^{-2} . About 30% of the incoming solar radiation on average is reflected or scattered back to space from the Earth's surface, clouds, small particles, or by Rayleigh scattering from molecules (Greenhouse Gases and Earth's Energy Balance retrieved from: https://resilience.earth.lsa.umich.edu/).

The spectral distribution of thermal radiation leaving the top of the atmosphere can identify the greenhouse gases responsible for this radiation, including water vapor, carbon dioxide, methane, ozone, and nitrous oxide (The Earth's Radiation Budget | Science Mission Directorate retrieved from: The Earth's Radiation Budget - NASA Science).

The presence of greenhouse gases in the atmosphere prevents more infrared radiation from escaping into space, leading to an accumulation of energy, and warming of the planet The Energy Budget - UCAR Center for Science Education; Houghton, 2005).

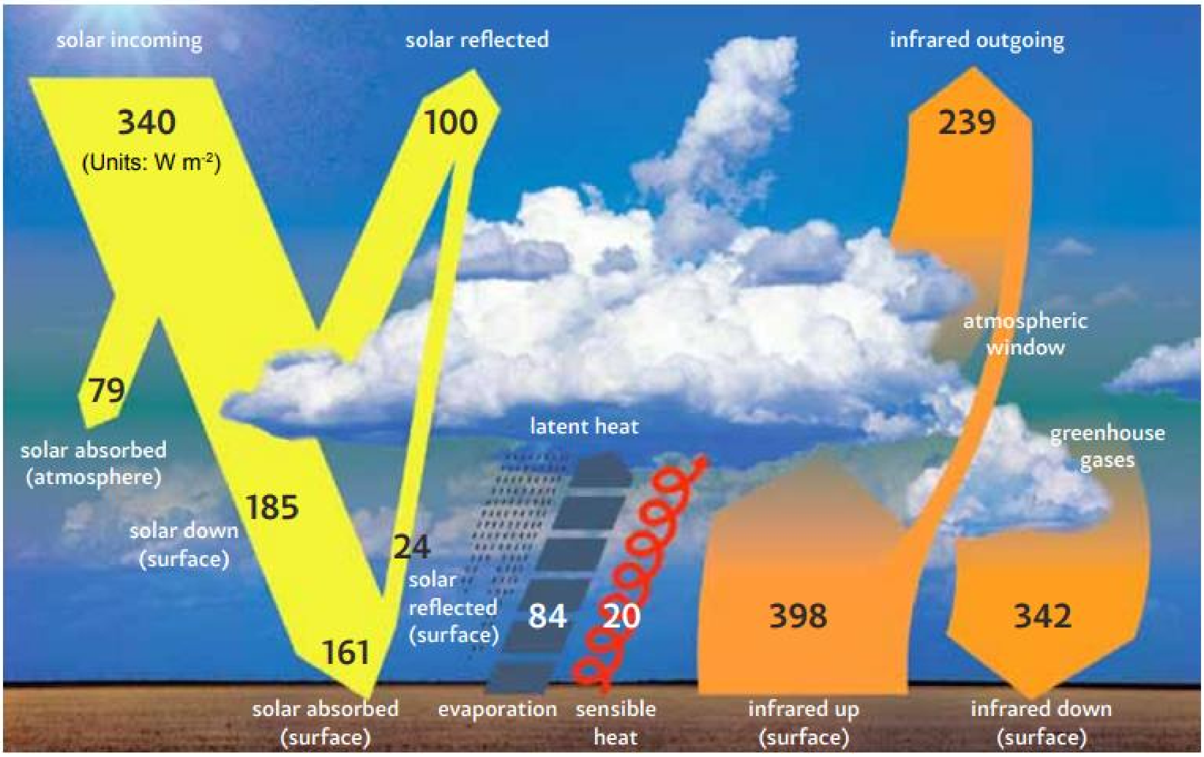


Figure 2.3 The rates at which energy exits the Earth system and enters it from the Sun roughly balance on a global scale (Houghton, 2005).

2.3.2 The natural greenhouse effect

The natural greenhouse effect due to greenhouse gases such as water vapor, carbon dioxide, ozone, methane, and nitrous oxide is responsible for maintaining the Earth's climate as we know it. Nitrogen and oxygen, which make up most of the atmosphere, do not contribute to the greenhouse effect. Without greenhouse gases, the Earth's surface temperature would be about -6℃, but the actual average temperature is about 15℃ due to the greenhouse effect. The size of the greenhouse effect depends on the temperature structure of the atmosphere where the gases are located. Clouds play a significant role in the Earth's radiation balance, reflecting some incident radiation back to space and absorbing and emitting thermal radiation. On average, clouds result in a slight cooling of the Earth's surface (Houghton, 2005).

2.3.3 The enhanced greenhouse effect

Over time spans ranging from decades to thousands of years and longer, the global climate naturally changes. These natural variations can come from two different sources: internal fluctuations that change the exchange of energy, water, and carbon between the atmosphere, oceans, land, and ice, and external influences on the climate system, such as changes in the energy from the sun and the results of volcanic eruptions. The quantities of CO2 and other greenhouse gases in the atmosphere, the concentrations of aerosols, and the reflectance of the Earth's surface can all be affected by human activity ("The science of climate change: Questions and answers", Australian Academy of Science, Canberra, 2015 www.science.org.au/climatechange).

2.3.4 Greenhouse gases

The study conducted by Bruhwiler et al., (2021) provides a comprehensive analysis of greenhouse gases (GHGs), which are crucial indicators for assessing climate change. The major GHGs discussed in their study include carbon dioxide (CO2), methane (CH4), nitrogen oxide (N2O), and halocarbons. These gases are significant due to their substantial contributions to climate change. The study underscores the significance of understanding these GHGs, their sources, and long-term measurements, as they play a pivotal role in driving climate change. In this section, we will briefly outline the major GHGs, their evolution over time, and their primary sources, drawing insights from the study by Bruhwiler et al., (2021). Understanding GHG atmospheric abundances over time helps track radiative forcing, track climate mitigation policies, and understand carbon-climate feedback processes, potentially influencing their effectiveness and success.

2.3.4.1 Carbon Dioxide

The combustion of fossil fuels and changes in land use have been the main causes of the increase in global atmospheric CO2 from 280 parts per million in the pre-industrial atmosphere (MacFarling Meure et al., 2006) to over 413 parts per million as of July 2020. By transferring carbon from rocks and sediments to the atmosphere over millennia, this quickens the natural geologic carbon cycle. Currently, two-thirds of the whole anthropogenic climate forcing from long-lived gases comes from CO2 (Hofmann et al., 2006).

2.3.4.2 Methane

Increasing by 160% since preindustrial times, the atmospheric CH4 quantity at present is unprecedented (Loulergue et al., 2008). Up to the late 1990s, there was a sharp increase in global CH4, which levelled down in the early 2000s and started to rise again around 2006 (Rigby et al., 2008; Dlugokencky et al., 2009). Not much is known about the reason for this recent atmospheric increase. 30–35% of all anthropogenic emissions are caused by human activity, of which 60% are attributed to livestock, agriculture, landfills, and sewage. According to a recent study, geology and fossil fuel emissions could be 20–60% more than previously believed. About 40% of emissions worldwide come from natural sources, primarily wetlands and terrestrial aquatic systems. About one-fourth of the worldwide total human radiative forcing is attributed to CO2, with CH4 contributing 0.52 Wm^{-2}.

2.3.4.3 Nitrous oxide

Nitrous oxide (N2O) is increasing in the atmosphere at a rate of 0.94 ppb $year^{-1}$. Its atmospheric lifetime is around 120 years, and it is mainly destroyed in the stratosphere through reaction with atomic oxygen and photolysis. Natural emissions are estimated at 10-12 Tg N2O-N $year^{-1}$, with anthropogenic emissions at 5.2-5.5 TgN2O-N $year^{-1}$. About 66% of this is likely due to agriculture, with 15% coming from fossil fuel combustion and 11% from biomass burning. Population growth is expected to continue increasing N2O levels (Davidson and Kanter, (2014); Röckmann and Levin, (2005); Park et al., (2012); Hansen et al., (2017)).

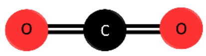
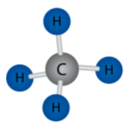
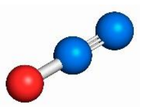
2.3.4.4 Halocarbons

Halogenated gases, prevalent since the mid-20th century to meet societal needs, were virtually absent in the atmosphere before that period (Velders et al., 2007). These compounds, which include chlorofluorocarbons, hydrochlorofluorocarbons, hydrofluorocarbons, halons, and certain chlorinated gases, exhibit remarkable persistence and serve as potent greenhouse gases, with Global Warming Potential values reaching up to 14,000 times that of carbon dioxide (Velders et al., 2007).

Although their atmospheric concentrations are significantly lower than CO2, they still contribute to climate forcing, albeit at approximately 17% of CO2's impact (Velders et al., 2007). Photolysis in the stratosphere, resulting in the formation of reactive chlorine and bromine species that deplete stratospheric ozone, is the primary means of their removal from the atmosphere (Velders et al., 2007).

The 1987 Montreal Protocol on Substances that Deplete the Ozone Layer has been a successful global treaty addressing ozone depletion and has also helped mitigate climate change due to the substantial global warming potential of these compounds (Velders et al. 2007). The control of their substitutes, particularly hydrofluorocarbons (HFCs), is vital for managing future warming. The 2016 Kigali Amendment to the Montreal Protocol seeks to reduce and stabilize HFC usage and its associated climate effects, pending ratification by all parties (Velders et al., 2007).

Table 2.2 (https://www.epa.gov/climate-indicators/greenhouse-gases)

GHG	**Brief explanation**	**Approximate remaining time in the atmosphere**
Carbon dioxide 	CO2 is responsible for most global warming. Burning (oil, natural gas, gasoline, and coal) trees and solid wastes leads to adding carbon dioxide into the atmosphere.it is absorbed by plants in the photosynthesis	Its lifetime cannot be represented as a number, it remains in the atmosphere and moves among different parts of the climate system.
Methane 	Methane is 25 times more potent than CO2; it is produced by livestock's, wetlands, and landfills.	12 years
Nitrous oxide 	Nitrous oxide comes from the combustion of fossil fuels, industrial processes, and fertilizers .it is far more potent than both methane and co2, but it is far less common.	For around a century
Water vapor and ground level ozone	Categorised in minor GHGs, Contribute to global warming	For less than a month
HCFCs	HCFCs also trap a lot of heat but are not very common since the widespread of CFCs was banned in 1987.	A few weeks to thousands of years

2.4 Climate Change in the past

Climate change is not only a future possibility, it had affected already the natural environment and societies in the past and it also exists right now, there are examples of vanished civilizations which are associated to the regional climate change such as Maya in Mexico because of drought and disappearance of Vikings in Greenland due to temperature decrease (Houghton, 2009). And in recent decades there are evident changes in the global climate such as Hot days and nights have become more frequent, more intense, and longer lasting, while cold days and nights have decreased in most parts of the world (Houghton, 2009).

2.5 Climate Change causes

As previously discussed, the ongoing climate change phenomenon is primarily attributed to the emissions of greenhouse gases (GHGs), and a comprehensive explanation of the greenhouse effect was provided. This section aims to delineate the key factors considered as the principal causes of climate change for better categorization and understanding, following subsection is inspired by (Kaddo, 2016; Riebeek, 2010; Berbesi et al., 2014).

Greenhouse gases play a pivotal role in driving climate change, primarily by trapping and absorbing heat within the Earth's atmosphere. This phenomenon, known as the greenhouse effect, occurs as incoming solar energy is absorbed by the Earth's surface and subsequently radiated back into space. Greenhouse gases intervene in this process by absorbing a portion of the emitted heat and re-emitting it back to the Earth's surface. Notably, the greenhouse effect stands as a significant concern for scientists, given that it is responsible for approximately 75% of global greenhouse gas emissions.

Moreover, the contemporary warming trend has been associated with the release of methane and CO2 from evolving petroleum systems. Studies have indicated that methane leakage rates in regions like the western Canada sedimentary basin and the Central Graben area of the North Sea amount to approximately 10-2 Tg/yr. However, it is important to note that thermal gas generation in hydrocarbon systems at a global scale has a relatively minor impact on climate.

Nature also contributes to climate change by emitting CO2 through volcanic activity. On average, volcanoes release between 130 and 230 million tons of CO2 annually. Nevertheless, human activities surpass these natural emissions by releasing over 26 billion tons of CO2 into the atmosphere each year.

Human activities significantly contribute to climate change due to our heavy reliance on fossil fuels for meeting our energy needs. These activities, encompassing energy production, agriculture, industrial processes, and transportation, lead to a substantial increase in greenhouse gas emissions. This increase has been particularly pronounced since the industrial revolution, with fossil fuel combustion being a primary driver of this surge in greenhouse gas emissions.

2.6 Emissions scenarios

the intensity of climate change consequences will depend on the overall emissions pathway, climate models can provide helpful information that how atmosphere will respond to different GHGs emission scenarios in global scale, but they are very uncertain, particularly in regional and local scale climate models cannot provide exact projections. Furthermore, several factors contribute to emission pathway scenarios such as socioeconomic changes therefore it is less probable to obtain exact outcomes; and models varies for every single case (Jackson, (2007). According to the projections provided by IPCC, possible impacts occur by 2100 under two emission pathways: the low emissions (RCP2.6) and high emissions (RCP8.5). pathways are more confidence in temperature projections than those for precipitation or sea-level rise. Due to future socio-economic scenarios, it is unlikely that future emissions reach the levels projected by RCP8.5 (National Research Council 2020. Climate Change: Evidence and Causes: Update 2020; Riahi et al., 2017; Shepherd, 2014).

2.6.1 Representative Concentration Pathways (RCP)

In the latest generation of emission scenarios, called Representative Concentration Pathways (RCP), greenhouse gas and aerosol concentrations are plotted along trajectories for particular climate projections (like radiative forcing values in 2100). Each trajectory represents a particular development scenario for anthropogenic emissions. Future anthropogenic emissions are heavily influenced by global political decisions, population growth, and technological advances. Various emission scenarios depict these uncertainties. Hence, RCP2.6 relies on a global agreement to drastically reduce greenhouse gas emissions. This scenario assumes an additional radiative forcing of 2.6 Watts per square metre by the end of the 21st century. RCP8.5 represents a situation where people continue to emit greenhouse gases in the same way as they have till now: This is equivalent to a radiative forcing of 8.5 Watts per square metre by the end of the century. Other scenarios involve greater and lesser levels of technical advancement, resulting in slight reductions in greenhouse gases between these two. Increasing radiative forcing values increases the severity of the shift in climate conditions. All these scenarios have been used as the basis for running climate models to show how political decision-making and other variables can affect the climate in the future. Therefore, emission scenarios indicate possible strategies. Without predicting which course of action is most likely, they allow the climate-related effects of several options to be quantified (https://www.nccs.admin.ch/nccs/en/home/climate-change-and-impacts/climate-basics/what-are-emission-scenarios-.html).

2.6.2 Climate models

''The problem is not whether our climate will change but rather in what direction and from what causes it will be changed. There are now, however, other factors than there were in the past to be weighed in any speculation about future climate changes, human is altering both the earth and the composition of the atmosphere and is releasing energy into the global environment on such a large scale that his influence may no longer be dismissed. Mankind may have already caused climate changes, although no one can yet be sure to what extent'' (Schneider & Dickinson, 1974).

desire to understanding the physical processes in climate system leads to looking for tools which build up a theory of climate and climate change. Since the climate system cannot be reproduced satisfactorily in the physic laboratory, there is a need to use mathematical studies, such as climate models, to supplement empirical evidence (Schneider & Dickinson, 1974).

The climate is influenced by various factors, including solar radiation, ocean currents, ice distribution, and atmospheric circulation. To comprehensively understand and model climate behaviour, it is essential to express these factors through the equations of general climate theory. This theory is grounded in fundamental principles, such as the conservation of mass, momentum, and energy. Additionally, it incorporates the thermodynamic and chemical laws that govern changes in the composition of the land, sea, and atmosphere (Schneider & Dickinson, 1974).

The core of the theory consists of a system of interconnected nonlinear three-dimensional partial differential equations. These equations need to be solved, considering external factors like solar radiation and the initial state of the Earth-atmosphere system. Furthermore, each variable within this system is interrelated with the others, creating a complex web of interactions. Changes in one variable can lead to simultaneous variations in others, and these changes, in turn, can produce feedback effects on the original variable (Schneider & Dickinson, 1974).

A climate model is a computational representation of the Earth's intricate climate system, encompassing the dynamics of the atmosphere, oceans, land surfaces, and polar ice. These models serve a dual purpose, enabling the reconstruction of past climates and the projection of future climate conditions (What is a climate model? https://ncas.ac.uk/learn/what-is-a-climate-model/).

Climate models undertake complex calculations of numerous climate parameters, including atmospheric temperature, pressure, wind patterns, and humidity levels. These calculations span a vast three-dimensional grid, involving innumerable points across the globe (What is a climate model? https://ncas.ac.uk/learn/what-is-a-climate-model/).

Through the application of mathematical equations rooted in the principles of fluid dynamics, thermodynamics, and radiative transfer, climate models offer the capacity to discern the evolution of the atmosphere and ocean over time (What is a climate model? https://ncas.ac.uk/learn/what-is-a-climate-model/).

The utility of climate models extends to validating and refining scientists' comprehension of the Earth's climate system, as well as making prognostications regarding forthcoming climatic shifts (What is a climate model? https://ncas.ac.uk/learn/what-is-a-climate-model/).

Researchers employ climate models for two primary purposes. First, these models are instrumental in scrutinizing and verifying our knowledge of the climate system's intricacies. Second, they are invaluable tools for predicting future climatic scenarios. For instance, scientists can introduce diverse global warming scenarios into these models and assess their repercussions on the climate. This approach yields insights into the potential consequences of global warming. Notably, the Intergovernmental Panel for Climate Change recently investigated the implications of a 1.5°C increase in temperature above pre-industrial levels by harnessing the capabilities of climate models (What is a climate model? https://ncas.ac.uk/learn/what-is-a-climate-model/).

2.7 Climate change impacts

Impacts of climate change are not only limited to global warming caused by emission of greenhouse gasses but also include vast number of phenomena such as widespread melting of the Greenland and West Antarctic ice sheets which causes large rise in sea water level (How Do We Know Climate Change Is Real? https://climate.nasa.gov/evidence/), changes in frequency and severity of extreme events, water availability, drought, human health, environment and ecosystems and physical infrastructures. intensity of these impacts can be varied by considering different climate change scenarios and results can be different but the common point in all these scenarios is that without climate change mitigation and adaptation actions, facing this changing climate can bring humans a fundamental challenge.

These impacts are all interrelated, occurring one can cause further issues. for instance, infrastructures can be damaged by floods, this can threat societies which use the infrastructure, transportation can be disrupted, by occurring floods more disease are spread and when human health is affected, rate of fatalities increases, work productivity will be affected which can bring more issues in the society (What Are the Different Climate Types? https://scijinks.gov/climate-zones/).

While some of the effects may be beneficial to both the economy and society, most are expected to be negative, at least for moderate temperature increases. Furthermore, at higher temperatures, the severity of the impacts is likely to be non-linear as certain temperature thresholds are exceeded, the likelihood of large economic and ecological damage increases (Landsberg ,1945).

Major Climate change events due to human activities or even based on natural ones are fractious. They lead to extinction of species, compulsory migration and noticeable changes in land surface and ocean circulation. The current rate of climate change is faster than most previous events, making adaptation more difficult for human societies and the natural world (National Research Council 2020. Climate Change: Evidence and Causes: Update 2020).

2.7.1 Frequency and severity of extreme events

Global climate warming in future is strongly dependent on cumulative CO_2 emissions (Houghton, 2009). Scientists have achieved significant improvements in observing and modelling the climate system. These improvements have led them to project future climate more confidently. But due to complexity of understanding the climate system feedback to changes in upcoming decades and impossibility to predict the amount of CO_2 emissions which human activities put in the atmosphere , (as it depends on several factors such as energy consumption patterns and global economy in the future) “there is a range of possible outcomes, even for a particular scenario of CO_2 emissions” and it makes it impossible to predict exactly the ?warming? trends .furthermore , over decades natural variability can modulate the effects of an underlying trend in temperature . By considering all these aspects, according to all model predictions, Earth will continue to warm significantly over the coming decades to centuries. Further global warming of 2.6 to 4.8 °C (4.7 to 8.6 °F) above current levels would be anticipated during the 21st century in absence of technical or legislative measures to slow down emission trends from their current trajectory (Earth's Climate Background Information. Lunar and Planetary Institute (LPI) https://www.lpi.usra.edu/education/explore/ice/background/iceEarth/).

Human induced GHG emissions causes the Earth’s lower atmosphere to become warmer and moistener, this phenomenon provides more energy for extreme events such as storms. Since global warming has occurred, more intense and frequent extreme events are observed around the world. scientists mention events as extreme when They differ from 90% or 95% of previous similar weather events in the same region. The occurrence of these events depends on several factors and not only anthropogenic activities, but natural climate events also such as El Nino and la Nina can make it difficult to attribute a climate event to a particular human-caused factor. on the other hand, studies show that the intensity and frequency of an extreme event can be related to human activities (Earth's Climate Background Information. Lunar and Planetary Institute (LPI) https://www.lpi.usra.edu/education/explore/ice/background/iceEarth/)

Extreme rainfall events are expected to become more frequent and intense as global average temperatures rise, because a warmer atmosphere contains more moisture. This is already being observed globally. Heavy rainfalls have become more frequent and intense over most land areas in recent decades, though these trends have varied significantly across regions and seasons (Houghton, 2009).

Projections from climate models that are done in Australia shows that under a high emission pathway, extreme rainfall events increase and climate models in global scale, project intensification of wettest days and decrease in the return time of extreme events with significant regional variation. There may be fewer tropical storms, but they are predicted to be stronger and cause more rain than they do now (Houghton, 2009).

More intense heat waves are expected to occur because of warmer climate Earth's Climate Background Information. Lunar and Planetary Institute (LPI) https://www.lpi.usra.edu/education/explore/ice/background/iceEarth/), high temperature events are expected to be hotter and cold events will be less cold. Extreme heat events that occur once in 20 years are likely to be over 4° hotter than what happens now. in addition, these events are going to be more frequent for instance if an extreme event was likely to happen every 20 years, due to warming climate it would happen every one or two years (Houghton, 2009).

Furthermore, Changes in rainfall have a significant impact on water availability because changes in rainfall are amplified by changes in runoff to rivers (Houghton, 2009).

2.7.2 Droughts

It is believed that Ozone layer depletion not only has serious effects on human health, but also will increase the occurrence of extreme weather events (drought, desertification) by removing the protective layer that shielded the planet from Sun radiation (Rahman, 2013).

Human-induced climate change is amplifying the occurrence and severity of droughts, particularly impacting agriculture, and water resources. This phenomenon has led to significant economic damage from drought-related disasters between 1970 and 2019. Vulnerable populations, including the poor, women, children, Indigenous Peoples, and the elderly, are disproportionately affected due to historical and socioeconomic disparities. Droughts, along with tropical storms and hurricanes, are major drivers of migration and displacement, impacting regions such as Asia, sub-Saharan Africa, and small island states in the Caribbean and South Pacific. Furthermore, the risks and societal damage associated with drought are projected to increase with each degree of warming, compounded by more frequent occurrences of simultaneous heatwaves and droughts due to ongoing global warming (IPCC, 2022: Climate Change 2022: Impacts, Adaptation and Vulnerability).

2.7.3 Sea level rise

Before the middle of the 19th century, the long-term global sea-level rise was negligible, only a few centimetres each century. Since then, the rate of sea level rise has increased significantly, and the global average sea level rose by nearly 19 centimetres. Furthermore, satellites and coastal sea- level data shows 3 centimetres increase in each decade in the past 20 years (Houghton, 2009).

Since the early 19th century two major contributors to sea level rise were the warming-induced expansion of ocean water and the extra amount of water from loss of the ice in the glaciers. Since 1990, the Greenland ice sheet's surface melting and the increased discharge of ice into the ocean from the Antarctic and Greenland ice sheets have both contributed (Houghton, 2009).

sea and ocean water level rise can significantly affect the life of people in costal belts and lowland areas. Many of the world's most populous regions have been built along the coastlines. Sea level rise could lead to serious repercussions and widespread evacuations in lowland coastal districts (Zillman,2009). Neumann et al. indicated that most densely populated coasts are in Asia and will be remained populated also in the future, so it is essential for governments and authorities to take precautionary actions to protect coastal residents by considering further consequences of flooding and enhancement of coastal infrastructures (Zillman, 2009).

beside the direct effects of seal level rise in coastal regions such as such as submergence of the infrastructures and disruptions in serviceability of urban structures, further impacts include submergence of transportation infrastructures like roads, highways and railways ,contamination of drinking water due to intrusion of salty water , damages to the wastewater networks and intensifying land subsidence .further social and economic consequences are expected if vital infrastructures be damaged ,which can heavily impact daily life of the people(Zillman, 2009).

2.7.4 Human health

Heatwaves will become more common as temperatures rise in the future (Houghton, 2009). People, particularly the elderly and the sick, can suffer from heat stress in extremely hot conditions (Houghton, 2009). Human health can be affected by global warming. heat waves are deadly phenomenon, human body is in dangerous of death in the temperature more than 42, even in less temperature the productivity decreases and human needs to do more breaks.

But all the population are not equally exposed to these impacts, Examples of populations that are more vulnerable to adverse climate-related health threats include: communities of colours, because some of them live in high-risk areas, they are subjected to cumulative exposure to multiple pollutants. Children; have higher risk of heat stroke and illness than adults. Elderly people are especially vulnerable to extreme weather events that cause power outages or necessitate evacuation. During flooding and in overcrowded shelters, low-income families are at risk of physical and mental illnesses (What Are the Different Climate Types? https://scijinks.gov/climate-zones/).

Hurricanes become stronger and wetter as ocean temperatures rise, causing both direct and indirect deaths. Dry conditions cause more wildfires, which pose numerous health risks. Increased flooding can result in the spread of waterborne diseases, injuries, and chemical hazards. Mosquitoes and ticks can spread diseases to new areas as their geographic ranges expand (Landsberg, 1945).

Extreme events can also have psychological consequences. Drought has been linked to depression and anxiety in farmers and pastoralists (Houghton, 2009).

2.7.5 Climate Change impact on infrastructures

The world is changing and climate change effects like extreme weather events and major demographic changes are evident, Infrastructure provision and operation will be impacted by climate change, but they also play an essential role in bringing resilience to face these impacts. According to a case study a major flood in Paris is modelled by OECD, results show that infrastructure sector will be impacted by 30 to 55 percent of direct damages causing by the flood itself while, 35% to 85% of business losses were caused by disruption to the transportation and electricity supplies and not by the flood itself , which shows the importance of building infrastructures which are resilient enough to the direct and indirect impacts of extreme events. The intensity of these consequences will depend on the overall emissions pathway, climate models can provide helpful information that how atmosphere will respond to different GHGs emission scenarios in global scale, but they are very uncertain, particularly in regional and local scale climate models cannot provide exact projections. (Pachauri et al., 2014; Riahi, et al., 2017; Shepherd, 2014).

There should be an assurance of infrastructures serviceability and their resilience to the future climate events. The Paris Agreement has the goal of holding temperature increases "well below 2°C above pre-industrial levels and limit the temperature increase to 1.5°C above pre-industrial levels". Infrastructure should be resilient to the effects of a changing climate while also being consistent with low-GHG transitions, due to long lifetime of infrastructures, they should be able to face future climate impacts, designed and constructed in a way to be resilient enough to potential impacts of climate change.

Climate change challenges which affect infrastructures are different for each country depending on their economic situation. Countries can be classified to different subgroups and subsequently adaptation and mitigation actions which are implemented are not the same: developing countries and emerging economies should construct new infrastructure as they are expanding new cities and urban areas. Also building infrastructure to face the risk of natural disasters. Industrialised countries mostly face the challenge of replacing and adapting existing infrastructure and networks, in particular increase efficiency and reduce emissions. Extreme weather events are strong evidence that how the serviceability of infrastructures is vulnerable to the effects of changing climate (Jackson, P. (2007).

For instance, Millions of homes lost power because of the 2011 flooding in eastern China, which also seriously damaged 28 rail connections, 21,961 highways, and 49 airports (Xi, 2016). Without adaptation, it is predicted that climate change will cause infrastructure damage from extreme weather events in Europe to grow tenfold by the end of the century (Forzieri et al., 2018). Trend changes will also have a big influence on infrastructure, in addition to extremes.

From an engineering perspective, it is important to assess the potential impact of future climate scenarios on infrastructure and the resilience of design practices. Recent research has focused on the stability of natural slopes in relation to climate change, with particular attention given to temperature-induced instability in permafrost regions. Geomaterials, which are granular materials that interact with their surroundings through water interactions, play a crucial role in this analysis. These interactions, such as drying from evaporation or wetting from rain or water courses, can affect the internal stress states and stability of the materials. Figure 2.4 illustrates potential interactions between geotechnical infrastructure and the atmosphere, including both direct interactions, such as moisture exchange, and their consequences, such as soil desiccation or swelling due to vegetation loss (Briceño et al., 2007; Dehn et al., 2000; Dixon et al., 2006; Gruber and Haeberli, 2007; Harris, 2005; Huggel et al., 2010; McInnes et al., 2007; Vardon, 2015)

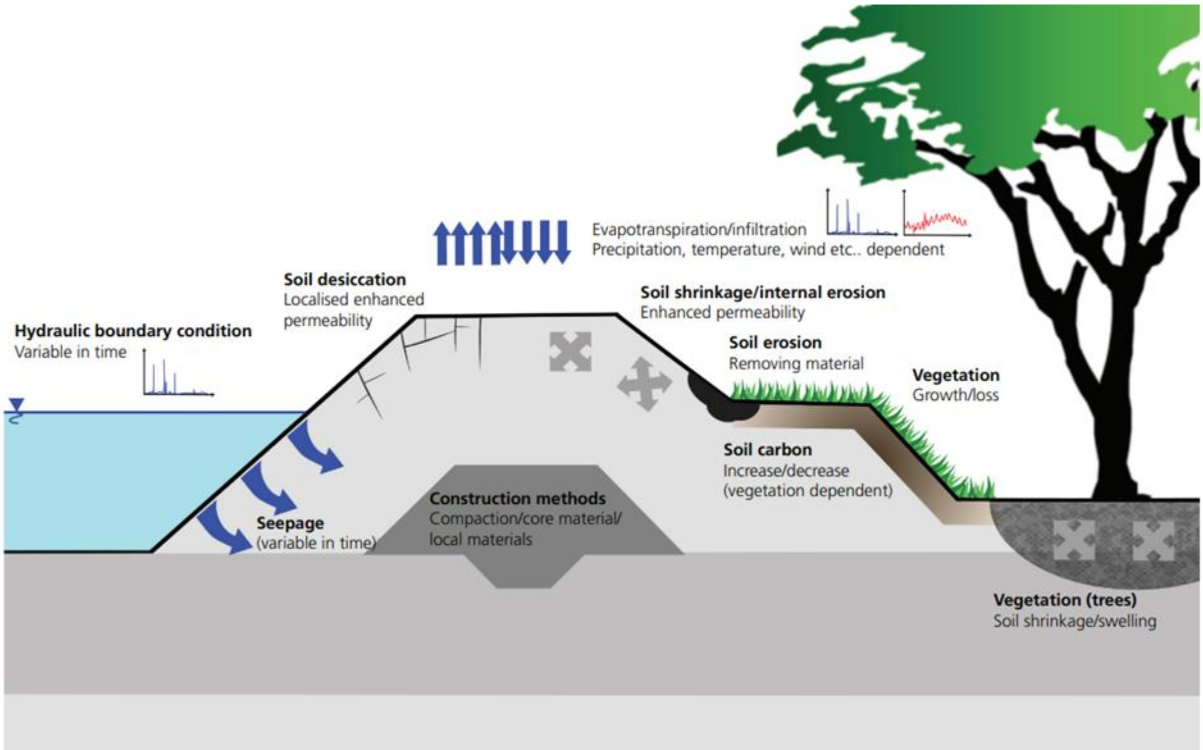


Figure 2.4 Potential interactions between geotechnical infrastructure and climate (vardon,2015)

2.7.6 Climate change factors which affect geotechnical infrastructures

According to Vardon, (2015), some impacts of climate change are well known, such as the effects of sea level rise on geotechnical infrastructure. However, he has identified other factors that may also have an impact (e.g., rising temperatures leading to soil drying, increasing average rainfall leading to a reduction in soil absorption capacity. increasing drought events leading to soil drying; and increasing heavy precipitation leading to soil erosion, flooding, and hydromechanical failure) (Vardon, 2015).

To effectively assess the potential effects of climate change on geotechnical infrastructures, it is crucial to classify and categorize all possible impacts. This chapter delves into previous research and aims to compile a comprehensive list that prioritizes the significance of these climate change impacts.

It is preferable to compare the results of different studies to expand the scope of studies to collect reliable information.

To keep a logical sequence, we first focus on the study of the impact of climate change on infrastructures. Since the main objective of this thesis is to specifically address the impacts of climate change on landslides, we then delve into this topic. This chapter serves as the foundation for subsequent chapters, particularly those in which we aim to compile a comprehensive list of the impacts of climate change as a major cause of landslides.

2.7.7 Impact of climate change on the stability of natural slopes

As a result of worldwide global warming, new precipitation and wind conditions are predicted. Vegetation, groundwater levels, and surface water levels will be significantly affected. Because of loss of soil suction, higher groundwater tables, increases in seepage velocities, frequent occurrences of rapid drawdown conditions, loss of soil reinforcements caused by roots and erosion from flooding, certain natural slopes will be less stable due to all these factors (Bo et al., 2008).

Global warming's potential impacts on natural slopes were reviewed by (Bo et al., 2008) shows Significant impacts will result primarily from indirect effects such as runoff, infiltration, and vegetation loss. It is possible to assess the effects of global warming on landslide-prone areas with a solid understanding of these mechanisms. It is predicted that landslides will increase in the future. Many natural slopes are steeper than the soil's angle of repose. Those slopes that are above or below development or can impact water courses upstream of development can be at greater risk of climate change impact (Bo et al., 2008).

Table 2.31 Slopes classification (Bo et al., 2008)

Slope type	Climate change phenomenon	Climate change impacts
Steep slopes in sandy or silty soil	heavy rainfall or vegetation loss	shallow slides
Slopes in clay soils	temperature changes from temperate to arid conditions	As these slopes desiccate, water infiltration increases, and shallow sliding occurs.
Slopes with sparse vegetation	even small climate changes can result in vegetation loss	shallow sliding
Permeable sloping terrain (e.g., sandy soil, weathered bedrock) with uphill areas susceptible to water ponding	Increased precipitation can raise water tables within these slopes	deep and extensive landslides, reactivation of large historic slides.
Slopes in silt or clay soil deposited with permeable interbeds	water pressures increase caused by small changes in uphill infiltration	extensive slides
Slopes susceptible to erosion from a water course at the toe	stabilizing toe support is lost because of higher flows and flood levels	resulting landslide can temporarily dam a river with disastrous downstream consequences when water breaks through the dam

Current relatively extreme events are likely to become the norm in the future. For example, the winter of 2000/1 was the wettest on record in some parts of the Britain and rainfall lead to more than 100 slope failures in the Southern Region of Railtrack alone. Heavy rainfall was also to blame for extensive slope failure in Scotland in 2001 and 2004 (Dixon et al., 2008). For slopes where stability is controlled by pore water pressure, the direct and indirect consequences of climate change will be important. Failure mechanisms may change; some sites may become higher risk areas and increased seasonality may have serviceability consequences. Because of the complexity of the climate-vegetation-slope systems, it is not possible to quantify the consequences of climate change reliably to enable the prediction of the behaviour of long-term infrastructure earthworks to enable the design of appropriate solutions and efficient asset management strategies.

2.8 Climate change mitigation and adaptation

Climate Change Mitigation and Adaptation are two key strategies in addressing the challenges posed by climate change. The current trend in climate change is the consequence of anthropogenic activities. Having discussed the causes and impacts of climate change in detail, it is crucial to discuss the solutions that can be implemented to avoid further impacts that may have severe effects on human life in various areas such as the economy, agriculture, and social sphere. In other words, the objective of most climate change studies is to demonstrate how climate change affects the environment and its consequences under a variety of climate change scenarios, and these studies serve as a foundation for policy makers to take decisions on greenhouse gas emissions and adaptation strategies based on these studies.

In this thesis we don't pursue climate change mitigation and adaptation strategies as this is a very broad concept and needs to be investigated under individual studies, but it is noteworthy to give the reader an image of these two definitions which are provided by IPCC. For instance, one of the sectors which is believed to be impacted by climate change is infrastructure sector, the first step to prevent the severe consequences on infrastructures which may lead to severe economic losses and in some cases, fatalities are reconsiderations in GHGs emissions and following by adaptation measurements. Therefore, it is crucial to implement feasibility studies in compatibility with current climate change trends.

- **Climate Change Mitigation**: This refers to efforts and actions taken to reduce or prevent the emission of greenhouse gases and other human activities that cause global warming and climate change. The primary goal of mitigation is to limit the extent of climate change by reducing the sources of greenhouse gas emissions, such as burning fossil fuels, deforestation, and industrial processes (IPCC, 2014: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change).
- **Climate Change Adaptation**: This refers to the strategies and actions taken to prepare for and respond to the impacts of climate change. Adaptation involves adjusting to the changing climate conditions to minimize the negative consequences on communities, ecosystems, and economies. It includes measures such as building resilient infrastructure, developing drought-resistant crops, and implementing early warning systems for extreme weather events (IPCC, 2014: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change).

CHAPTER 3

Key climate change variables and datasets selection

3.1 Introduction

Within this chapter, the initial focus is on elucidating various approaches to studying climate change and the specific parameters utilized as inputs when studying the impact of climate change on landslides.

The primary step in studying climate change within a specific region involves accessing reliable climate data. These data must exhibit temporal consistency, ensuring they cover a sufficient duration to detect climate change while avoiding biases induced by seasonal variations, temporal weather shifts, and short weather events. A larger volume of available climate data greatly enhances the depth of our understanding of climate change and allows for measurements at a considerable horizontal resolution.

Data collection and analysis methods can vary based on the study's ultimate goals, its scale, and the data's accessibility. In the context of this thesis, focusing on a relatively small region in northern Italy, the challenges in data collection are notable. The study demands highly detailed climate data due to the region's intricacies, emphasizing the need for both high resolution and temporal consistency in the climate data.

The significance of studying climate change lies in its potential to drive actions for mitigation and adaptation. As noted by Hewitson et al. (2013), there's an ethical dimension to providing climate change projections, crucial for impact and adaptation projects. These projections serve as the foundation for real decisions and investments, shaping infrastructure, society, and the environment, affecting tangible outcomes for both people and ecosystems, as highlighted by Maraun et al. (2015).

This chapter delves into the examination of datasets crucial for understanding the climate within the study area, considering both the area's specific characteristics and the challenges associated with accessing climatological data. By the chapter's conclusion, readers can anticipate a comprehensive grasp of the significance of selecting appropriate climatological datasets and the essentiality of validating data in regional climate change studies. Subsequently, in the following chapter, we explore the data collection challenges encountered in the Valle d’Aosta region. We also outline the methodology used to validate the chosen datasets and evaluate their efficacy in analysing climate change.

3.2 Key parameters in climate change studies

As the aim of this study is to establish a foundation for understanding the impact of climate change on landslides, our primary focus lies on essential climate parameters that play a role in mass movement occurrences. We begin by discussing these key variables, followed by providing examples of past mass movement events that support our selection of these crucial climate variables for this case study.

The objective of this chapter is to identify and evaluate the principal climate variables influencing slope failures and instabilities in both natural and man-made slopes and infrastructure. This exploration aims to comprehensively understand these variables and their potential impacts. To accomplish this, we first examine fundamental climate variables within the climate system and then focus on those demonstrated to affect geo-structures. This chapter introduces climate variables within the climate system and justifies our selection of variables believed to impact infrastructure due to climate changes. We will provide past examples that investigated the relationship between climate variables and slope stability. Based on these investigations, we will select the climate variables to examine within our case study area.

3.2.1 Essential climate variables

Essential climate variables (ECVs) play a critical role in characterizing Earth's climate, providing a global picture of climate change and serving as empirical evidence to support climate science and predict future change. They are used to guide mitigation and adaptation measures, assess climate risks, attribute climatic events to underlying causes, and support climate services. The concept has been widely endorsed by both science and policy circles, who use ECVs to study drivers, interactions, and feedback due to climate change, as well as teleconnections, tipping points, and fluxes of energy, water, carbon, and to predict future change. (https://climate.esa.int/en/evidence/what-are-ecvs/; https://gcos.wmo.int/en/essential-climate-variables/table)

Table 3.1 Essential climate variables (Bojinski, et al., 2014).

Earth's component	Climate variable
Atmospheric	Surface: Air temperature, wind speed and direction, water vapor, pressure, precipitation, surface radiation budget Upper air: Temperature, wind speed and direction, water vapor, cloud properties, Earth radiation budget (including solar irradiance) Composition: Carbon dioxide, methane, other long-lived greenhouse gases, ozone and aerosol supported by their precursors
Oceanic	Surface: Sea surface temperature, sea surface salinity, sea level, sea state, sea ice, surface current, ocean colour, carbon dioxide partial pressure, ocean acidity, phytoplankton Subsurface: Temperature, salinity, current, nutrients, carbon dioxide partial pressure, ocean acidity, oxygen, tracers

Terrestrial	River discharge, water use, groundwater, lakes, snow cover, glaciers and ice caps, ice sheets, permafrost, albedo, land cover (including vegetation type), fraction of absorbed. photosynthetically active radiation, leaf area index, above-ground biomass, soil carbon, fire disturbance, soil moisture

Table 3.1 presents a range of climate variables, highlighting the vast array within the climate system. However, studying all these variables is an expansive task. In this thesis, our focus centres on assessing Precipitation and Temperature. These two factors are key elements in understanding climate change and their influence on the occurrence of mass movements amidst changing climatic conditions. In the upcoming sections, we aim to illustrate our choice of precipitation and temperature as pivotal parameters in studying climate change within this case study. This will be accomplished by presenting various examples of past events triggered by climate change factors. These examples are intended to clarify and reinforce the significance of precipitation and temperature as key determinants in our examination of climate change.

3.2.2 Precipitation and temperature as key determinants

As previously mentioned, selecting the relevant climate parameters depends on the specific goals of the study. In this thesis, our focus lies in examining the extended ramifications of climate change on infrastructures. In section 2.6.5, we delved into the effects of climate change on these infrastructures. This section entails a comprehensive investigation of the key climate parameters that significantly influence infrastructures, illustrated by real examples derived from past events.

The selection of precipitation and temperature as essential parameters for investigating the impact of climate change on mass movements is justified by numerous studies that have explored the relationship between climate records and landslide inventories in various case studies. This approach enhances our understanding of the role of climate variables in the occurrence of landslides through real-world examples.

Global warming is undeniable, and assessing the effects of climate change on the natural environment both challenges the scientific community and poses thought-provoking problems for policymakers and politicians (Diffenbaugh and Field, 2013; IPCC, 2014; LoPresti et al., 2015), but the effects of global warming, and the related changes in climate, on geo-hydrological hazards (e.g., floods, landslides, droughts) remain difficult to determine, and to predict. There is the need to understand and measure how climate variables and their variability affect geohydrological hazards, including landslides (Gariano & Guzzetti, 2016). Additionally, (Huggel et al., 2012) highlight how little has been known about the factors influencing changes in landslides frequency and magnitude caused by climate change, despite several decades of recorded atmospheric warming.

Understanding how climate change affects geo-hydrological hazards like floods, landslides, and droughts is crucial to understanding the complex issue of climate change's effects on the environment. A number of variables, including variations in temperatures, precipitation, snowmelt, seismic activity, volcanic eruptions, and human activity, affect the stability of slopes and can cause landslides. Climate and its variations influence these factors, particularly precipitation and temperature. On the other hand, little is known about how climate variations affect slope stability, landslides, landslide hazards, and related risks. The Intergovernmental Panel on Climate Change (IPCC) admits that variations in heat waves, glacial retreat, permafrost degradation, and heavy precipitation will affect slope instabilities and landslides in specific regions, but it has not offered a thorough worldwide overview of landslides (Gariano & Guzzetti, 2016).

Gariano and Guzzetti (2016) conducted an exhaustive literature review focused on studies investigating landslides within the context of a changing climate. This endeavour provided a nuanced and comprehensive understanding of the intricacies associated with this subject. While we refrain from delving into the specifics within this discussion, we proceed by offering in Table 3.2 a condensed overview of select studies and their findings pertaining to landslides in the context of climate change.

Table 3.2 Insights from Climate Change Studies: Impacts on Natural Hazards and Slope Stability

Title of the paper	Authors	Remarkable findings
Changes in climate patterns and their association to natural hazard distribution in South Tyrol (Eastern Italian Alps)	Schlögel et al (2020)	Due to several triggers and locally driven ground responses, it is challenging to determine the overall response of natural hazard occurrence, magnitude, and frequency to changes in climate variables, even in a data-rich region like the one under analysis. On the other hand, there appears to be an increase in the average yearly duration of rainfall events and the frequency of debris flows.
Geomorphological evolution of slopes and climate changes in Northern Italy during the Late Quaternary: spatial and temporal distribution of landslides and landscape sensitivity implications	Soldati et al (2006)	Climate can be identified as a key factor based on the temporal distribution of potential triggering factors. The alternation between dry and humid phases causes slope instability, either directly, such as in the case of rainfall regimes, or indirectly, such as in the case of deglaciation. Although rockfalls are not directly related to climate, deglaciation and permafrost melting may have played an important role in their occurrence. Meanwhile, landslides and land flows show clearer climate dependence. The relationship between landslides and climate is certainly complex, therefore consistent, and reliable detailed studies and extensive databases is necessary.
Climate change impacts on mass movements — Case studies from the European Alps	Stoffel et al (2014)	debris-flow activity would be altered due to increase of rainfall in spring and fall. Due to increased Sediment delivery to the channels and the anticipated rise in heavy precipitation events, the size of debris flows may increase. The frequency of rock slope failures is expected to rise due to factors such as abnormally warm air temperatures, glacier shrinkage, and warming and thawing permafrost, all of which have an adverse effect on rock slope stability. Variations in elevation will probably affect changes in the frequency of landslides in the French and Western Italian Alps. Elevation may play an important role in landslide activity in Alpine regions. Above 1500 m above sea level, the projected decrease in snowpack and duration in future winters and

		springs will probably affect the frequency, number, and seasonality of landslide activations.
Is climate change responsible for changing landslide activity in high mountains?	Huggel et al (2012)	One significant effect of climate change that has been mentioned is the rise in landslides in high mountains. More research is needed to determine the relationship between climate and landslide frequency, especially in Alpine regions that are home to glaciers and permafrost. Even in climates with stable conditions, these regions are susceptible to land slide occurrences; changes in temperature and precipitation can exacerbate the risks of landslides. Drawing from a number of case studies, they suggest that the following mechanisms can modify the frequency and magnitude of landslides, and consequently the hazard, in a significant way when temperatures rise: positive feedback operating on mass movement processes that, following a first climatic stimulus, may develop independently of changes in climate; threshold behavior and tipping points in geomorphic systems; significant lag-time effects associated with the storage of sediment and ice.
Implementation of Climate Change Effects on Slope Stability Analysis	Bracko et al (2022)	Conducting a slope stability analysis in Slovenia, considering rain infiltration theory, indicates that the slope was initially stable despite having low stability before intense rainfall. However, the situation changed post-heavy precipitation, rendering the slope unstable. The study underscores that in a changing climate, the increased frequency of extreme precipitation events may impact the overall water infiltration into slopes, consequently altering slope stability.
Effects of climate change on shallow landslides in a small coastal catchment in southern Italy	Ciervo et al (2017)	An integrated approach to managing climate and sub-daily downscaling model uncertainties and estimating future variations in the shallow landslip hazard is presented in this paper. This method is tested on a small basin on the southern Italian Amalfi coast, demonstrating how local slope stability magnitude scenarios could be impacted by anticipated changes in precipitation patterns. In a framework of climate change, the paper concludes with qualitative assessments of the local operational warning system's future efficacy.

Our effort involved presenting case studies from mountainous regions that resemble Valle d'Aosta case study. In summary, these studies emphasize the importance of conducting thorough investigations into the impact of climate change on the occurrence of natural hazards and the complexity of the issue, specifically landslides. A key aspect of these studies is the need for detailed analyses, supported by comprehensive databases and precise climate models capable of capturing climate variability. Notably, precipitation and temperature play a significant role as triggering factors in the occurrence of mass movements across most of these studies.

Based on our brief literature review, we have chosen to focus our analysis on temperature and precipitation. These two climate variables are considered among the most significant factors that can potentially influence slope stability in the context of a changing climate.

In the following subsections we explain the necessity to use reanalysis datasets and GPCC as alternatives to conduct a consistent and comprehensive assessment to study climate change impacts in Valle d’Aosta.

3.3 Available datasets in absence of consistent observed data

To commence a climate change study, the initial crucial step involves obtaining accurate datasets with the appropriate spatial and temporal resolution to effectively capture the variability of climate parameters. While one potential source is data derived from meteorological stations, utilizing these datasets can be challenging. Meteorological stations are often sparsely distributed across the region, and their temporal coverage may not provide sufficiently long-term, continuous data to simulate the impact of climate change. Moreover, conventional weather stations, frequently dispersed unevenly, struggle to fully represent the climate conditions, especially in areas with significant climatic variations like Valle d’Aosta where climate variables including temperature and precipitation are strongly affected by altitude. Additionally, these weather station records may lack coverage for the intended simulation period, leading to data gaps in the analysis (Sidike et al., 2016).

Selection of datasets hinges on various factors, including the desired temporal resolution for studying climate change in the case study area, spatial coverage, data accessibility, and the intended use of climate variables as inputs for models, all contingent on the study's ultimate goals. While certain datasets may perform well in specific regions and for objectives, their accuracy and applicability can vary across different regions.

In this thesis, the objective is to assess key parameters that may impact infrastructure under changing climatic conditions. This involves considering various criteria and conducting a comprehensive assessment aligned with the study's overarching goal. Emphasis is placed on the need for a consistent dataset covering a minimum of 30 years of climate data to detect potential changes in the climate of Valle d’Aosta.

Following a primary analysis comparing data from meteorological stations with other available datasets, several datasets emerged as potential alternatives to address the limitations of meteorological stations. These alternatives were tested using QGIS software, and a meticulous analysis was performed to evaluate their suitability as climate inputs for the Valle d’Aosta case study.

An important factor in choosing the appropriate climate dataset was its horizontal spatial resolution, given the relatively small size of Valle d’Aosta. The challenge is in selecting a reliable dataset that could offer consistent data over at least 30 years. After applying these criteria, the initial options were filtered, resulting in the selection of two gridded datasets for temperature and precipitation: ERA5-Land and GPCC.

It is essential to note the importance of conducting a brief review of similar studies conducted worldwide. This review serves to address challenges encountered in this thesis, drawing insights from approaches employed in different parts of the world to overcome similar obstacles.

3.3.1 Climate datasets

Rodrigues et al. (2021) emphasized the significance of reanalysis models in providing weather data when observational data is insufficient, quality control is uncertain, and access to these datasets is not freely available (Aboelkhair et al., 2019).

The reanalysis products are generated through numerical weather data assimilation systems, incorporating diverse atmospheric and sea surface observations to yield long-term values for atmospheric and land surface variables (Sheffield et al., 2006).

A variety of reanalysis datasets are accessible, differing in spatial and temporal resolutions. Examples include the ERA-Interim reanalysis products from the European Centre for Medium-Range Weather Forecasts (ECMWF), the NASA Modern Era Retrospective Analysis for Research and Applications (MERRA), and NASA Prediction of Worldwide Energy Resource (NASA POWER), the National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR), Climate Forecast System Reanalysis (CFSR), the Japanese Meteorological Agency (JRA-55) (Rodrigues et al., 2021).

In this case study we have used ERA5-Land which is one of the products of Climate Data Store Implemented by ECMWF as part of The Copernicus Programme. The Climate Data Store (CDS) is a new approach to making climate data accessible, offering a unified web interface for accessing data from multiple sources. It includes a global database of quality-assured surface weather observations, in-situ upper-air observations from 1979, gridded climate data records for essential climate variables, various global and regional reanalysis products, and seasonal predictions from various sources. The CDS builds upon existing data maps, forecasts, and analysis data, making it easier for users to analyse and create data products(browsed on 21/11/2023 https://climate.copernicus.eu/the-climate-data-store).

*Table 3.3 Comparison of selected climate reanalysis datasets (*Mihalevich *et al., 2022).*

Dataset	**Provider**	**Spatial Resolution**	**Temporal Resolution**	**Spatial Coverage**	**Available period**
ERA5	ECMWF	30 × 30 km	1 hr	Global	1979–present
ERA5-Land	ECMWF	9 × 9 km	1 hr	Global	1950–present
CERRA-Land	ECMWF	5.5 km x 5.5 km	3 hr	Europe	1981-present
NASA POWER	NASA	55.5 km x 69 km	1 hr	Global	1981-present
CFSR	NCEP	38 × 38 km	1 hr	Global	1979–2014

Table 3.3 lists few reanalysis datasets and brief information about them. Paying attention to these parameters in the early stages of data assessment is essential as the final choice of the reanalysis dataset is mainly a variable of spatial and temporal resolution.

The Climate Data Store (CDS) by Copernicus offers a user-friendly interface and a diverse range of freely available datasets. Key factors influencing the selection of ERA5-Land for the Valle d’Aosta case study included considerations of temporal and horizontal resolution, the historical period covered by climate data, and the feasibility of dataset analysis in QGIS software. While CDS includes another dataset, CERRA-Land, with superior spatial resolution compared to ERA5-Land, it covers fewer years (30 years less data). Consequently, ERA5-Land was chosen for analysis in this thesis (Figure 3.1).

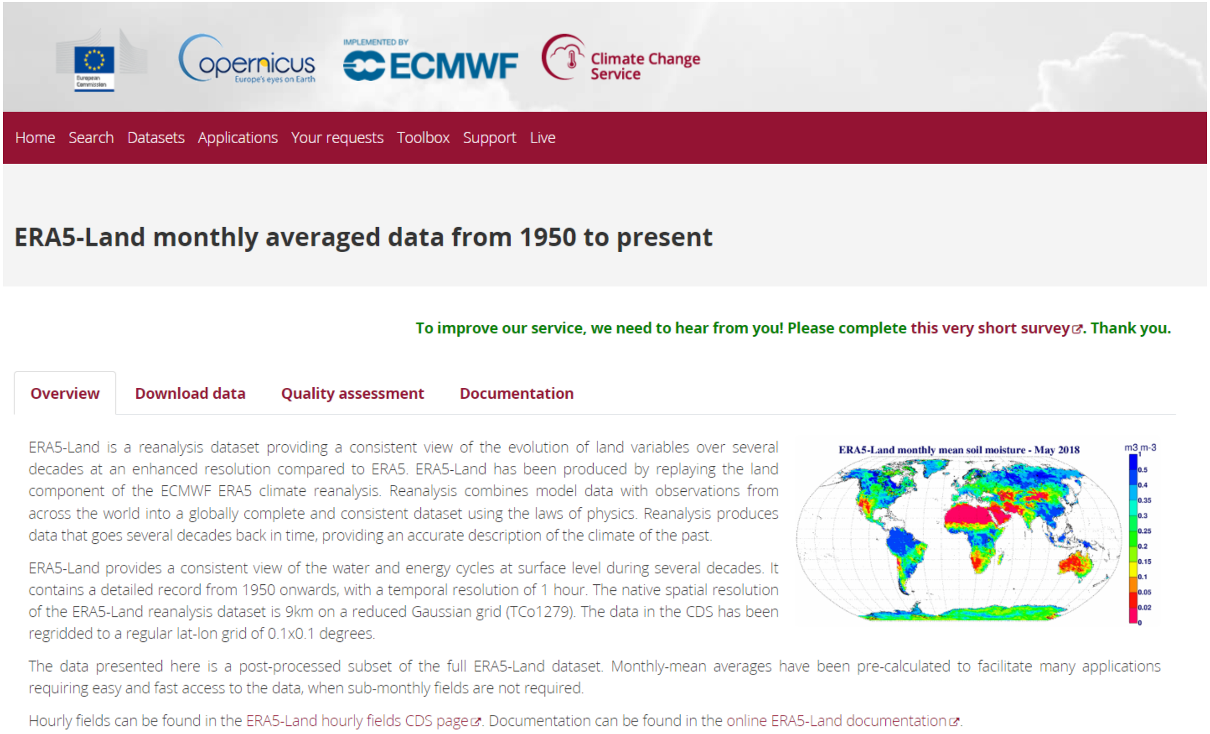


Figure 3.1, ERA5-Land platform (https://cds.climate.copernicus.eu/).

We conclude this chapter by few examples of previous studies which were conducted about the evaluation of reanalysis models and their performance mostly by comparing them with observed data from in-situ sites (Table 3.4).

Table 3.4 Assessing climate reanalysis datasets: Insights from case studies.

Case Study	Climate Variables	Study Area	Reanalysis Dataset	Results
Evaluation of the ERA5-Land Reanalysis Data Set for Process-Based River Temperature Modeling Over Data Sparse and Topographically Complex Regions by (Mihalevich et al., 2022)	Air Temperature, Relative Humidity, Wind Speed	Colorado River basin (Grand Canyon)	ERA5-Land	The corrected ERA5-Land elevation can be employed to forecast river temperatures across extensive temporal and spatial ranges in regions with limited data. Modifying the spatial resolution of ERA5-Land had minimal effects on the predictions of river temperature.
Evaluation of NASA POWER	Maximum Temperature,	Alentejo Region,	NASA POWER	Results show that NASA POWER can be useful for the

Reanalysis Products to Estimate Daily Weather Variables in a Hot Summer Mediterranean Climate by (Rodrigues et al., 2021)	Minimum Temperature, Solar Radiation, Relative Humidity	Southern Portugal		generation of weather data sets where ground weather stations data is of missing or unavailable.
Evaluation of Three Air Temperature Reanalysis Datasets in the Alpine Region of the Qinghai–Tibet Plateau by (Huang et al., 2022)	Surface air temperature	Qinghai–Tibet Plateau	ERA5L, GLDAS, CLDAS	The assessment outcomes regarding temporal changes and spatial distribution characteristics reveal that the three reanalysis datasets align well with in-situ observations in the alpine region of the Qinghai-Tibet Plateau (QTP). Among them, CLDAS demonstrates higher consistency with observations and a superior ability to depict the finer details of temperature distribution and variation compared to ERA5L and GLDAS.

All the case studies listed in Table 3.4 employed statistical metrics to assess the reliability of reanalysis datasets. While some studies used similar approaches for this evaluation, the extent of agreement regarding how well the reanalysis data align with observed climate data may differ based on the study's goal and the desired levels of accuracy and precision. The next chapters will provide a comprehensive explanation of the necessity for data evaluation and will present detailed results regarding the compatibility of these gridded datasets for the Valle d'Aosta case study. It's essential to note that for precipitation analysis, another gridded dataset (GPCC) is utilized, while more details of this dataset are thoroughly discussed in Chapters 4 and 5, we conclude this chapter by mentioning 3 of the case studies in GPCC data evaluation and their findings, which is provided in Table 3.5.

Table 3.4 Assessing climate reanalysis datasets: Insights from case studies.

Case Study	Climate Variables	Study Area	Dataset	Results
Spatio-temporal evaluation of global gridded precipitation datasets across Iran by Hosseini-Moghari et al., (2018)	Precipitation	Iran	Climatic Research Unit (CRU), Global Precipitation Climatology Centre (GPCC), PERSIANN-	Precipitation data evaluation of 4 different precipitation datasets was conducted over main basins of Iran by comparing in-situ observed data from 85 meteorological stations for the period 1984–2013, Analysis showed despite all the 4 datasets underestimated or overestimated precipitation values, they could

			Climate Data Record (PCDR), University of Delaware (UDEL)	correctly capture precipitation patterns. GPCC showed the better performance to predict precipitation over Iran.
Evaluation of ground-based, daily, gridded precipitation products for Upper Benue River basin, Nigeria by Salaudeen et al., (2021)	Precipitation	Benue River basin, Nigeria	Climate Research Unit (CRU), Climate Prediction Centre (CPC), Global Precipitation Climatology Centre (GPCC)	Due to the limited availability of in-situ observations in the Benue Basin, a study was conducted to assess three distinct gridded precipitation datasets. The assessment involved a comparison with observed data from eight stations spanning the period 1982-2006 within the study area. The findings indicate that all three datasets effectively capture rainfall patterns over the basin. Among the evaluated datasets, GPCC demonstrated superior performance compared to the other two. The conclusion drawn from this evaluation is that these gridded datasets, including GPCC, are reliable and can be employed as inputs for subsequent studies, such as climate change or hydrological models, in the Benue Basin region.
Performance of Two Long-Term Satellite-Based and GPCC 8.0 Precipitation Products for Drought Monitoring over the Yellow River Basin in China by Wei et al., (2019)	Precipitation	Yellow River Basin, China	PERSIANN-CDR, CHIRPS and GPCC	Precipitation estimations of these three datasets were compared with estimates of the China Gauge-based Daily Precipitation Analysis (CGDPA) dataset over Yellow River Basin , over a period of (1983-2016), Evaluations indicated that GPCC performed better than other two datasets , and used to estimate (SPI) standardized precipitation indices to conduct drought monitoring over the basin.

CHAPTER 4

Data Acquisition and Validation: Case Study of Valle d'Aosta

4.1 Introduction

The Aosta Valley is located at the northernmost terminus of the Alpine range, where it changes direction from south-north to west-east. The territory, which is almost rectangular in shape, is around 80 kilometres long and 40 kilometres wide. It borders Piedmont to the east and south, Switzerland to the north, and France to the west.

The Aosta Valley is bordered by some of the most magnificent Alp's massifs; only in the southeast corner do the mountains leave an opening through which the Dora Baltea river flows into the Canavese plain.

Air masses are transferred from the western and northern origins to the internal side of the Alpine chain via mountain passes into Switzerland and France.

The major valley, spanned by the Dora Baltea and stretching around 100 km, goes south-north from Pont-Saint-Martin to Montjovet, then bends east-west till Avise. It then turns southeast-northwest. The lateral valleys are crossed by torrential Dora Baltea tributaries.

The territory covers about 3,260 square kilometres, with an average altitude of 2,106 meters, varying from approximately 310 meters in the southeast to 4,810 meters at Mont Blanc, with over 60% of the land situated above 2,000 meters in altitude.

A considerable part of the land is preserved in its natural state due to the orographic conformation: 40% is made up of rocky or glacial areas, 51% is made up of pastures or forests, and only 9% is suitable for agriculture and human habitation. These areas are mainly found in the central valley and the lateral valleys (Il quadro conoscitivo, PARTE I: https://www.regione.vda.it/allegato.aspx?pk=8055).

4.2 Climate of Valle d'Aosta

The Aosta Valley region belongs to the oceanic temperate macroclimate of the middle latitudes, with a mountain mesoclimate from the western Alps of the Mediterranean slope. Within the region, there's a considerable variety of topoclimates (specific to individual valleys) and microclimates, influenced by altitude variations and different slope exposures. These latter two factors are particularly crucial in determining the climate in a region with a complex topography like the Aosta Valley (Il quadro conoscitivo, PARTE I, retrieved from: https://www.regione.vda.it/allegato.aspx?pk=8055).

The Western Alps' core contains the mountains of the Valle d'Aosta and Piemonte regions (Giardino et al., 2017). The Western Alps' climate is influenced by a moderate to low oceanic moisture supply; its mean annual precipitation is 900 mm, which is less than that of the northern and eastern Alpine regions (Biancotti et al. 1998).

The elevation layer of the Valle d'Aosta administration map is depicted in Figure 4.1, revealing substantial variations in altitude.

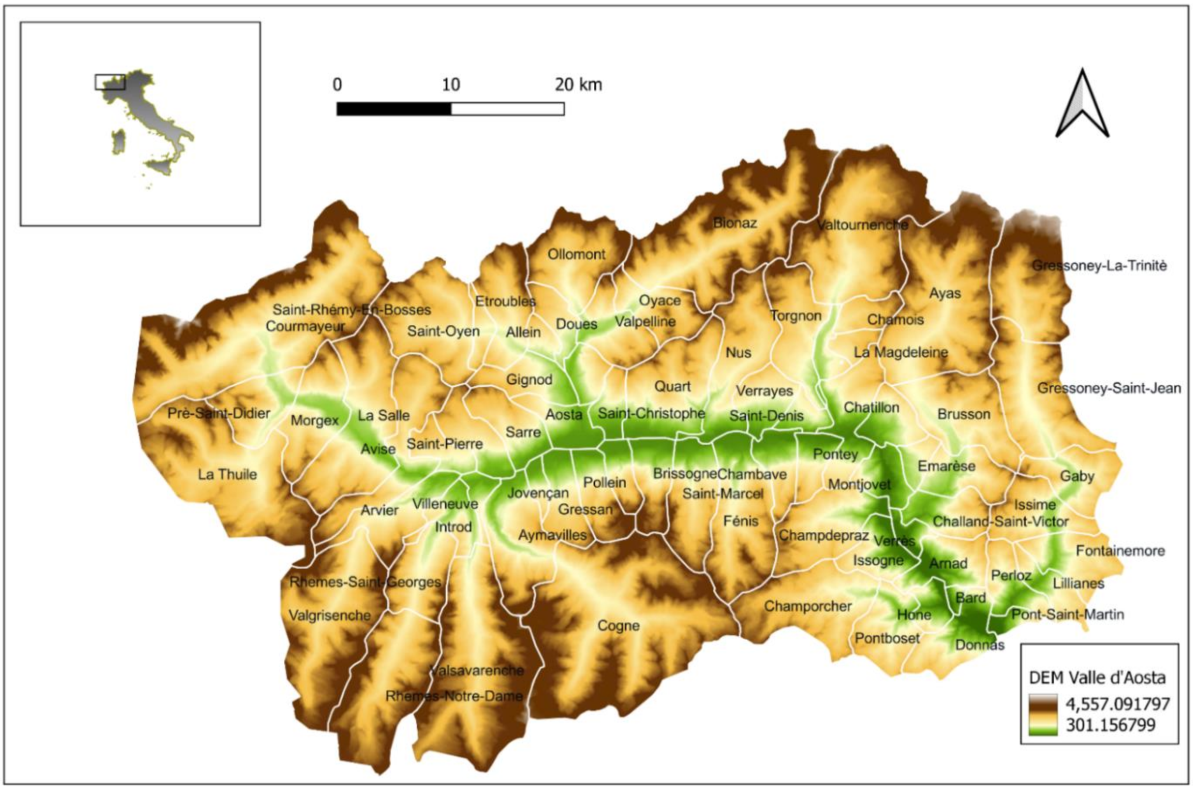


Figure 4.1 Valle d'Aosta administrative regions, DEM file is retrieved from TINITALY, a digital elevation model of Italy with a 10 meters cell size (Tarquini et al., 2007), and processed in QGIS software.

4.2.1 Effects of Altitude

In the 'Il quadro conoscitivo'(https://www.regione.vda.it/allegato.aspx?pk=8055), the primary effects of altitude are outlined as altitude increases, the following trends for key meteorological measurements can be identified:

- Decrease in air temperature, averaging 0.65°C every 100 meters (moist adiabatic gradient).
- Increase in the number of days with snow cover and frost.
- Improved air transparency and visibility due to lower aerosol concentration (from $1010/m^3$ at sea level to $109/m^3$ at 3000 meters) and reduced water vapor content.
- Increase in solar radiation intensity: at 200 meters above sea level, approximately 40-50% of solar radiation is received from the Sun, while at 3000 meters, it's about 60-70%. At the latitude of the Alps, this fraction equates to the energy received in equatorial plains.
- Rise in wind speed.
- Decrease in atmospheric pressure, following an approximately exponential pattern (retrieved from: https://www.regione.vda.it/allegato.aspx?pk=8055).

In the 'Il quadro conoscitivo' report, a comprehensive analysis of various climatic elements, encompassing temperature, precipitation, and wind, is presented. Notably, the report includes an analysis of average annual isotherms, derived from data gathered across 14 stations situated between 500 and 3500 meters, spanning the period from 1950 to 2002. However, there is a notable limitation in the availability of long-term meteorological data for the Valle d’Aosta region. The subsequent sections of the report delve into the challenges associated with collecting historical data covering a substantial area for in-depth case studies, emphasizing the critical need for consistent, long-term data regarding temperature and precipitation in the Valle d’Aosta region.

4.3 Significance of Investigating Climate Change in Valle d'Aosta

This thesis constitutes a pioneering stride within the ambit of the PNRR NODES (Nord-Ovest Digitale e Sostenibile, 'Digital and Sustainable North-West') project, which centres on Northwestern Italy. Specifically, this research focuses on the Valle d'Aosta region, employing a framework to construct landslide risk maps that factor in the implications of climate change. However, beyond its primary focus on landslide risk assessments, this study addresses various facets of environmental sustainability and provides a foundational basis for comprehensive regional risk management strategies.

Giardino et al., (2017) in a comprehensive research study: ' The Glaciers of the Valle d’Aosta and Piemonte Regions: Records of Present and Past Environmental and Climate Changes ' mention the importance of studying the Major glaciers which are in these regions (Lys, Miage, Belvedere, Rutor and Sabbione) of the highest peaks of the Western Alps (Mt. Bianco, Mt. Rosa) for their specific scientific, environmental, cultural and economic importance, where they highlight the glacial landscape's unique dynamic quality, active glacial formations, and associated slope instability, which can become more hazardous as a result of climate change.

Valle d'Aosta is home to the largest and most abundant glaciers, situated in the highest massifs of the Italian Alps. These glaciers, constituting two-thirds of Western Italian glaciers and covering 80% of the overall glaciated area (approximately 166 km^2), make this region a glacial hotspot. Among them, the notable Miage Glacier spans 10.6 km^2, while the Lys Glacier covers 9.5 km^2. Impressively, glaciers encompass 4% of the entire Valle d'Aosta (Giardino et al., 2017).

The observed reduction in glacier size in the Western Italian Alps is a consequence of various climatic, topographic, and latitudinal factors. Currently, the only glaciers in the Western Italian Alps that are not subject to this trend are those situated at the highest altitudes, specifically those exceeding 3500 meters above sea level (Giardino et al., 2017).

Giardino et al. (2017) highlights the significance of Alpine glaciers, emphasizing their role as a vital reservoir for European nations, representing a crucial source of fresh water in its solid state, often referred to as "white gold" ("oro bianco" in Italian, "houille blanche" in French). Consequently, numerous dams have been constructed in the primary glacierized drainage basins to harness this resource for purposes such as hydropower generation, irrigation, and flood control.

The significance of the Miage Glacier and the Veny Valley, situated in the Mt. Bianco region of the Graian Alps, is studied bt Giardino et al, (2017). The Veny Valley exhibits distinctive geomorphological features, primarily characterized by the Miage debris-covered glacier and the steep rock slopes of Mt. Bianco. Notably, the Miage Glacier, ranking as the third-largest glacier in Italy and the longest, is nourished by four tributary glaciers and snow avalanches. Historical records indicate that until the late nineteenth century, the surface of the Miage Glacier remained free of debris. However, in contemporary times, nearly the entire ablation tongue is covered with a layer of debris, typically ranging from centimetres to meters in thickness, predominantly originating from rock falls (Giardino et al., 2017).

The region experiences heightened mass movements. The distribution of rock fall events in the Veny Valley is influenced by local geological and geomorphological conditions, including lithological and structural settings, as well as factors such as weathering and preceding morphogenetic processes that create varying topographic environments. Furthermore, the active mass movements are potentially exacerbated by permafrost degradation induced by climate change, as discussed by Bertotto et al. (2015).

In this section, our aim is to provide the reader with a comprehensive insight into the significance of studying the climate of Valle d’Aosta, supplemented by specific examples. Undoubtedly, the analysis of climate change impacts is a multifaceted subject that lends itself to in-depth exploration from various perspectives, including economic, environmental, social, and more. As we've delved into the distinctive features and challenges posed by the climate of Valle d’Aosta, it becomes apparent that a nuanced understanding of its dynamics is crucial for addressing the broader implications of climate change.

4.4 Data Collection

In Chapter 3, we delved into a detailed examination of the selection process for climate elements, specifically focusing on temperature and precipitation, as integral components for studying the regional climate. Transitioning from this, the current section directs its focus towards the intricacies of data collection, encompassing sources, methods, and tools for data analysis. As previously highlighted, investigating climate parameters in regions characterized by complex topography and limited historical data proves especially challenging, particularly when the study is conducted at a regional scale. Our approach thus far has been to gather observed data from open-access datasets, known for their capacity to capture local events more effectively. Despite the advantages, we encountered a series of challenges in accessing this data. Therefore, it is pertinent to address these issues in a subsequent section, providing a comprehensive account of the obstacles faced during the data acquisition process.

4.4.1 Overcoming Data Obstacles: Difficulties Faced in the Gathering of Climate Parameters

It was mentioned in section 4.2.1 that in the 'Il quadro conoscitivo' report they had done climate data analysis for the period of 1950 to 2002 over the Valle d'Aosta based on the meteorological data collected from 14 weather stations. Also, they mentioned that "To accurately describe the climate of a region, it is necessary to have historical data series covering a period of at least 30 years." We faced challenges accessing historical data for regions not publicly available. For our final data analysis, we obtained data from the official website of CENTRO FUNZIONALE REGIONE AUTONOMA VALLE D'AOSTA (https://presidi2.regione.vda.it/str_dataview). While this site offers user access to meteorological data, it comes with drawbacks like a lack of historical data and aggregation on an hourly and daily basis, necessitating further processing for monthly and annual analyses.

Despite the valuable data, these limitations posed significant barriers for climate change studies. To overcome these challenges, we sought an alternative approach and opted to work with reanalysis datasets. Widely used in contemporary climate change studies, these datasets address the shortage of historical data and are open access. This choice proved beneficial, enabling us to conduct our study effectively.

4.4.2 Description of weather data from meteorological stations

Environmental data, including temperature and precipitation records, were collected from 87 stations in the Valle d'Aosta region. These measurements were taken on an hourly basis and obtained from the CENTRO FUNZIONALE REGIONE AUTONOMA VALLE D'AOSTA (cf.regione.vda.it). While this dataset covers a majority of the regions within Valle d'Aosta, there are some areas where data is not available. Due to our interest in studying climate patterns over longer periods of time, we face challenges such as limited historical data availability. Additionally, the uneven distribution of weather stations across Valle d'Aosta can affect the accuracy of temperature and precipitation interpolations.

To indicate these issues, it is necessary to illustrate the distribution of weather stations on Valle d'Aosta map. Additionally, the longitude, latitude, and altitude of these stations is provided in Table 4.1, together with the temporal range over which these data are available. As it can be seen from the table, data availability is not consistent in time and most of the stations are established in recent years which encounters problems in studying the changing of climate over the region.

Table 4.1 Geographic information of meteorological stations located in Valle d'Aosta; all the data are collected from: (cf.regione.vda.it).

Id	Station Name	Latitude	Longitude	Altitude	Data available from
1	Aosta - Mont-Fleury	45.73155	7.2984101	577	01/07/1996
2	Aosta - Piazza Plouves	45.73707	7.3234126	580	01/01/1996
3	Arvier - Chamençon	45.70176	7.1674473	1238	21/09/2001
4	Arvier - Cooperativa Enfer	45.7047	7.1664265	738	28/10/2010
5	Ayas - Alpe Aventine	45.85072	7.7519993	2080	05/10/2009
6	Ayas - Champoluc	45.83223	7.7255284	1566	04/08/2011
7	Aymavilles - Ponte Dora Baltea	45.7011	7.2407751	618	18/03/1999
8	Aymavilles - Vieyes	45.64974	7.2509226	1139	25/06/2003
9	Bard - Albard	45.6167	7.75	662	08/04/2013
10	Bionaz - Place Moulin	45.87408	7.4229591	1979	24/10/2002
11	Brusson - Tchampats	45.75806	7.7295595	1288	04/06/2013
12	Chamois - Lac de Lou	45.29021	6.5288605	2020	19/11/2001
13	Champdepraz - Chevrère	45.68531	7.6568643	1260	29/11/2002
14	Champdepraz - Ponte Dora Baltea	45.68531	7.6568643	370	13/03/1999
15	Champorcher - Chardonney	45.62283	7.6088524	1430	01/01/2000
16	Champorcher - Petit-Mont-Blanc	45.62552	7.6081109	1640	07/08/2013
17	Champorcher - Rifugio Dondena	45.61201	7.5514993	2181	07/02/2002
18	Cogne - Crétaz	45.61556	7.3423307	1470	11/06/2002
19	Cogne - Gimillan	45.61693	7.3573075	1785	01/01/1996
20	Cogne - Grand-Crot	45.6087	7.356	2279	08/12/2006
21	Cogne - Lillaz	45.5932	7.3899131	1613	19/11/2001
22	Cogne - Valnontey	45.5863	7.3392376	1682	01/10/2001
23	Courmayeur - Dolonne	45.79234	6.9663305	1200	01/01/2006
24	Courmayeur - Ferrachet	45.79692	6.9689626	2290	11/07/2002
25	Courmayeur - Lex Blanche	45.79692	6.9689626	2162	09/07/2002
26	Courmayeur - Mont de la Saxe	45.79692	6.9689626	2110	11/07/2002
27	Courmayeur - Pré-de-Bard	45.79692	6.9689626	2040	09/07/2002
28	Donnas - Clapey	45.6	7.7667	318	01/01/1996
29	Etroubles - Chevrière	45.82218	7.2379256	1339	01/01/1996
30	Fénis - Clavalité	45.73307	7.4969209	1531	01/10/2003
31	Fénis - Lavodilec	45.736	7.4944	2250	27/07/2007
32	Gressan - Pila-Leissé	45.72145	7.2898939	2280	17/07/2007
33	Gressoney-la-Trinité - Alpe Courtlys	45.86744	7.8095992	1992	23/02/2014
34	Gressoney-la-Trinité - D'Ejola	45.83049	7.8231541	1837	11/12/2013
35	Gressoney-la-Trinité - Diga del Lago Gabiet	45.8495	7.8483005	2373	17/08/2023
36	Gressoney-la-Trinité - Eselbode	45.83049	7.8231541	1642	19/09/2001
37	Gressoney-Saint-Jean - Bieltschocke	45.78033	7.8250484	1370	17/12/2013
38	Gressoney-Saint-Jean - Capoluogo	45.78033	7.8250484	1373	19/09/2001
39	Gressoney-Saint-Jean - lago di Seebna	45.78033	7.8250484	2270	07/10/2010
40	Gressoney-Saint-Jean - Weissmatten	45.78033	7.8250484	2038	08/11/2002
41	Hône - Ayasse	45.61212	7.7368571	367	20/03/2023

42	Hône - Ponte Dora Baltea	45.20197	8.0344571	340	11/06/2002
43	Issime - Capoluogo	45.68671	7.8549696	960	23/01/2003
44	Jovençan - Pompiod	45.70934	7.2613822	670	28/10/2010
45	La Thuile - La Grande Tête	45.70466	6.9108134	2430	10/07/2002
46	La Thuile - Les Granges	45.70466	6.9108134	1637	01/01/1996
47	La Thuile - Villaret	45.70466	6.9108134	1488	10/07/2002
48	Lillianes - Granges	45.63103	7.8430523	1256	19/09/2001
49	Morgex - Capoluogo	45.75786	7.036318	938	24/05/2013
50	Morgex - Lavancher	45.76303	7.031325	2842	11/07/2002
51	Nus - Les Iles	45.8072	7.4879	534	23/12/2006
52	Nus - Saint-Barthélemy - Osservatorio	45.78969	7.4784382	1675	11/04/2013
53	Ollomont - By	45.84894	7.3108232	2017	19/11/2001
54	Pontboset - Fournier	45.59892	7.6723894	1087	11/07/2002
55	Pontey - Ponte Dora Baltea	45.20197	8.0344571	473	27/09/2001
56	Pont-Saint-Martin - Monte - Lys	45.59493	7.798357	340	30/10/2014
57	Pré-Saint-Didier - Capoluogo	45.75959	6.9465852	996	11/06/2002
58	Pré-Saint-Didier - Gare	45.76359	6.991068	1000	01/01/2023
59	Pré-Saint-Didier - Plan Praz	45.75959	6.9465852	2144	10/07/2002
60	Quart - Ollignan	45.75223	7.3696746	650	28/10/2010
61	Rhêmes-Notre-Dame - Chanavey	45.57909	7.1231203	1690	28/09/2000
62	Rhêmes-Notre-Dame - Chaudanne	45.55899	7.1151231	1794	19/12/2013
63	Rhêmes-Saint-Georges - Capoluogo	45.62348	7.1486031	1179	27/11/2002
64	Rhêmes-Saint-Georges - Feleumaz	45.62348	7.1486031	2325	26/10/2005
65	Roisan - Moulin	45.79165	7.3077728	745	11/04/2002
66	Roisan - Preyl			935	08/11/2013
67	Saint-Christophe - Aeroporto	45.75	7.35	545	01/01/1996
68	Saint-Denis - Raffort	45.75	7.55	840	04/04/2013
69	Saint-Marcel - Surpian	45.7341	7.452867	540	01/05/2000
70	Saint-Oyen - Moulin	45.82466	7.216742	1310	13/06/2002
71	Saint-Pierre - Lago delle Rane	45.71	7.226	2370	03/02/2010
72	Saint-Rhémy-en-Bosses - Crévacol	45.82037	7.1488464	2018	19/11/2001
73	Saint-Rhémy-en-Bosses - Gran San Bernardo	45.89388	7.1875437	2360	25/07/2007
74	Saint-Rhémy-en-Bosses - Mont-Botsalet	45.83559	7.1838312	2500	06/12/2006
75	Saint-Vincent - Terme	45.74945	7.6531116	626	03/10/2012
76	Valgrisenche - Menthieu	45.61355	7.052198	1859	09/10/2001
77	Valpelline - Chosoz	45.82577	7.3267545	1029	27/09/2001
78	Valsavarenche - Eaux-Rousses	45.56715	7.2086195	1651	29/08/2000
79	Valsavarenche - Orvieille	45.5792	7.1912375	2170	26/10/2005
80	Valsavarenche - Pont	45.5857	7.2113406	1951	14/06/2013
81	Valtournenche - Breuil Cervinia	45.93452	7.6311235	1998	29/04/2013
82	Valtournenche - Cime Bianche	45.88821	7.6239275	3100	01/10/2003
83	Valtournenche - Grandes Murailles	45.95472	7.600655	2566	14/12/2006
84	Valtournenche - Lago Goillet	45.92938	7.665045	2541	01/10/2003
85	Valtournenche - Maen	45.86906	7.6172968	1310	29/08/2000
86	Verrès - Capoluogo	45.66244	7.6938048	375	01/04/2014
87	Villeneuve - S.R. Saint-Nicolas	45.7024	7.2076	839	11/04/2013

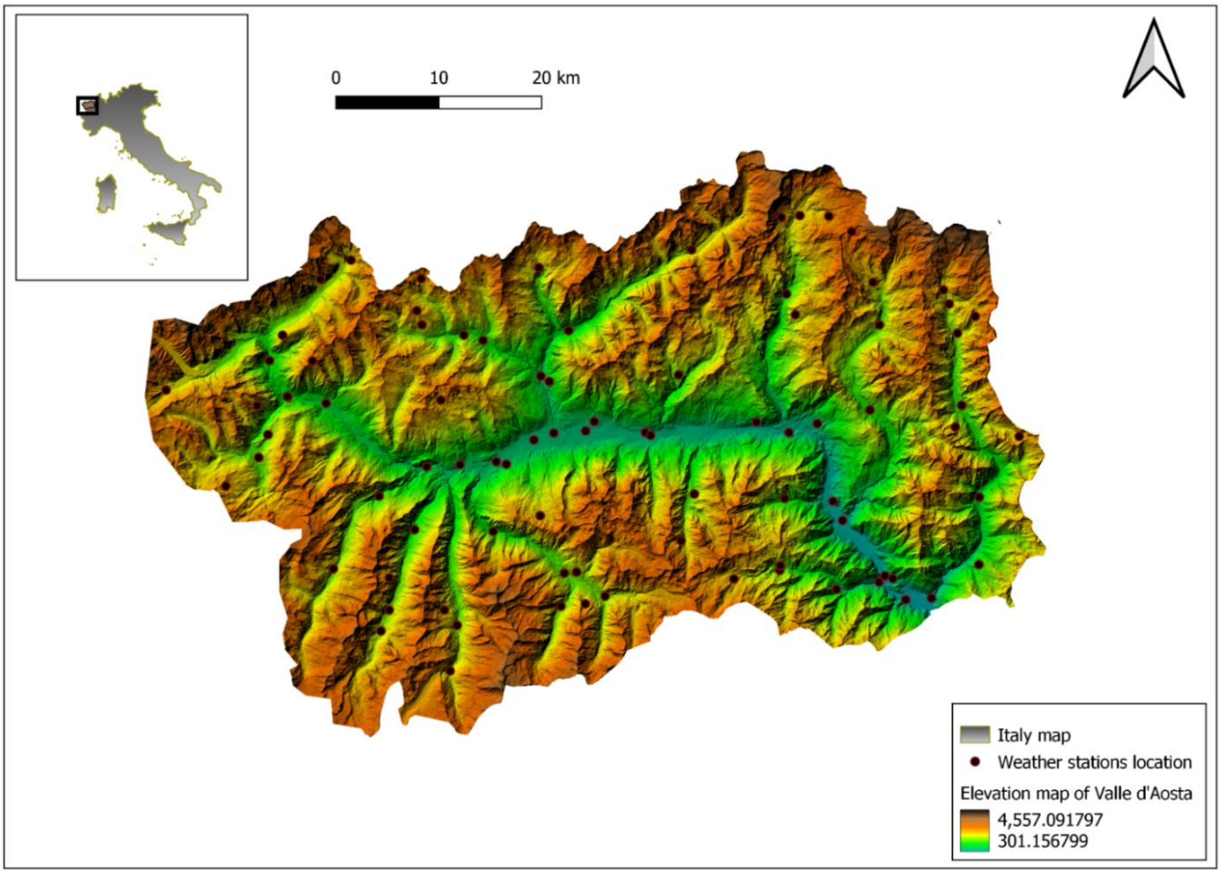


Figure 4.2 Distribution of the meteorological stations over the Valle d'Aosta.

As it can be seen from Figure 4.2, stations are less abundant over the higher altitudes and are mostly located on the valley which hosts most of the settlements and population.

4.5 Data Analysis: Temperature

In the third chapter, we covered the topic of reanalysis datasets and their significance to access data in topographically complex regions where it is nearly impossible to access data in remote locations and where there is a lack of historical data to study the region's climate. In this case study, we employ two distinct approaches to analyse the two climate elements—precipitation and temperature—because each element has unique intrinsic characteristics that require the use of specific tools and methods to study. Precipitation will be treated in Chapter 4.6.

In this data analysis we investigate the reliability of the chosen reanalysis dataset to compensate for shortage of data in the region , but due to the complex topography of the region and as the most authentic reanalysis datasets are created for global scale analysis and have coarser spatial resolution to study in a regional scale , it is essential to evaluate the reanalysis datasets for the further climate change studies, specifically in Valle d'Aosta whose climate is strongly affected by altitude and where local variations in topography are significant. Therefore, it is more challenging to use the reanalysis datasets and data validation is crucial before any conclusion from these data is drawn.

4.5.1 Input Meteorological Data: CENTRO FUNZIONALE REGIONE AUTONOMA VALLE D'AOSTA

Since we needed a reference dataset to implement reanalysis dataset validation, we selected the years 2014–2022 for a smaller region in the east of the Aosta valley as our reference period for temperature data analysis. As previously mentioned, all these data are collected through the online portal of CENTRO FUNZIONALE REGIONE AUTONOMA VALLE D'AOSTA, processed, and aggregated in monthly scales. Since these observed data are point data, no interpolation method is used for further analysis of temperature data.

In the selected area, there are 13 meteorological weather stations; however, their installation spans different timeframes, with the majority being set up in the last decade. The rationale behind selecting the reference period of 2014-2022 was its uniform time consistency across all 13 stations.

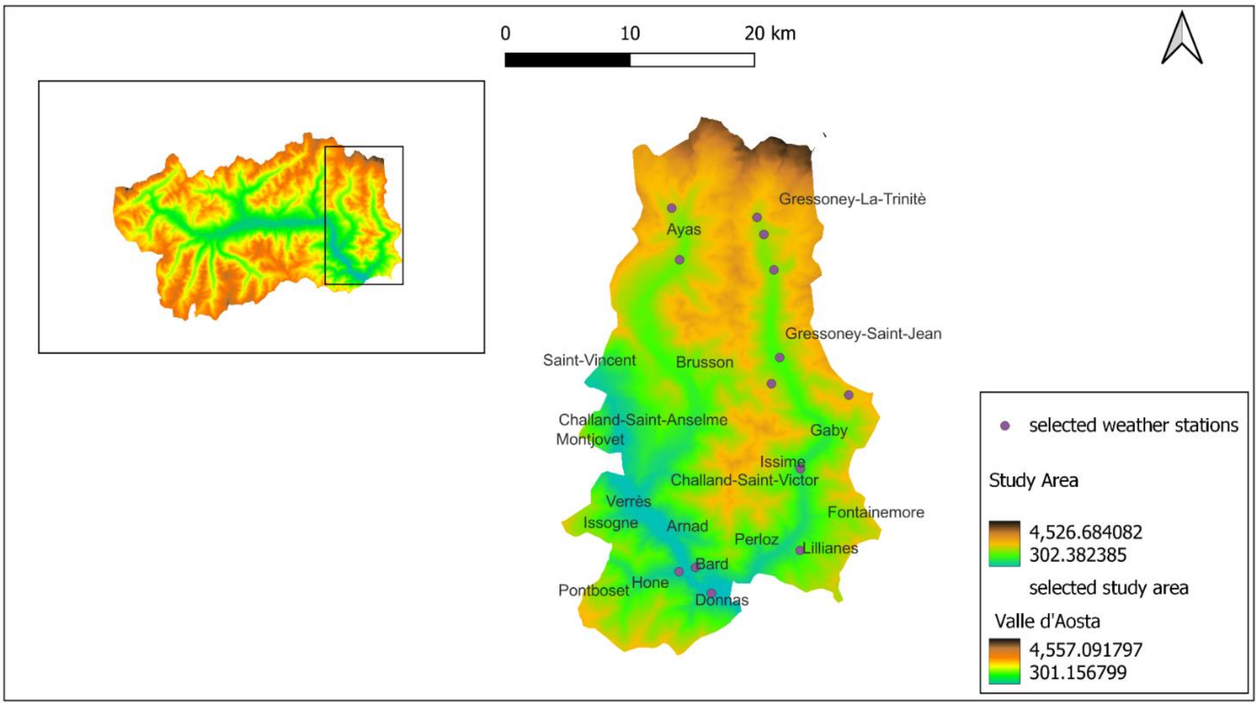


Figure 4.3 Distribution of weather stations located in the eastern part of the Valle d'Aosta which are chosen as a sample to perform temperature data validation.

4.5.2 Reanalysis Dataset: ERA5-Land

A variety of open-access reanalysis datasets are available and widely employed in global climate change studies, as detailed in chapter 3. The selection of a reanalysis dataset depends on factors such as the study scale (global or regional), accessibility, characteristics of the study area, and the required temporal and spatial resolution. Given the significant influence of altitude on Valle d'Aosta's climate, our data analysis necessitated a reanalysis dataset with high horizontal spatial resolution, historical data coverage, accessibility, and practicality for processing.

After careful consideration, the ERA5-Land dataset emerged as the optimal choice. This dataset covers the period from 1950 to the present and stands out for its high spatial resolution. Additionally, the dataset is readily accessible, and its monthly-mean averages have been pre-calculated, simplifying data processing for various applications (Muñoz Sabater, 2019). These attributes collectively made ERA5-Land well-suited for our study requirements.

The ERA5-Land reanalysis dataset provides an enhanced resolution of land variables over several decades compared to ERA5. Based on the ECMWF ERA5 climate reanalysis, ERA5-Land was produced. Through reanalysis, model data and observations from around the world are combined into a global dataset that is consistent and accurate. By reanalysing data from the past, we can obtain a comprehensive picture of the climate of the past several decades ago (Muñoz Sabater, 2019). In Table 4.2 the main peculiarities of the ERA5-Land dataset are listed.

Table 4.2 Data description of ERA5-Land dataset (Muñoz Sabater, 2019; Copernicus Climate Change Service (C3S) Climate Data Store (CDS). DOI: 10.24381/cds.68d2bb30 (Accessed on 14-11-2023).

Data type	**Gridded**
Projection	Regular latitude-longitude grid
Horizontal coverage	Global
Horizontal resolution	0.1° x 0.1°; Native resolution is 9 km.
Vertical coverage	From 2 m above the surface level, to a soil depth of 289 cm.
Vertical resolution	4 levels of the ECMWF surface model: Layer 1: 0 -7cm, Layer 2: 7 -28cm, Layer 3: 28-100cm, Layer 4: 100-289cm Some parameters are defined at 2 m over the surface.
Temporal coverage	January 1950 to present
Temporal resolution	Monthly

4.5.3 Comparison of ERA5-Land and observed data

In order to use reanalysis datasets for further climate change studies, especially in more controversial cases, it's crucial to validate these datasets before drawing any conclusions. This involves checking if the data is reliable and if it aligns reasonably well with observed data collected from ground stations.

The simplest way to compare temperature values from datasets is to subtract the observed values from the reanalysis values. This temperature difference between the observed and reanalysis data provides insight into the degree of correlation between the two datasets (McNicholl et al., 2021).

To carry out the data assessment, the input parameters include mean annual temperatures for each meteorological station. The temperature data provided by CENTRO FUNZIONALE REGIONE AUTONOMA VALLE D'AOSTA has hourly temporal resolution, requiring processing to align with the temporal resolution of ERA5-Land data. These meteorological station data are aggregated on a monthly scale.

"The primary input parameter for the ERA5-Land dataset is the air temperature at 2 meters above the surface of land, sea, or inland waters. The computation of this 2m temperature involves interpolation between the lowest model level and the Earth's surface, considering atmospheric conditions ", as outlined by Muñoz Sabater (2019) and documented by the Copernicus Climate Change Service (C3S) Climate Data Store (CDS).

To compare the two types of data, it's important to note that reanalysis datasets are gridded (with approximately 9km x 9km horizontal resolution), while observed data consists of points with specific longitude, latitude, and altitude. We utilized QGIS software for the analysis, comparing temperature values in each grid of the reanalysis dataset with the observed point data falling within the corresponding grid.

However, this comparison faces challenges, such as differences in altitude. Grid cells provide an average altitude over each cell, whereas points have individual altitude values. This distinction is significant, especially in regions like Valle d'Aosta, where topography and local altitude variations are common over short distances. To address this, we considered the digital elevation model (DEM) of Valle d'Aosta, calculating the average elevation for each grid (9km x 9km). During the comparison, we accounted for the altitude difference between observed and reanalysis datasets.

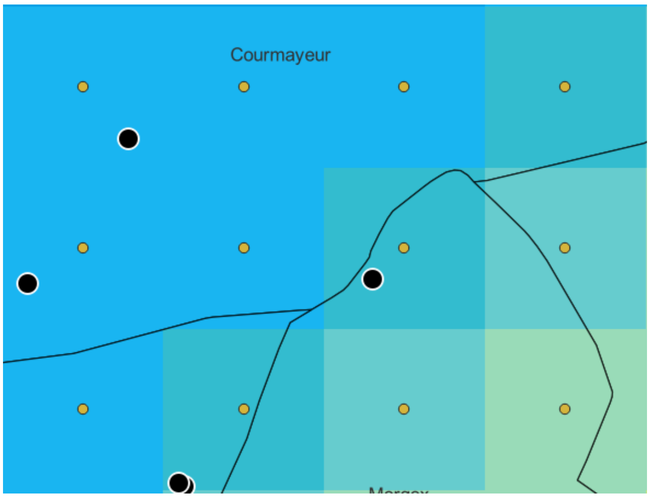


Figure 4.4 Comparison of observed data from weather stations (black points) and reanalysis datasets (yellow points in the centre of each cell represent the temperature value for reanalysis dataset).

Table 4.3 shows the disparity of measured altitude of weather stations and the average altitude of each ERA5-Land grid (9km×9km). This altitude residual will cause further error in ERA5-Land estimations as the climate of the region is strongly dependent on altitude variations.

Table 4.3 Comparison in altitude between punctual weather stations located in the selected study area and ERA5-Land cell those stations fall in.

Station	Longitude	Latitude	Altitude	Altitude of reanalysis grid which the observation point data falls in	Altitude difference
Ayas - Alpe Aventine	45.874	7.71923	2080	2506	426
Ayas - Champoluc	45.8368	7.72821	1566	2506	940
Bard - Albard	45.615	7.74982	662	1267	605
Donnas - Clapey	45.5966	7.76643	318	1801	1483
Gressoney-la-Trinité - Alpe Courtlys	45.8683	7.80761	1992	2096	104
Gressoney-la-Trinité - D'Ejola	45.8561	7.81496	1837	2096	259

Gressoney-la-Trinité - Eselbode	45.8306	7.82587	1642	2096	454
Gressoney-Saint-Jean - Bieltschocke	45.7674	7.83305	1370	1634	264
Gressoney-Saint-Jean - lago di Seebna	45.741	7.90497	2270	1455	-815
Gressoney-Saint-Jean - Weissmatten	45.7484	7.82505	2038	1634	-404
Hône - Ayasse	45.6117	7.73277	367		-367
Issime - Capoluogo	45.6873	7.85621	960	1222	262
Lillianes - Granges	45.6283	7.85695	1256	1222	-34

4.5.4 Data Evaluation

After conducting a comparison between ERA5-Land temperature data and the temperature data measured at corresponding stations, it is essential to validate these comparisons to affirm the reliability of ERA5-Land as input data for further climate change studies in the region. To achieve this goal, a statistical evaluation is implemented, and the metrics are explained in this chapter. This method represents a common approach for evaluating reanalysis datasets in climate change studies. Statistical indicators are employed to assess the degree of agreement between reanalysis datasets and station observations.

The estimation accuracy of mean annual temperature was assessed through the metrics listed in table 4.4, where R_i and O_i (i = 1, 2, . . ., n) represent ERA5-Land data and in-situ observed data, respectively, and $\bar{R}$ and $\bar{O}$ are the respective mean values and n is the number of samples of each variable:

Table 4.4 Evaluation criteria used in this study, inspired by (Zhao et al., 2023; Huang et al., 2022).

Metric	**Name**	**Formula**	**Optimal value**	**Unit**	
r	Pearson correlation coefficient	$\frac{\sum_{i=1}^{n}(R_i-\bar{R})(O_i-\bar{O})}{\sqrt{\sum_{i=1}^{n}(R_i-\bar{R})^2}\ \sqrt{\sum_{i=1}^{n}(O_i-\bar{O})^2}}$	1	-	(1)
RMSE	Root-mean-square-error	$\sqrt{\frac{1}{n}\sum_{i=1}^{n}(R_i-O_i)^2}$	0	°C	(2)
MBE	Mean bias error	$\frac{1}{n}\sum_{i=1}^{n}(R_i-O_i)$	0	°C	(3)
MAE	Mean absolute error	$\frac{1}{n}\sum_{i=1}^{n}\lvert(R_i-O_i)\rvert$	0	°C	(4)
$\boldsymbol{R^2}$	Coefficient of determination	r^2	1	-	(5)

The Pearson correlation coefficient (r) measures how closely the grided dataset (ERA5-Land, GPCC) matches the observations. It ranges from -1 to 1. A higher correlation (r) indicates a stronger relationship, while a lower correlation indicates a weaker relationship. When r>0, similar trends will appear, while opposite trends will appear (Huang et al., 2022).

Root-mean-square-error (RMSE) refers to the discrepancy between observed and estimated values; the smaller the discrepancy, the greater the accuracy (Rodrigues et al., 2021).

An average of bias errors is known as a mean bias error (MBE) (Yang et al., 2022). According to Rodrigues et al., 2021, the MBE measures overestimation or underestimation with the positive or negative values respectively.

Mean absolute error (MAE): By calculating the average difference between the predictions and the actual values, the MAE offers a simple method of evaluating the accuracy of predictions. A lower MAE indicates better prediction accuracy.

Coefficient of determination (R^2): As per Rodrigues et al. (2021) and Henseler et al. (2009), when R^2 values are 0.25, 0.50, and 0.75, it means the fit is considered weak, moderate, and significant, respectively.

4.5.5 Bias Correction

In various sections of this thesis, we highlighted that Valle d'Aosta is a region characterized by intricate topography, and its climate elements are notably influenced by altitude. Given the impracticality of having observed data throughout the entire territory, the examination of the region's climate necessitates the use of interpolation methods or reanalysis datasets. While these methods can address data gaps in inaccessible areas, they introduce biases. To mitigate disparities between temperature values derived from meteorological stations and reanalysis datasets, we can employ bias correction methods to improve the accuracy of the results.

Bias correction seeks to reduce the differences between the ERA5-Land data and the observed data, since forecast products are often biased due to errors in the host weather forecast models (Rodrigues et al., 2021; Berg et al., 2003).

In topographically complex terrain, weather data can exhibit significant spatial variations, particularly in the vertical dimension. The nearly linear increase in air temperature with decreasing altitude is known as the "air temperature lapse rate" (Mihalevich et al., 2022). Elevation can have an impact on relative humidity and wind speed, as noted by Liston & Elder (2006), Sen Gupta & Tarboton (2016), and TVA (1972), though these connections are not always straightforward. When forecasting temperatures in mountainous areas, enhancing input weather data is possible by applying elevation corrections tailored to specific parameters. This involves relating the elevation of weather stations or the reference elevation of CRD[1] grids (in this case ERA5-Land) to the actual elevation, as suggested by Mihalevich et al. (2022).

[1] Acronym for Climate Reanalysis datasets

4.6 Data Analysis: Precipitation

In contrast to the methodology employed for temperature analysis, which was based on the location of each meteorological station falling within the corresponding reanalysis grid, for precipitation analysis, we conducted an aerial assessment at the basin scale. This approach aligns with common practice in hydrological studies, as they are typically conducted on a basin scale (Hosseini-Moghari et al., 2018).

We chose not to use the same reanalysis gridded dataset (ERA5-Land) that was previously analysed for temperature data. This decision stemmed from the poor results observed in the early stages of the study, where the ERA5-Land model demonstrated a significant underestimation of precipitation across Valle d'Aosta (Figure 4.5). Consequently, we pursued alternative precipitation datasets that could offer historical data and maintain an acceptable spatial horizontal resolution suitable for precipitation studies on a regional scale in our study area.

In this section a gridded precipitation dataset: Global Precipitation Climatology Centre (GPCC) dataset (Schneider et al., 2022) is evaluated across Valle d'Aosta to investigate its potential reliability as an alternative source to be used as a consistent dataset for precipitation analysis where there is the absence of historical data.

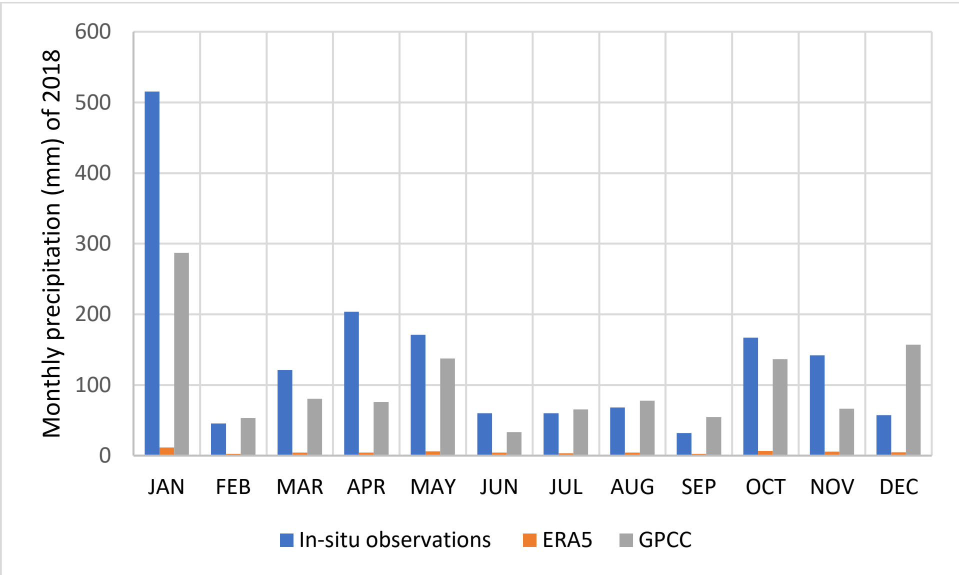


Figure 4.5 Comparison of ERA5-Land, in-situ observations and GPCC for monthly precipitation over Valle d'Aosta basin.

Figure 4.5 illustrates that although ERA5-Land demonstrates reliability in estimating temperature across the case study region, it notably underestimates monthly precipitation. For instance, we can observe this trend in the selected year, 2018, which experienced higher precipitation compared to the mean annual precipitation in Valle d'Aosta. ERA5-Land not only cannot capture extreme precipitation of January 2018, But also have a considerable underestimation of precipitation for all the months, which definitely criticises its reliability for further precipitation analysis of Valle d'Aosta ,therefore this dataset was rejected in early stages of our study and we did not perform statistical evaluations, and consequently ERA5-Land is not used as precipitation dataset.

4.6.1 Precipitation patterns in Valle d'Aosta

In the Aosta Valley, the lowest precipitation values are recorded in the stretch of the central valley between Villeneuve, Aosta, and Châtillon (approximately 500 mm annually). This area remains, in fact, in a rain shadow condition both in relation to the southeast flows and in relation to those from the north and west. From the analysis of historical data from the 1921-1950 thirty-year period, it is observed that the minimum annual precipitation occurs in Saint-Marcel with 494 mm (Il quadro conoscitivo valle d'aosta).

The Mont Blanc and Great St. Bernard areas receive the highest amount of precipitation in the region. On average, the entire area experiences an annual precipitation of approximately 950 mm.

The rainfall regime, i.e., the distribution of precipitation throughout the year, is characterized by two peaks in the intermediate seasons, two minimums in summer and winter. In the eastern sector, the spring peak prevails, in the western sector, the autumn peak, and in the intermediate zone, the difference between the two peaks is reduced (Il quadro conoscitivo valle d'aosta).

4.6.2 Data collection: in-situ observations

The data collection process and the challenges encountered during this phase were thoroughly detailed in section 4.4. Hence, we refrain from repeating this information for precipitation. The data collection procedure mirrored that of temperature, apart from utilizing ERA5-Land as the second dataset for temperature analysis, compensating for the lack of historical data in the region. Additionally, for temperature data analysis and ERA5-Land dataset evaluation, the analysis was confined to the eastern part of Valle d'Aosta, where 13 meteorological stations are situated. In contrast, an aerial assessment approach is implemented for precipitation data analysis across Valle d'Aosta.

Table 4.5 Characteristics of Valle D'Aosta.

Basin	**Total Area (KM^2)**	**No of Stations**	**average annual precipitation 2001-2020 (mm)**
Valle d'Aosta	3260	87	1030

All the in-situ precipitation data are obtained from official portal of CENTRO FUNZIONALE REGIONE AUTONOMA VALLE D'AOSTA (https://presidi2.regione.vda.it/str_dataview) and are processed and aggregated on monthly basis for all the 87 stations distributed over Valle d'Aosta .

4.6.3 Precipitation data collection: GPCC

As an alternative to in-situ precipitation data, we consider the use of the GPCC dataset (The Global Precipitation Climatology Centre), operated by Deutscher Wetterdienst (DWD, National Meteorological Service of Germany) as Germany's contribution to the World Climate Research Programme (WCRP). The GPCC is governed for the global analysis of daily and monthly precipitation on the Earth's land surface, relying on in situ rain gauge data (Schneider et al., 2022). These rain-gauges are distributed all over the globe including Italy (Figure 4.6).

The Global Precipitation Climate Change (GPCC) is an international organization that supplies gridded precipitation datasets for global land surfaces based on gauge measurements. These datasets are accessible in spatial resolutions of 1.0° latitude by longitude, with alternative resolutions of 0.25°, 0.5°, and 2.5° depending on the specific product. The GPCC's latest global precipitation climatology V.2020 serves as the foundational climatology for other analytical purposes. Boasting data collected from over 124,000 diverse stations, it stands as the world's largest precipitation database. The precision of precipitation analyses derived from rain gauges relies on the spatial density of the utilized stations. The entirety of the data undergoes thorough checking, processing, reformatting, and integration within a Relational Database Management System (RDBMS), enabling the GPCC to identify and rectify data discrepancies. The GPCC assesses the sampling error of gridded monthly precipitation data across different regions, with the relative sampling error ranging between ± 7 to 40% of the true area mean (Schneider et al., 2022).

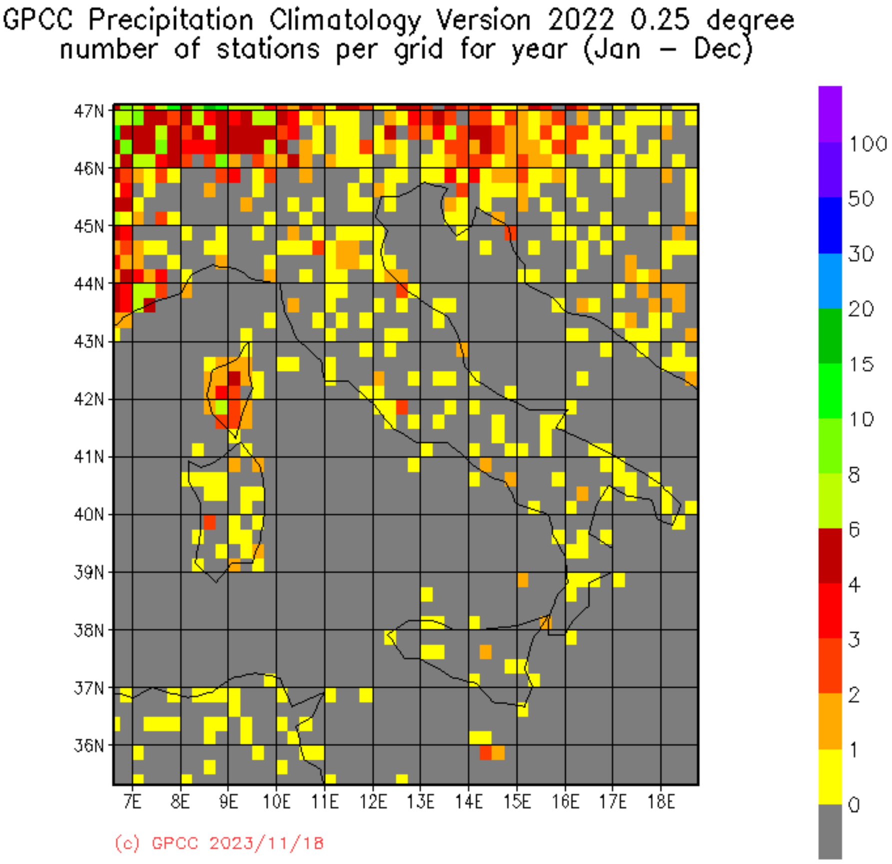


Figure 4.6 Number of rain-gauges per grid used by GPCC, example of Italy. (retrieved from GPCC VISUALIZER; GPCC VISUALIZER (dwd.de))

4.6.4 Methodology for precipitation data analysis

To conduct the data analysis of precipitation, we processed in-situ precipitation measurements and GPCC datasets through several steps using QGIS software. The observed data were provided on a daily basis, while GPCC data were provided on a monthly basis. To facilitate comparison and further evaluation of the GPCC dataset, we needed both datasets in the same temporal scale.

In the first step, data from 87 stations across Valle d'Aosta for the period of 2011-2020 were downloaded and interpolated for the areas without measured data using QGIS software. This process resulted in a raster layer of precipitation values on a daily basis. Subsequently, these values were summed up for each month using the raster calculator command in QGIS. This process was repeated for all the months from 2011 to 2020. As this interpolated raster layers had a much higher resolution than grided data of GPCC (0.25°×0.25°), raster layers should be resampled (decreased resolution) to be able to perform comparison of these two datasets.

Each dataset consists of a number of grids, depending on the raster resolution. To compare mean monthly precipitation values across Valle d'Aosta for GPCC and in-situ observations, we converted pixel values to point data. Subsequently, we took the average of these point data for both datasets over Valle d'Aosta. The results are presented in the 5th chapter on a monthly, seasonal, and yearly scale.

The same data evaluation and statistical metrics were employed to assess the reliability of precipitation estimates from GPCC across Valle d'Aosta. Hence, the evaluation methodology for precipitation dataset is not reiterated here as same metrics (Table 4.4) was used and the method was completely explained.

CHAPTER 5

The case study of Valle d'Aosta: data analysis

5.1 Introduction

Up to this point, we have elucidated the method for comparing observed and reanalysis datasets. Emphasizing the simplicity of illustrating the proximity between these two datasets, we highlighted that subtracting the reanalysis temperature values from in-situ observations offers a straightforward indication of their closeness. Additionally, we illustrated various statistical metrics for evaluating the reanalysis datasets that will be here employed and described. The data evaluation stage holds significant importance as it constitutes a crucial step in investigating the reliability and usability of reanalysis datasets for subsequent climate change studies, particularly in regions where historical data is lacking. In this chapter, our aim is to present a coherent sequence of results, offering the audience a clear understanding of the procedures undertaken in this thesis.

5.2 Results of data analysis for the temperature climate variable

5.2.1 Comparative analysis of ERA5-Land and in-Situ observations

Before delving into the results of the reanalysis data evaluation, we illustrate the disparities between in-situ observations and reanalysis datasets using relevant graphs and tables. This visual representation allows us to discern the variations between the datasets. Subsequently, in the following sections, we present the evaluation results. These results shed light on whether ERA5-Land temperature data align with the temperature data from meteorological stations or exhibit discrepancies.

Referring to Table 4.3, it is evident that there exists an altitude difference between the reanalysis grid encompassing the observation point data and the altitude of the meteorological station where temperature measurements are taken. To provide a more comprehensive understanding, it would be beneficial to illustrate the correlation between altitude and temperature using a simple linear regression model. Such an approach can offer insights into the impact of altitude on temperature in this specific region, which serves as the sample for our study, encompassing 13 weather stations located in the eastern part of Valle d'Aosta. Such linear regression is displayed in Figure 5.1.

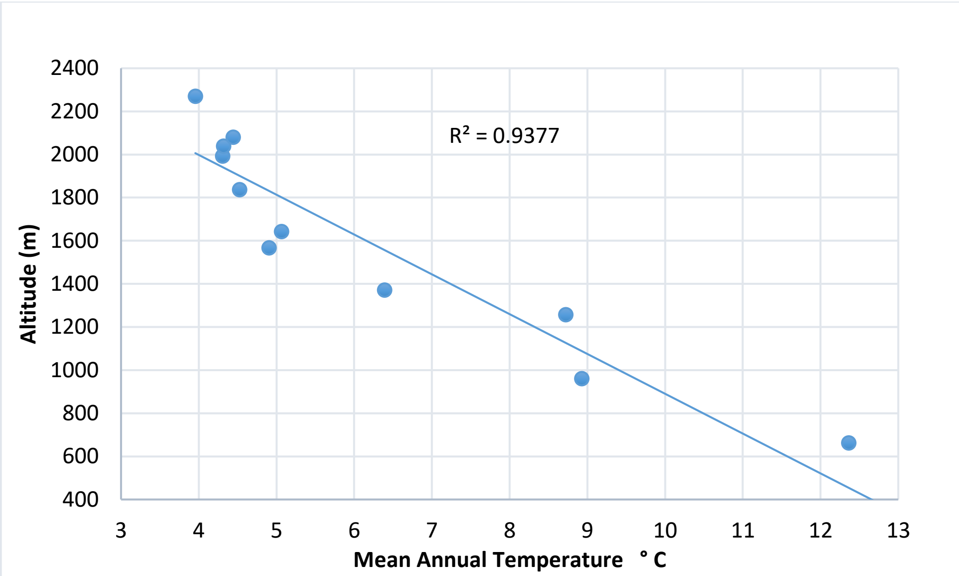


Figure 5.1 Relationship between Mean Annual Temperature (2014-2022) recorded by meteorological stations and Altitude in the eastern part of Valle d'Aosta, with indication of the coefficient of determination for the linear regression.

The R^2 value obtained is 0.9377 indicates a strong linear relationship between altitude and temperature, explaining approximately 93.77% of the variability in temperature across 13 stations. The remaining 6.23% of variability is not accounted for by the linear model, possibly due to unconsidered factors, random variations, or nonlinear relationships. While the high R^2 value implies that altitude is a significant predictor of temperature, it's crucial to note that correlation does not imply causation. The robust linear relationship suggests that altitude plays a substantial role in explaining temperature variability across the stations.

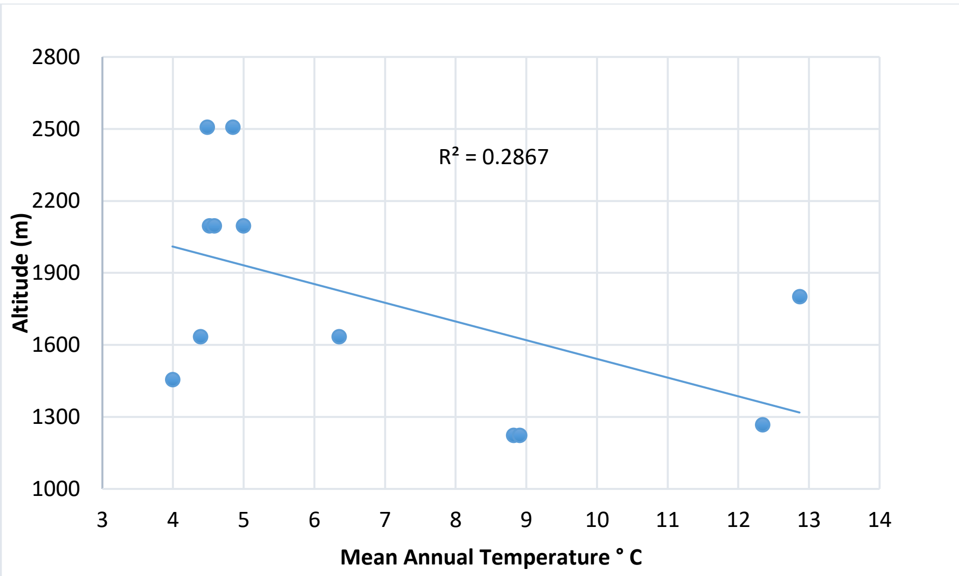


Figure 5.2 Scatter plot of Mean Annual Temperature of ERA5-Land reanalysis model vs average altitude of each grid (9km × 9 km) in the eastern part of Valle d'Aosta, trendline shows the Coefficient of determination $R^2 = 0.2867$

On the other hand, as depicted in Figure 5.2, a weak linear relationship is observable between the temperature values derived from the ERA5-Land reanalysis dataset and the altitude of each grid in the model. This contrasts with the robust relationship between temperature and altitude evident in the observed data. This weak correlation can be interpreted as a limitation of the model in capturing the regional characteristics of the climate.

Additionally, it's crucial to note that this weak correlation may be attributed to the coarse spatial horizontal resolution of the reanalysis model. In Valle d'Aosta, local variations in topography are substantial, and the use of an average altitude value for each grid can significantly impact the results. The limitations in capturing fine-scale topographical variations may contribute to the observed weak correlation between temperature and altitude in the reanalysis dataset.

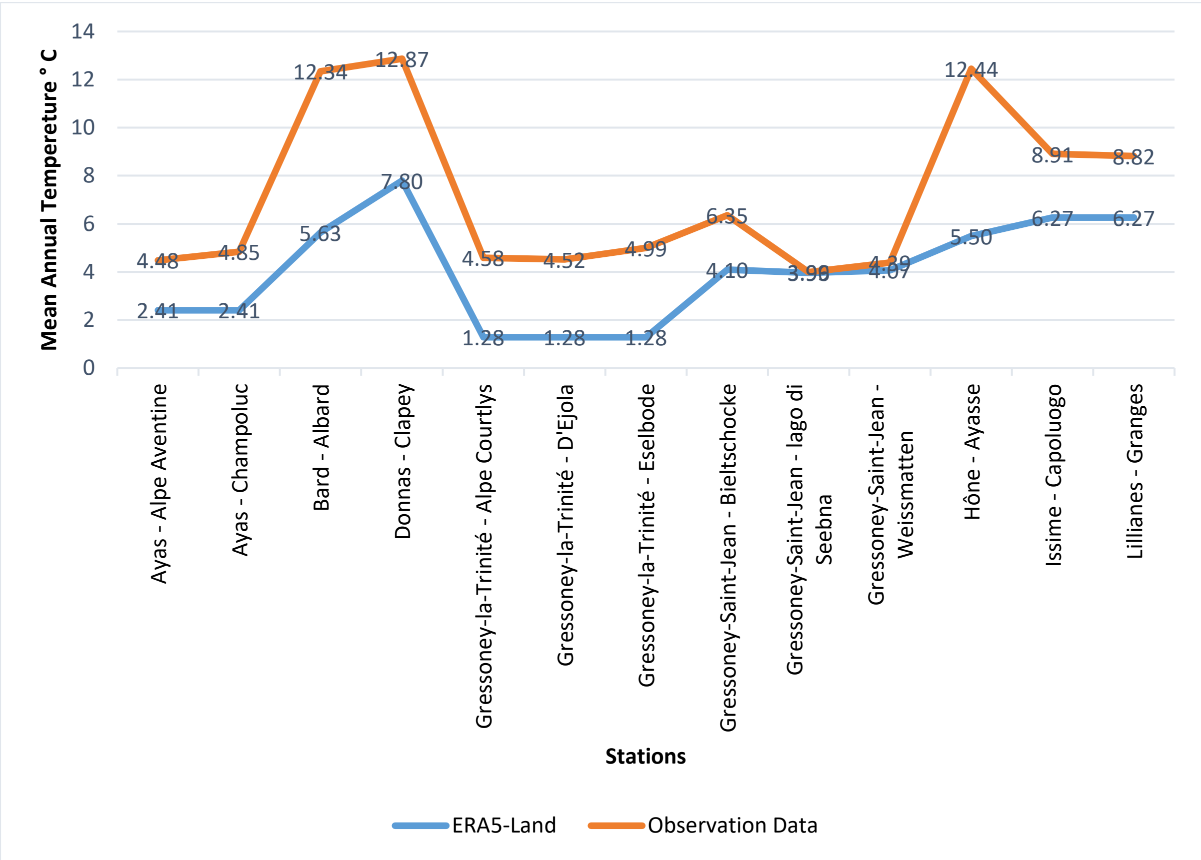


Figure 5.3 Comparison between ERA5-Land and weather stations mean annual temperature (2014-2022).

According to Figure 5.3, ERA5-Land underestimates temperature values compared to all the stations; however, what is evident is that overall ERA5-Land can capture the temperature patterns in a way consistent with in-situ observations. Indeed, the trends are highly comparable. This indicates a degree of reliability in the ERA5-Land reanalysis dataset for representing temperature trends.

The differences could arise from various factors, such as variations in data sources, measurement techniques, and the assimilation models used in the reanalysis process, regional climate patterns and coarser spatial resolution of the reanalysis datasets. Despite potential differences in absolute values, the reanalysis data can be relied upon for capturing the relative patterns and trends in temperature across the studied stations in Valle d'Aosta. We enhance this statement by using statistical metrics (Table 4.4) to evaluate the reliability of the ERA5-Land dataset.

5.2.2 Evaluation of ERA5-Land reliability by using statistical indicators

To evaluate reanalysis dataset, an authentic statistical method using statistical indicators (as presented in Chapter 4) is used. Such method has been implemented in several previous studies (Mihalevich et al., 2022; Rodrigues et al., 2021; Huang et al., 2022; McNicholl et al., 2021; Mooney et al., 2011; Zhao et al.,2023; Yang et al., 2022). The reference period for the evaluation carried out in the current study is 2014-2022. Results expressed in terms of the statistical indicators mentioned above are presented in Table 5.1.

Table 5.1 Results of ERA5-Land evaluation (2014-2022) for mean annual temperature in 13 sites located in the eastern part of Valle d'Aosta expressed in terms of statistical indicators.

Station	RMSE	MBE	MAE	r	R^2
Ayas - Alpe Aventine	2.044	-2.033	2.033	0.898	0.807
Ayas - Champoluc	2.506	-2.490	2.490	0.805	0.648
Bard - Albard	6.728	-6.726	6.726	0.963	0.929
Donnas - Clapey	5.327	-5.296	5.296	0.726	0.527
Gressoney-la-Trinité - Alpe Courtlys	3.282	-3.022	3.022	0.388	0.150
Gressoney-la-Trinité - D'Ejola	3.249	-3.240	3.240	0.851	0.725
Gressoney-la-Trinité - Eselbode	3.801	-3.780	3.780	0.669	0.447
Gressoney-Saint-Jean - Bieltschocke	2.307	-2.293	2.293	0.832	0.692
Gressoney-Saint-Jean - lago di Seebna	0.652	0.0085	0.008	0.588	0.346
Gressoney-Saint-Jean - Weissmatten	0.390	-0.312	0.312	0.869	0.755
Hône - Ayasse	6.542	-6.159	6.159	0.864	0.747
Issime - Capoluogo	2.673	-2.660	2.660	0.817	0.668
Lillianes - Granges	2.921	-2.455	2.455	-0.083	0.006
Total Average	3.26	-3.112	3.113	0.707	0.573

In the comparison of ERA5-Land reanalysis values for temperature and observation data, Weissmatten station demonstrates the highest agreement, boasting the smallest Root Mean Square Error (RMSE) at 0.3902 and the coefficient of determination at 0.7553. On the contrary, Bard station yields weaker results with an RMSE of 6.72. However, it presents a high coefficient of determination, indicating a substantial correlation between the reanalysis dataset and observed data. Consequently, we've chosen to focus specifically on these two stations to explore potential residuals between reanalysis and observed data.

The overall average of the statistical indicators suggests a moderate to good agreement of the reanalysis datasets as a temperature input for climate change studies in the region, especially given the absence of historical data. It's essential to note that the ERA5-Land reanalysis model, designed for global coverage, provides coarse horizontal spatial resolution for regional climate studies. Challenges arise when applying most reanalysis models in regions with complex topography, where climate variables are significantly influenced by local altitude variations, such as in this case.

The justification for selecting ERA5-Land lies in its extensive time coverage, high horizontal resolution, and user-friendly interface that enables public access and implementation for regional studies, as demonstrated in our case study using QGIS. Numerous similar studies worldwide, including those in regions with complex topography, attest to the model's credibility. However, it's crucial to acknowledge that Valle d 'Aosta's unique climate characteristics distinguish it from regions with less complex topography. This study underscores the importance of evaluating reanalysis climate data in regions like Valle d'Aosta.

It's important to note that there is a variety of gridded datasets providing climate change projections, implemented in climate change studies across different regions. Analysing ERA5-LAND data, being a gridded dataset, not only offers valuable insights into the significance of data evaluation for historical climate change studies but also serves as a foundation for policymakers and decision-makers. This underscores the idea that, whether for historical climate change data or future projections, when implementing climate models on a regional scale with gridded datasets estimating climate variables over a grid rather than a point, it is crucial to evaluate their reliability before any implications that may lead to subsequent decisions. Hence, the findings from the ERA5-Land reanalysis dataset can raise critical considerations for studies utilizing climate change models (projections or reanalysis) without a careful data evaluation to examine climate change on regional scales, particularly in regions with contentious climatic characteristics.

5.2.3 Analysis of statistical indicator results: Weissmatten and Bard

The comparison and evaluation of ERA5-Land and observed data for 13 stations located in the eastern part of Valle d'Aosta for the period of 2014-2022 have been conducted, with all results summarized in Table 5.1. To delve into the results and understand potential causes of differences between reanalysis and observed data, we have chosen to investigate two stations as samples: Weissmatten, which demonstrates high agreement, and Bard station, which exhibits a significant RMSE while showing a high Coefficient of determination (Figure 5.4). Additionally, we would apply elevation correction based on the method proposed by Mihalevich et al. (2022) to examine if the residual between the reanalysis dataset and observed data is influenced by elevation bias.

Table 5.2 Evaluation Criteria for sample stations.

Station	**RMSE (° C)**	R^2	**Altitude at the Station (h1) (m)**	**Mean altitude over the reanalysis grid (h2) (m)**	**(h2-h1)**
Gressoney-Saint-Jean - Weissmatten	0.390	0.755	2038	1634	-404
Bard - Albard	6.728	0.929	662	1267	605

Table 5.2 indicates, for the Weissmatten station an altitude difference of 404 meters between the observed data and the gridded reanalysis dataset. In this scenario, ERA5-Land appears to have underestimated the actual elevation, providing data that aligns with high accuracy very closely to the measured temperature at the station.

On the other hand, Bard's evaluation results reveal an altitude difference of 605 meters between the two datasets, leading to a significant difference (RMSE=6.73). In this station, unlike the Weissmatten case, the altitude is overestimated over the reanalysis grid, resulting in a considerable underestimation of almost 7 °C between ERA5-Land and observed data.

This observation may suggest that the discrepancy between the observed and reanalysis data could stem from an overestimation of the altitude effect in ERA5-Land calculations, especially when the gridded altitude is overestimated.

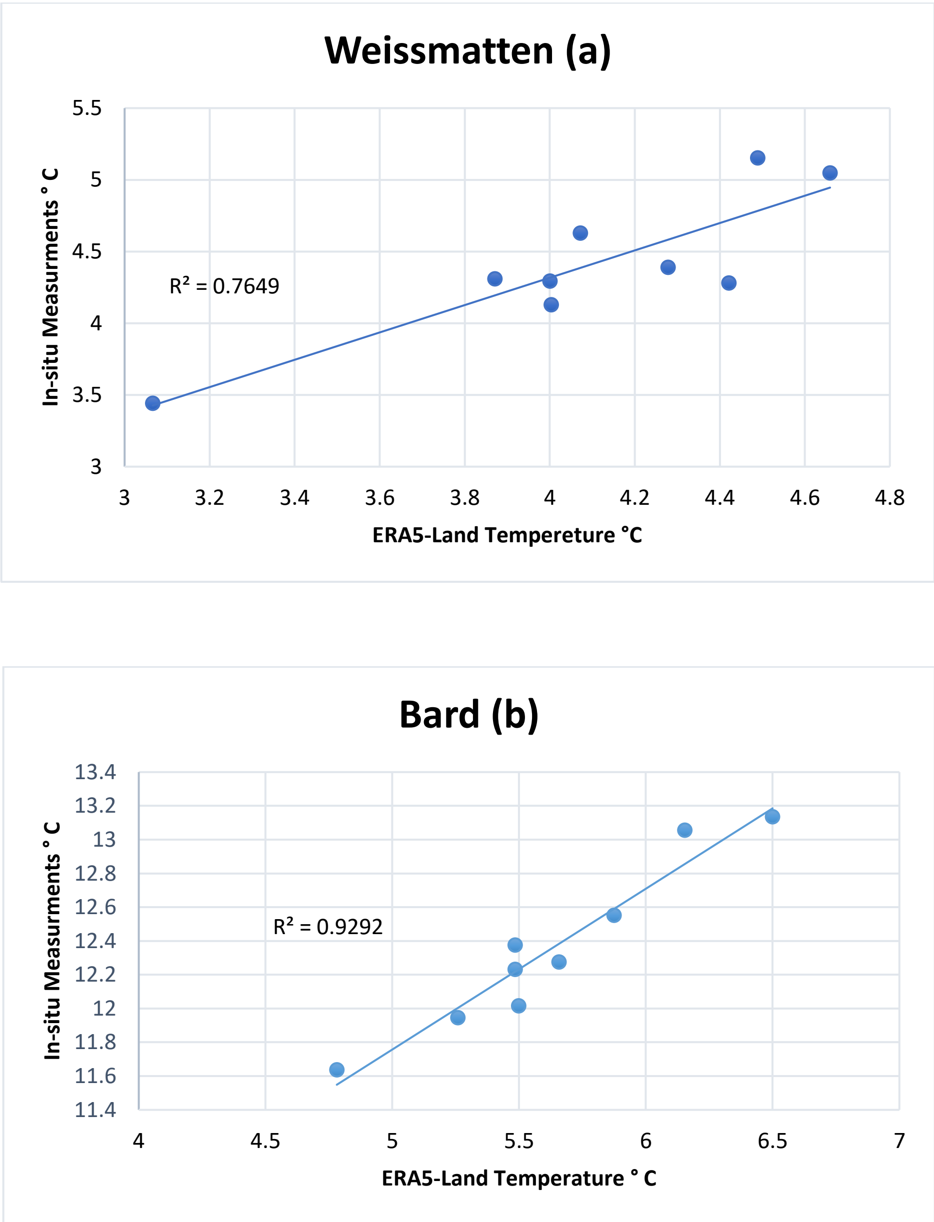
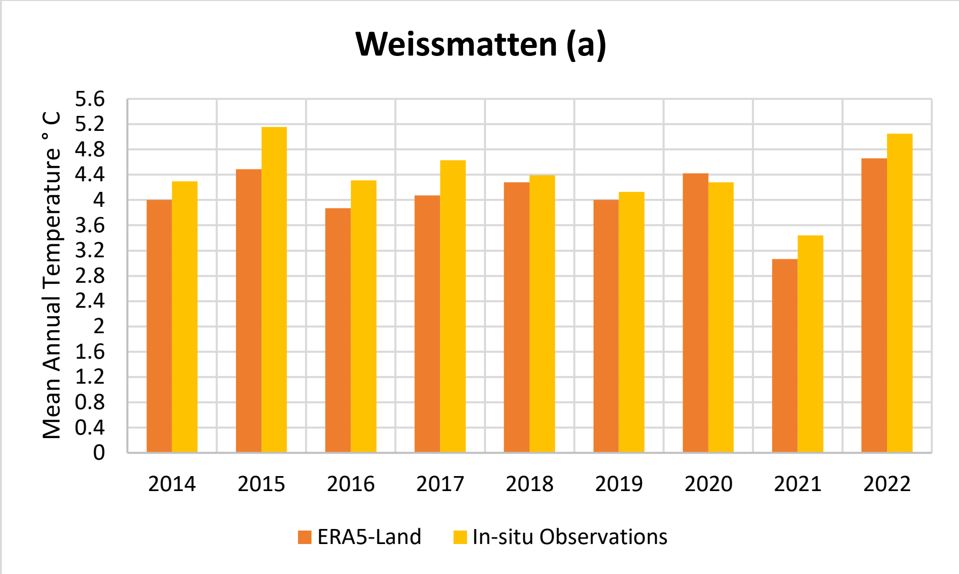


Figure 5.4 Coefficient of determination (R^2) for the two sample stations: (a): Weissmatten , (b): Bard.



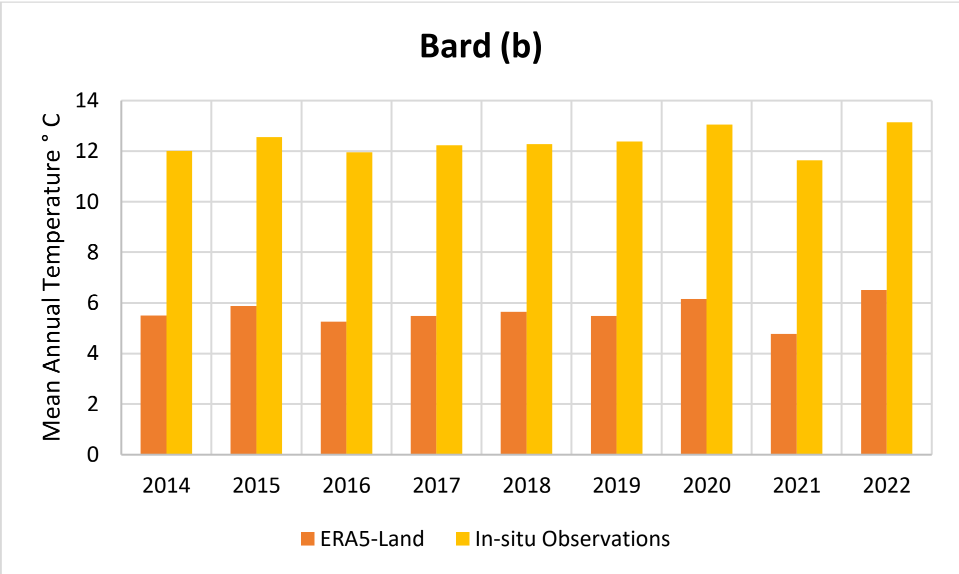


Figure 5.5 Mean annual temperature (a): Weissmatten (b): Bard.

Figure 5.5 highlights a high agreement between reanalysis datasets and observed temperatures at Weissmatten. In contrast, Bard exhibits a high disparity but with a notable correlation (Figure 5.4) between reanalysis data and observed temperatures. This serves as a motivation to implement elevation bias correction for these two stations as samples, aiming to assess if any improvement in results can be observed.

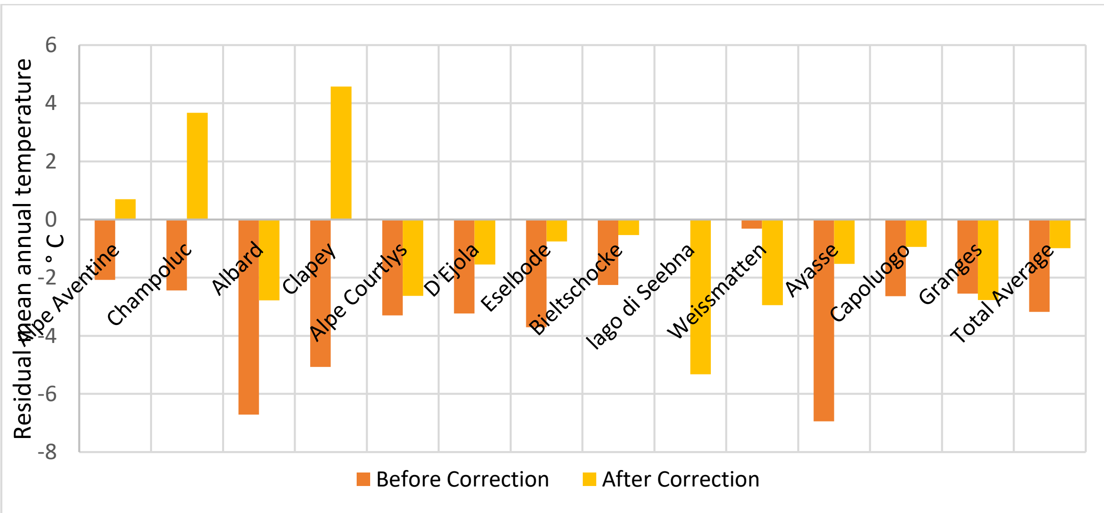
5.2.4 Elevation bias correction

The method employed in this section is strongly influenced by the assumption of the substantial impact of altitude on temperature in Valle d'Aosta. Following the approach recommended by Mihalevich et al. (2022), we test this assumption specifically for Bard Station, which exhibits a noteworthy RMSE for temperature. The objective is to assess if the differences in the reanalysis dataset results are influenced by the 605 meters difference in altitude or if there are other contributing factors.

Air temperature is commonly elevation corrected by applying the linear environmental lapse rate of $6.5°C\ km^{-1}$ (Berg et al., 2003; Iizumi et al., 2017; Krogh et al., 2015; Mizukami et al., 2014). Due to the wide variation in lapse rates over space and time, some refinement can be gained by varying lapse rates on a monthly basis (Liston & Elder, 2006; Mihalevich et al., 2022). Also, lapse rates can be calculated using air temperature profiles over vertical pressure levels (Gao et al., 2012; Sen Gupta & Tarboton, 2016; You et al., 2019); however, not all CRDs[1] provide this data, e.g., ERA5-Land (Mihalevich et al., 2022).

Several studies (Zhao et al., 2022; Mihalevich et al. 2022; Sheridan et al., 2010) have focused solely on addressing biases resulting from elevation differences between observed data and reanalysis grid altitude. While the intention here is not to introduce a specific method for bias correction, it is crucial to emphasize the need for a detailed and precise analysis of this issue. The objective is to test this assumption within the context of our sample study region. In this study Equation (1) was used (Sheridan et al., 2010) to calculate temperature variations caused by elevation error, where $\delta h = h_a - h_m$ is the difference in height between the actual elevation at the site of interest (h_a) and the ERA5-Land height at the selected grid point (h_m) and $\gamma = 6.5°C\ km^{-1}$. To obtain the corrected temperature δT is added to the temperature of the ERA5-Land grid point (Sheridan et al., 2010).

$$\delta T = -\delta h \times \gamma \qquad (1)$$



[1] CRDs stands for Climate Reanalysis Datasets.

Figure 5.6 Elevation bias correction.

Table 5.3 Elevation bias correction of ERA5-Land mean annual temperature.

Station	R_i[1]	O_i	$R_i - O_i$	h_a	h_m	$h_a - h_m$	δT	$R_i + \delta T$	$R_i + \delta T - O_i$
Ayas - Alpe Aventine	2.409	4.484	-2.074	2080	2506	-426	2.769	5.178	0.694
Ayas - Champoluc	2.409	4.845	-2.435	1566	2506	-940	6.11	8.519	3.674
Bard - Albard	5.632	12.343	-6.710	662	1267	-605	3.932	9.565	-2.778
Donnas - Clapey	7.796	12.866	-5.070	318	1801	-1483	9.639	17.4361	4.569
Gressoney-la-Trinité - Alpe Courtlys	1.283	4.584	-3.300	1992	2096	-104	0.676	1.959	-2.624
Gressoney-la-Trinité - D'Ejola	1.283	4.515	-3.232	1837	2096	-259	1.683	2.967	-1.548
Gressoney-la-Trinité - Eselbode	1.283	4.992	-3.708	1642	2096	-454	2.951	4.234	-0.757
Gressoney-Saint-Jean - Bieltschocke	4.095	6.350	-2.254	1370	1634	-264	1.716	5.811	-0.538
Gressoney-Saint-Jean - lago di Seebna	3.964	3.991	-0.027	2270	1455	815	-5.297	-1.333	-5.324
Gressoney-Saint-Jean - Weissmatten	4.071	4.387	-0.316	2038	1634	404	-2.626	1.445	-2.942
Hône - Ayasse	5.497	12.442	-6.945	367	1200	-833	5.414	10.912	-1.530
Issime - Capoluogo	6.265	8.906	-2.640	960	1222	-262	1.703	7.968	-0.937
Lillianes - Granges	6.265	8.818	-2.553	1256	1222	34	-0.221	6.044	-2.774
Total Average	**4.019**	**7.194**	**-3.174**					**6.208**	**-0.986**

Elevation bias correction was applied to our sample data. It's important to note that this is a preliminary estimate, and the results haven't been evaluated as thoroughly as before. However, it provides a sense of the potential improvements in the case of elevation biases. This correction seems to enhance ERA5-Land results in stations where elevation errors led to a significant underestimation of mean annual temperature, like Bard and Ayasse. It reduced the mean annual temperature residuals from -6.71098 to -2.77848 and from -6.9451 to -1.5306, respectively. Conversely, for Weissmatten and

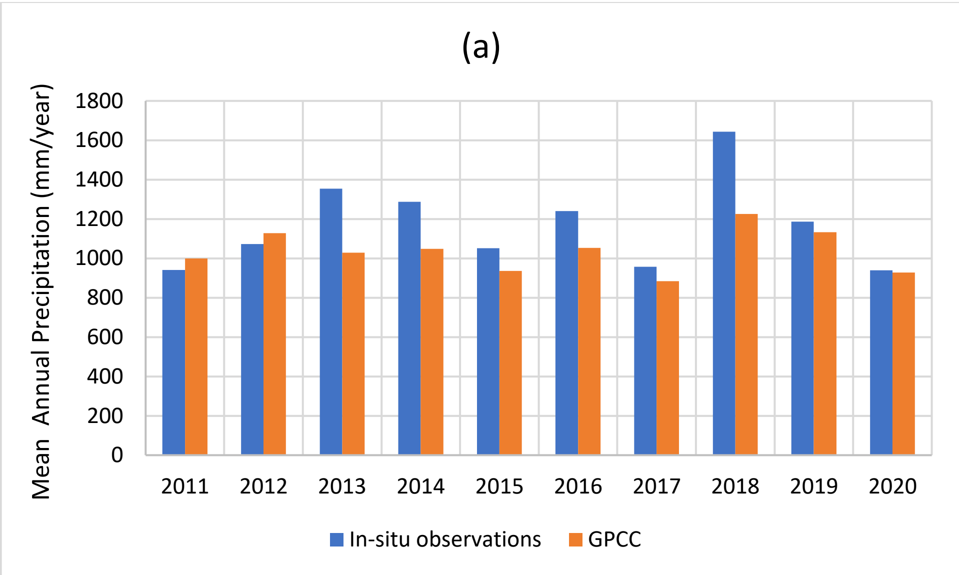
[1] R_i stands for temperature estimated by ERA5-Land and O_i presents observed data where i stands for Stations.

Lago di Seebna, where ERA5-Land underestimated the altitude by 404 and 815 meters, respectively, elevation bias correction resulted in larger residuals compared to the pre-correction results. This suggests that elevation bias correction may improve results in stations where ERA5-Land overestimated the corresponding grid altitude but could negatively impact the results for stations where their altitude was underestimated by ERA5-Land.

5.3 Results of data analysis for the precipitation climate variable

Areal assessment was conducted at a basin scale for precipitation. Monthly, seasonal, and annual variations of in-situ observations and GPCC dataset were compared and evaluated for each dataset. In the seasonal scale, DJF refers to December, January, and February; MAM stands for March, April, May; JJA for June, July, August; and SON for September, October, and November.

To assess the accuracy of the precipitation dataset (GPCC) and its reliability to be used in Valle d’Aosta case study, we utilized statistical metrics as outlined in Table 4.4. The results have been presented through tables and graphs.



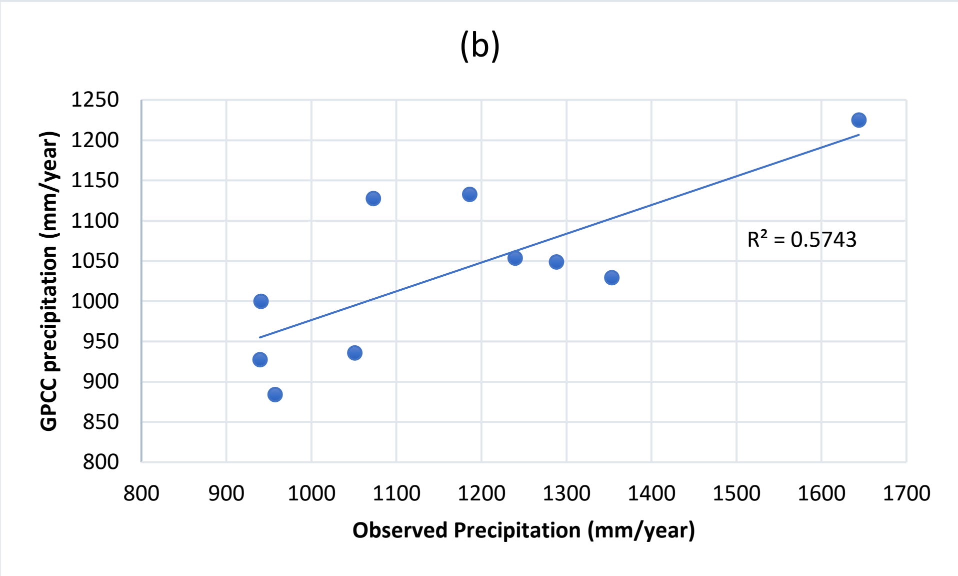


Figure 5.7 Comparison of the mean annual precipitation data of GPCC and observed data (a), (b).

In Figure 5.7(a), the alignment between GPCC and in-situ observations is depicted. Both datasets exhibit analogous patterns in identifying the lowest and highest precipitation values spanning the years 2011 to 2020. Notably, both datasets highlight the year 2018 as having the highest precipitation, 1644 mm/year for in-situ observations and 1225 mm/year for GPCC.

Examining the minimum precipitation values within the period of 2011-2020, meteorological stations in Valle d'Aosta recorded 939 mm in 2020. In contrast, GPCC indicates a minimum of 884 mm in 2017 and 927 mm in 2020. Despite GPCC accurately capturing precipitation in 2020 compared to in-situ observations, it designates 2017 as the year with the minimum precipitation.

Throughout the 2011-2020 timeframe, GPCC consistently tended to underestimate precipitation values, doing so in 80 percent of the years.

Upon evaluating the precipitation data from the GPCC dataset, it appears to have limitations in accurately estimating intense precipitation events. This is evident in instances where the dataset underestimates precipitation for years when local meteorological stations recorded higher precipitation compared to other years. For example, in 2018, in-situ observations in Valle d'Aosta indicate a significant discrepancy (477 mm) from the average annual precipitation (2011-2020). Further investigation reveals that in this year, the precipitation in January was much higher (515 mm) than the mean average precipitation in January for the period of 2011-2020 (129 mm). These findings suggest that GPCC may struggle to accurately capture heavy precipitation events. In this year the estimated precipitation in the month of January was 287 mm, although it could estimate precipitation in a similar pattern but still have a significant residual which can affect further studies which may need more accurate estimations of extreme events.

Gariano & Guzzetti (2016) highlight a pertinent concern in their recent discussion. They emphasize the substantial uncertainty linked to downscaled projections, particularly for short and intense rainfall events, in comparison to prolonged rainfall. This uncertainty, especially in predicting high-intensity and short-duration precipitation, poses challenges for landslide-climate studies. In this context, the reliability of climate variables becomes crucial, with projections based on temperature deemed more dependable than those based on precipitation. Considering the uncertainties associated with forecasting intense precipitation events, particularly those triggering shallow landslides, the authors suggest that meaningful results are more likely to be obtained from regional landslide-climate studies.

This insight aligns with our own findings, emphasizing the importance of evaluating the accuracy of precipitation datasets in capturing intense precipitation events for effective landslide-climate studies in specific regions.

In following sections, seasonal and monthly variations in both GPCC and VDA[1] in-situ observed data is presented.

[1] VDA stands for Valle d'Aosta, in some of the graphs of this thesis we used this acronym which refers to in-situ collected data.

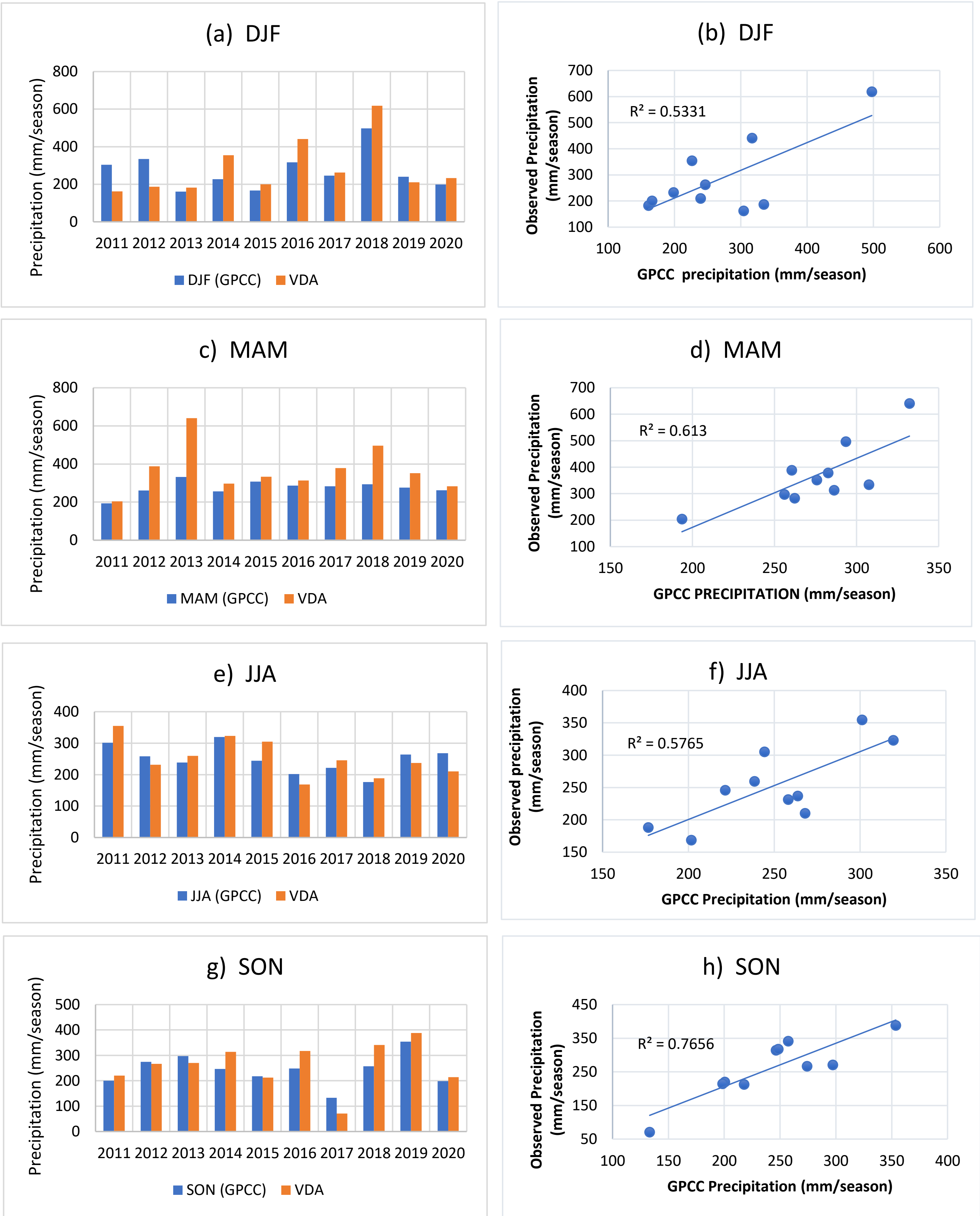


Figure 5.8 Seasonal variations in precipitation, comparison of GPCC and Valle d'Aosta observed data: (a)to(h).

Table 5.4 GPCC evaluation results (Seasonal scale) .

Season	r	R^2	RMSE	MBE	MAE
DJF	0.730	0.533	96.044	-15.702	79.698
MAM	0.782	0.613	130.876	-93.513	93.512
JJA	0.759	0.576	36.945	-2.994	31.957
SON	0.874	0.765	47.783	-18.698	39.210
Average	0.786	0.622	77.912	-32.727	61.094

To assess the outcomes from GPCC, we applied the same methodology as detailed in Chapter 4. The statistical metrics employed indicate notable variations in GPCC's performance across different months. Specifically, during June, July, and August, GPCC exhibits the lowest Root Mean Square Error (RMSE) at 37 mm, indicating relatively accurate performance. In contrast, its performance weakens during March, April, and May, with an elevated RMSE of 131 mm. This discrepancy may be attributed to GPCC's challenges in capturing extreme precipitation events during these months.

The evaluation of the GPCC dataset's performance on a monthly scale followed a similar approach. The results reveal significant variability in the accuracy of precipitation estimations across different months. Notably, in July, the dataset demonstrates a low RMSE of only 13 mm for the period 2011-2020, indicating better performance. Conversely, the dataset exhibits its poorest performance in April, with an elevated RMSE of 81 mm. These findings once again underscore GPCC's limitations in accurately capturing precipitation values, especially during months characterized by higher precipitation levels compared to other months of the year (Figure 5.9 and Table 5.5).

*Table **5.5** GPCC evaluation results (Monthly scale).*

Month	r	R2	RMSE (mm)	MBE (mm)	MAE (mm)
January	0.939	0.882	77.291	-27.745	41.584
February	0.967	0.935	40.212	-28.566	30.610
March	0.848	0.719	38.474	-32.227	32.639
April	0.847	0.718	81.093	-61.670	61.823
May	0.790	0.624	41.053	0.384	31.975
June	0.820	0.673	23.106	-10.115	18.422
July	0.946	0.895	12.840	4.911	10.248
August	0.808	0.652	20.430	2.209	14.861
September	0.626	0.392	19.173	9.911	16.869
October	0.952	0.907	25.869	-5.602	22.740
November	0.828	0.687	46.277	-23.008	39.050
December	0.726	0.527	69.374	40.609	46.542
Average	0.841	0.718	34.885	-10.909	30.614

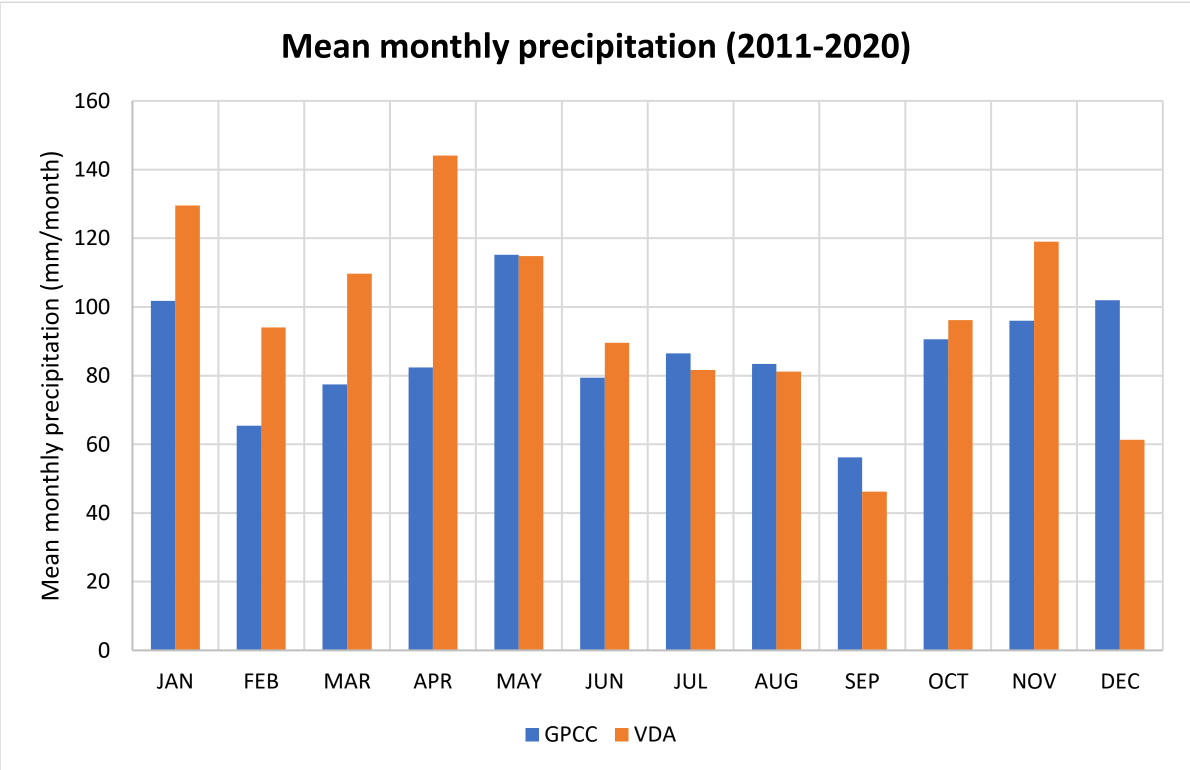


Figure 5.9 Monthly variations in precipitation, comparison of GPCC and Valle d'Aosta observed data.

5.4 Climate change in Valle d'Aosta

This study aims to demonstrate the reliability of the ERA5-Land and GPCC datasets as inputs for climate change studies in Valle d'Aosta. Through statistical evaluations, we assessed how well these datasets align with in-situ observations in a region characterized by inconsistent climate records spanning at least 30 years and influenced by altitude variations. After careful data analysis, ERA5-Land and GPCC show a moderate and a moderate to good agreement with in-situ observations respectively. Notably, ERA5-Land exhibits a good alignment with observed temperature data at specific stations, such as Weissmatten, with a slight RMSE of 0.39 °C for the reference period of 2014-2022. This outcome is remarkable, allowing for the analysis of a time-consistent dataset from 1950 to the present, providing a highly reliable basis for examining temperature trends over several decades.

It's important to note that this analysis covered a limited area of Valle d'Aosta with only 13 stations, suggesting the potential for improvement by expanding the study area to include all 87 meteorological stations in Valle d'Aosta.

Analysing the recorded temperature and precipitation in Valle d'Aosta using https://cf.regione.vda.it, we found a lack of consistent temporal patterns in temperature and precipitation records. The region faces a data shortage, which prevents a comprehensive study of its climate and the identification of potential climate change occurrences relying solely on meteorological station data.

While GPCC struggles to capture extreme precipitation events, it remains a generally reliable dataset with a moderate-to-good agreement in our case study. In summary, our application of these datasets to detect potential climate change in Valle d'Aosta leverages their strengths and acknowledges their limitations. Therefore, in this section we perform a data analysis by using non-parametric Mann-Kendall test for both precipitation and temperature using GPCC and ERA5-Land as inputs.

5.4.1 Mann-Kendall (Mk) Trend Test

The Mann-Kendall non-parametric test is a valuable tool for detecting significant long-term trends in temporal data, particularly in fields like climate science, where the variation of variables such as temperature and precipitation over time is crucial for studies on climate change (Shadmani et al., 2012). This statistical method operates on the basis of two hypotheses: the Null Hypothesis (H0), assuming no trend in the data, and the Alternate Hypothesis (H1), suggesting the presence of a trend (Shadmani et al., 2012).

In our study, we used Mann-Kendall test to analyse temperature and precipitation data over a 50-year period (1971-2020) in Valle d'Aosta region. Weissmatten station was chosen for temperature analysis due to the strong agreement between its corresponding ERA5-Land temperature data and in-situ observations. For precipitation analysis, we employed the GPCC dataset as input for Mann-Kendall test, evaluating mean annual precipitation variations across the Valle d'Aosta basin.

To perform the Mann-Kendall test, we employed the XLSTAT software (Figure 5.10), a widely used tool for statistical analysis. This approach allows us to assess whether there is a statistically significant increasing or decreasing trend in the temperature and precipitation data over the specified 50-year period. The results of this trend analysis contribute to a better understanding of the climate change in the Valle d'Aosta region, especially in the context of long-term climate change studies.

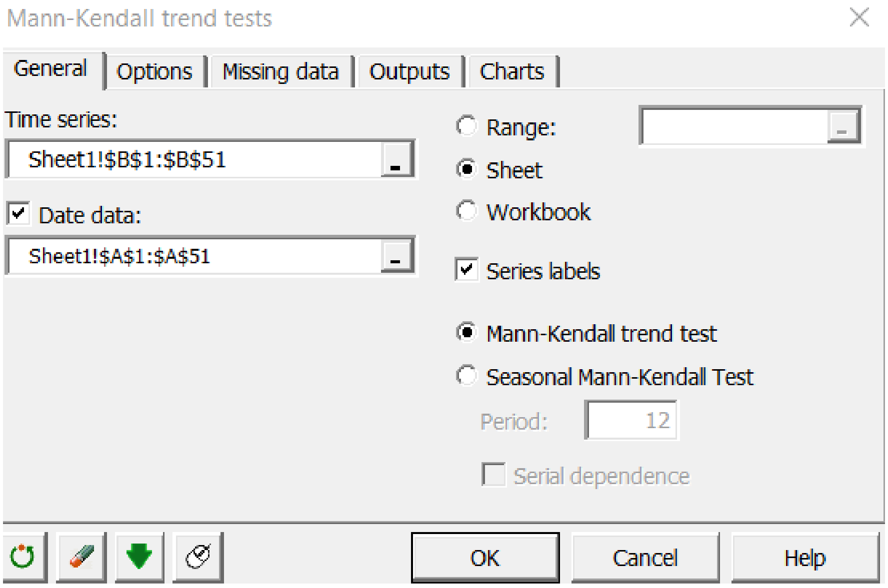


Figure 5.10 Mann-Kendall trend test by XLSTAT.

5.4.2 Temperature trend analysis

Mann-Kendall trend test is performed for a 50-year period (1971-2020) and, Weissmatten station was chosen as a sample to investigate any possible climate change in the eastern part of Valle d'Aosta[1] .XLSTAT compute a variety of statistics to conduct (MK) test , furthermore these metrics can give the audience a general image of temperature variations by presenting metrics such as minimum , maximum ,mean and standard deviation of the temperature(Table 5.6) .

Table 5.6 Summary of temperature statistics (Weissmatten station), analysis performed by XLSTAT.

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Temperature	50	0	50	1.478	4.489	2.984	0.791

Table 5.6 indicates, mean annual temperature of 50 years (1971-2020) was used as inputs to conduct the trend analysis, results show that Weissmatten station experienced the highest mean annual temperature of 4.489° in 2015 and minimum temperature of 1.478° in 1984, with the total average of 2.984 ° C (1971-2020).

[1] Keep it in mind that, Due to local altitude variations and its strong influence on temperature in Valle d'Aosta, we avoid generalizing trend analysis of Weissmatten station to whole region. But it can be a valuable insight to study the climate change of Valle d'Aosta.

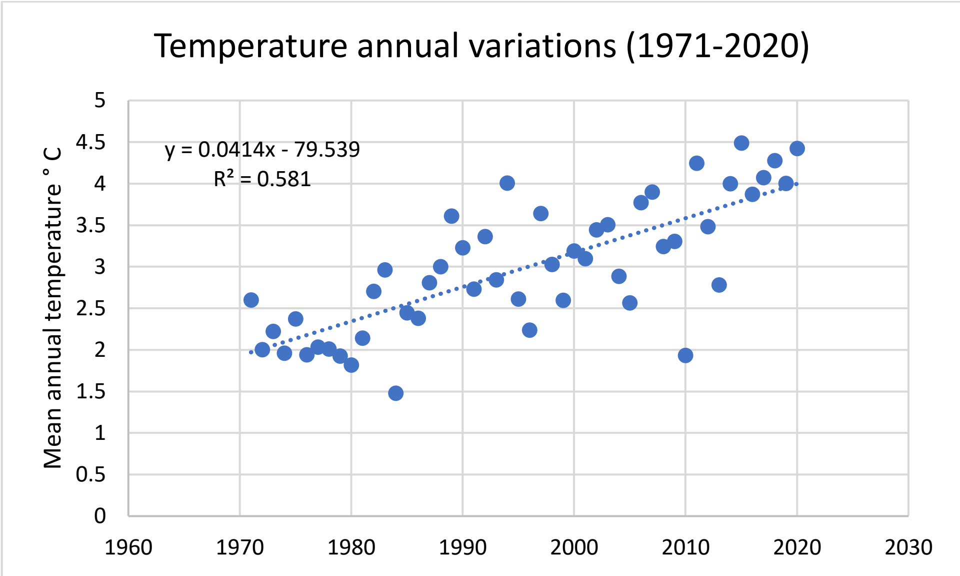


Figure 5.11 Scatter plot of mean annual temperature of Weissmatten.

Figure 5.11 indicates a linear increasing trend for mean annual temperature (1951-2020) as it can be seen by the trend line equation, we enhance this statement by providing Mann-Kendall test.

Table 5.7 Results of Mann-Kendall test (XLSTAT).

Series\Test	**Kendall's tau**	**p-value**	**Sen's slope**
Temperature	0.570612245	5.26189E-09	0.044298808

XLSTAT provides interpretation of the conducted trend analysis, due to its interpretation, As the computed p-value is lower than the significance level alpha=0.05, one should reject the null hypothesis H_0, and accept the alternative hypothesis, Ha. As the p-value is less than 0.05 it means there is significant trend in our temperature data over (1971-2020). Furthermore, XLSTAT uses other metrics such as Sen's slope to provide a measure for the trend, due to the results of XLSTAT.

In this statistical trend test two metrics are important to be discussed: 1- (p-value) which shows the existence of any increasing or decreasing trend when (p-value<0.05) in our dataset (in this case study the mean annual temperature of Weissmatten time series) 2- Sen's slope (Sen, 1986): is a non-parametric estimator which can measure the trend slope magnitude (Gocic et al., 2013).

Figure 5.12 indicates there is a linear increasing trend for annual temperature in Weissmatten, as it can be seen the variation of temperature values for 1971 approximately 2.6 ° C to 4.5 in 2020, is considerable. This trend analysis shows that in a 50-years period, climate change has happened in the eastern part of Valle d'Aosta relying on the climate data analysis of Weissmatten station.

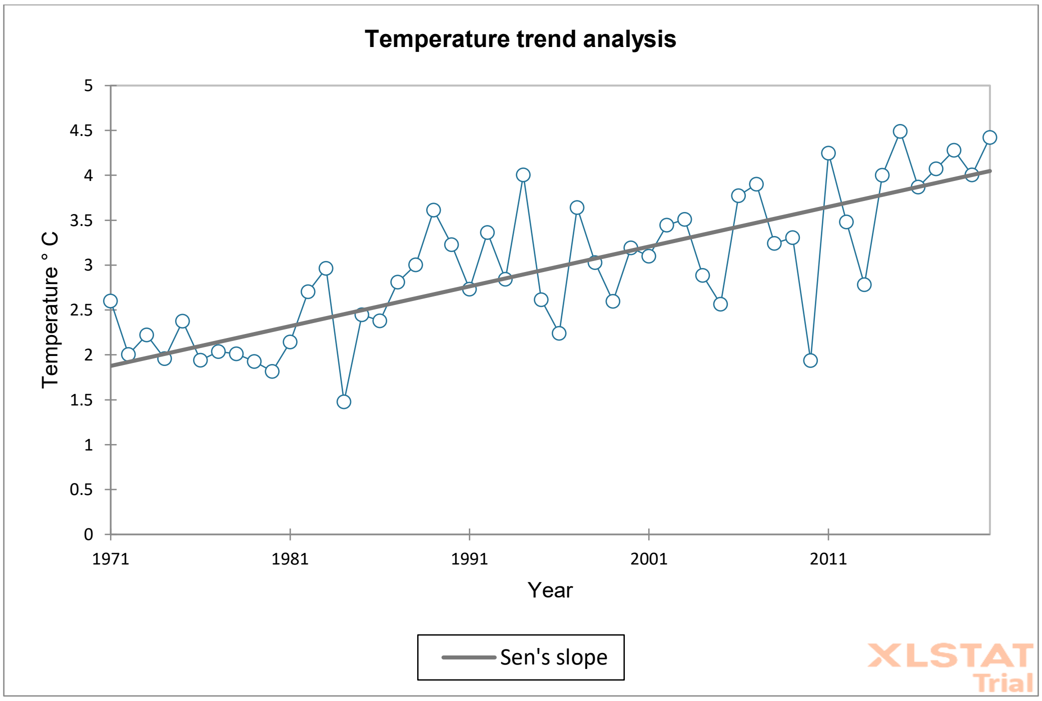


Figure 5.12 Mean annual temperature timeseries of Weissmatten.

Positive Sen's slope magnitude shows that there is an increasing trend while negative values indicate the decreasing trend (Dawood, 2017). Results (Table 5.7) shows a positive Sen's slope magnitude of 0.044, which means an increasing temperature trend in Weissmatten (1971-2020),

The calculated Sen's slope of mean annual temperature (1971-2020) shows the estimated average rate of change in temperature per unit of time (Dawood, 2017), in this case degrees Celsius per year. We can interpret this value from different aspects, 1- positive sign indicates increasing trend in mean annual temperature over the 50-year period, 2- 0.044 degrees Celsius per year represents the average annual increase in temperature over the 50-year period. In other words, on average, the temperature is estimated to have increased by 0.044 degrees Celsius each year during this time span.

5.4.3 Precipitation trend analysis

The methodology employed for trend analysis of precipitation, including the specific trend test and tools, has been thoroughly detailed in section 5.4.2, and to avoid redundancy, it is not reiterated in Section 5.4.3. The analysis involved the application of the Mann-Kendall trend test and Sen's slope non-parametric estimator, using XLSTAT.

The results of the trend analysis, as presented in Table 5.8, indicate that there is no increasing or decreasing trend in precipitation data over the Valle d'Aosta region for the period spanning 1971 to 2020. This conclusion is drawn based on the comparison of the p-value to the significance level alpha=0.05. The obtained p-value surpasses the threshold of 0.05, leading to the inability to reject the null hypothesis (H_0). Consequently, the findings suggest that there is no statistically significant trend in precipitation values over the specified time frame.

Table 5.8 Results of Mann-Kendall test by XLSTAT.

Series\Test	Kendall's tau	p-value	Sen's slope
precipitation (mm)	0.083299	0.398178	0.926727

Figure 5.13 illustrates the precipitation timeseries over Valle d'Aosta from 1971 to 2020. Upon visual inspection of the figure, it is evident that no discernible trend is observable in the precipitation data.

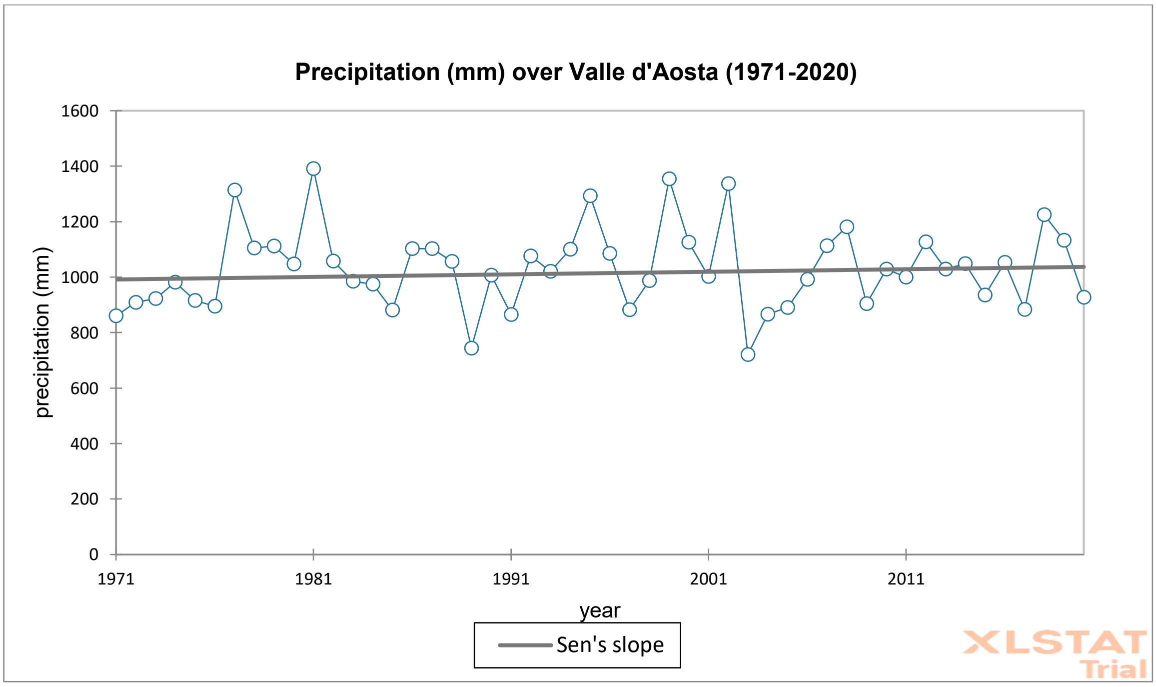


Figure 5.13 Mean annual precipitation over Valle d'Aosta.

5.5 Conclusion

Climate change is a pressing reality with potentially severe consequences if proactive measures for mitigation and adaptation are not implemented by policymakers and authorities. In the second chapter of this thesis, we aimed to elucidate the potential consequences of climate change, including global warming, increased frequency of extreme events, droughts, heightened occurrences of natural hazards such as landslides, and the potential impact on human health. These impacts can cascade into social and economic ramifications, emphasizing the critical need for effective adaptation measures.

The initial step in identifying climate change adaptation strategies is to conduct accurate and reliable climate change studies. The scale of these studies can range from global to regional, depending on the research's scope and ultimate goals. In our thesis, we undertook a comprehensive study focused on Valle d'Aosta to establish a foundation for subsequent climate change investigations in the region. This involved a meticulous analysis of reliable and authentic climate data.

Studying the climate change in Valle d'Aosta is particularly significant due to its complex topography, substantial local altitude variations, and its location in the Western Alps, housing two-thirds of Western Italian glaciers. These glaciers serve as crucial reservoirs of solid freshwater in Europe, with notable features like the Miage Glacier and the Veny Valley exhibiting dynamic glacial landscapes sensitive to climate fluctuations. The socio-economic vulnerability of the region to climate change is underscored by potential alterations in the water cycle and ice melting, leading to increased hazards such as landslides, rock avalanches, and debris flows in high mountain areas (Giardino et al., 2017).

The primary challenge faced during this thesis was obtaining consistent, reliable, and temporally extensive weather records for the region. To address this, we explored the use of alternative gridded datasets: ERA5-Land and GPCC. These open-access datasets, validated in numerous global studies, were scrutinized for their applicability to the Valle d'Aosta climate context. The evaluation revealed a moderate agreement for ERA5-Land and moderate to good agreement for GPCC with in-situ observations.

Despite their utility, certain caveats were identified. ERA5-Land is susceptible to altitude bias, which may impact results, and GPCC struggles to accurately capture extreme precipitation events. The importance of these datasets lies in their potential contribution to climate change adaptation measures, but caution is advised to prevent erroneous policies with economic and, in some cases, fatal implications.

Building on these considerations, a trend analysis was conducted for Valle d'Aosta. Utilizing ERA5-Land, a significant linear increasing trend was observed at Weissmatten station for the period 1971-2020, signaling a potential climate change alarm in the region. Conversely, GPCC indicated no discernible trend over the same period in Valle d'Aosta. It is crucial to note that this absence of trend in GPCC may be attributed to its limitations in capturing intense and short-duration precipitations, which are vital contributors to hazards like landslides in the region.

5.5.1 Remarkable findings and recommendations

In conclusion, the findings of this thesis, conducted in Valle d'Aosta and focusing on the evaluation of two widely used climate change datasets, can be summarized as follows:

1. Numerous studies highlight the uncertainty surrounding the relationship between landslides and climate change, emphasizing the need for further regional-scale investigations.
2. Despite the availability of an open-access portal for Valle d'Aosta climate data, the dataset lacks consistency and historical data, preventing the examination of long-term climate change patterns in the region.
3. The complex topography and altitude-dependent climate of Valle d'Aosta pose significant challenges for a case study, necessitating precise climate datasets for accurate analysis.
4. Various approaches, including in-situ observations, satellite images, and reanalysis models, exist for studying regional climates. However, their application in regions with significant climate variability, such as Valle d'Aosta, can be challenging.

5. Reliable in-situ observations are crucial, but in their absence, accessing reliable datasets becomes essential. Reanalysis datasets, although widely accessible, pose challenges in regional studies due to their global coverage and coarser horizontal spatial resolution.

6. The reliability of grided climate model projections can be tested as these datasets have a coarser horizontal spatial resolution to study the climate change in a regional scale. This issue matters as these studies guide adaptation actions, emphasizing the importance of economic and fatality considerations.

7. ERA5-Land and GPCC exhibit a moderate agreement with in-situ observations, serving as alternatives for regions with limited historical data like Valle d'Aosta. However, their coarse spatial resolution, especially in capturing extreme local precipitation events, presents challenges.

8. Essential climate variables like precipitation and temperature can be subject to underestimation or overestimation. ERA5-Land, despite better horizontal resolution, underestimates temperature over Valle d'Aosta and neglects altitude effects.

9. As case study results influence economic decisions, using climate models that accurately capture regional characteristics becomes crucial. Due to the absence of a consistent dataset, conducting a regional climate model for Valle d'Aosta is highly recommended.

10. The data analysis of ERA5-Land and GPCC provides insights into the limitations of gridded datasets in capturing local variations in regions with complex topography.

11. To enhance existing datasets and address biases, continuous evaluation and improvement are necessary. This is particularly important given the potential fatal and economic consequences of decisions based on these datasets.

12. The study underscores the significance of data evaluation, highlighting that datasets behave differently in various global regions and are sensitive to the spatial scale and specific climate characteristics of the study area.

13. The evaluation of ERA5-Land data can be extended to cover a broader area, encompassing the entire Valle d'Aosta, including 87 meteorological stations. Employing the same methodology outlined in the thesis, it has been demonstrated that certain stations in the region exhibit a high degree of similarity to observed data. Leveraging these stations as inputs for an interpolated spatial model across Valle d'Aosta becomes a viable approach. Through the implementation of a reliable interpolation method, a comprehensive dataset for temperature spanning from 1950 to the present can be established. This dataset would serve as a valuable resource for future climate change studies in the region.

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