ORIGINAL ARTICLE

Trend analysis of precipitation, temperature and snow water equivalent in Lombardy region, northern Italy

Hamzah Faquseh[1,2] · Giovanna Grossi[1]

Abstract

The analysis of precipitation, temperature, and snow water equivalent (SWE) trends offers a scientific approach for understanding the impacts of climate change. This paper presents a comprehensive analysis of climate change indicators in Lombardy, Italy, covering the yearly and monthly trends of precipitation and temperature from 1990 to 2020. Additionally, the yearly and monthly SWE variations. For this purpose, a range of statistical tests have been used including Mann–Kendall, Pettitt's change point detection and Sen's slope estimator. Precipitation trend shows a slight annual increase of around 5.42 mm per year. This trend is not statistically significant with a Mann–Kendall p value of 0.1448 and no changing point has been detected. Moreover, seasonal precipitation patterns show minor variations, with Kendall's Tau values ranging from -0.0431 to 0.1761. However, none of these trends are statistically significant, as reflected in Mann–Kendall p values ranging from 0.1679 to 0.7339. Conversely, Lombardy is experiencing a significant annual temperature increase of 0.0436 °C. Notably, in Autumn, temperatures rise at a rate of 0.0565° per year. Summer also shows a significant warming trend, with temperatures increasing by 0.0421° per year. In Winter and Spring, there are milder, non-significant temperature trends, with Kendall's Tau values around 0.17. SWE trend shows minor annual variations (5–10%) and monthly shifts. Winter shows a slight decrease (2–3%), implying delayed snow accumulation, while Spring indicates minor change (1–2%) suggesting earlier snowmelt. This study emphasizes temperature's strong impact on SWE and stresses the importance of climate monitoring and collaboration for understanding changing climate patterns.

Keywords Climate change · Precipitation · Temperature · Snow water equivalent

Introduction

Since the late 1700s, human activities have been steadily increasing the Earth's average surface temperature (Pachauri and Meyer 2015). Global climate change is evident through several key indicators. These include a significant increase in precipitation volume with a shifting seasonal pattern, a rising trend in both monthly and seasonal surface temperature variations, and unusual changes in snow cover extent and depth.

Between 2009 and 2018, the annual average global surface temperature experienced a significant increase of more than 1 °C compared to the preindustrial period (Von Schuckmann et al. 2020). In the lowest emissions scenario and the highest emissions scenario, respectively, it is expected that the global temperature will increase by 0.3–1.7 °C (Masson-Delmotte et al. 2021). Several studies have shown a decrease in recorded precipitation during dry seasons, considering the variations in seasonal precipitation, it is possible for arid regions to become even drier (Kumar et al. 2015). However, future projections related to climate change suggest a potential increase in precipitation (Marvel et al. 2017; Chou et al. 2013). Snow is an important resource for maintaining ecological and social systems in mountains in addition to being a source of water (Freppaz et al. 2018). Decreased snowpack water storage could lead to a negative effect on towns that depend on snowmelt as their main source of water (IPCC 2022). The decrease in worldwide snow cover will impact over 1 billion people. This is a critical issue because more

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than one-sixth of the global population relies on glaciers and seasonal snowfall to meet their water needs (Barnett et al. 2005). From 1970 to 2010, the Northern Hemisphere's snow cover decreased by 0.88 million square kilometers, a trend that aligns with the observed rise in Earth's surface temperature (Yang et al. 2013). At low latitudes across Europe, air temperature has a stronger impact on snow cover extent, while at higher elevations, precipitation significantly affects the snow cover (Diodato and Bellocchi 2020). Snow Water Equivalent (SWE) is an important factor to study the dynamics of snow and it is essential for forecasting floods, droughts (Vionnet et al. 2020) and the recharge of mountain aquifers (Lucianetti et al. 2017).

The European Alps, which cover about 1200 km, pass through the central part of the European continent, and have a significant impact on its geography. These Alpine regions are primarily shaped by snow, relying on a combination of snowfall and glacial melting to maintain their characteristics. Since 1900, the glaciers in the Alpine region have lost more than 50% of their volume due to the growing impact of climate warming. A 2–4 °C increase in global temperature by the end of the century could result in the loss of 50–90% of the ice mass contributed by mountain glaciers (Beniston 2012). A study in the Central Italian Alps discovered a notable decrease in Spring SWE between 1965 and 2007 (Bocchiola and Diolaiuti 2009). Alpine regions make up 35% of the basin of the Po River system and generate on average 53% of the overall discharge. The effects of climate change may have accelerated the melting of glaciers and snow in the Alps, potentially resulting in higher springtime discharges in the Po River (Ninfo et al. 2018). The Po River is the longest river in Italy with a length of 652 km from the Cottian Alps to the Adriatic Sea, its basin covers over 71,000 km^2, which belongs to 3200 municipalities in 7 regions. The Po River basin experiences diverse precipitation patterns because of the complex hydrological system influenced by various climates from the Mediterranean, Continental, Atlantic, and Polar regions (Turco et al. 2013). In the basin, a study observed rising temperatures but no annual trends in precipitation or discharge (Turco et al. 2013). The complex climate and topography of the Po basin make it difficult to study the water cycle and its changes. Therefore, a more practical approach is to assess the basin regionally.

Lombardy is a significant region in the Po basin, it is the first in Italy in terms of both population and population density and the fourth in terms of surface area. Precipitation, temperature, and snow cover are essential variables in climate science and hydrology used to measure the extent and degree of climate change and variability (Birch 2014). In recent decades, Lombardy has experienced notable shifts in temperature, precipitation, and extreme weather events and these changes are part of broader global trends. The results of a previous study in the area indicate a significant decrease

in the number of rainy days per year, along with an increase in both average and maximum daily precipitation levels. Additionally, there is an overall increase in the frequency of dry days occurring between wet days (Todeschini 2011). Since the early 1980s, temperatures in the Alps have risen over 1 °C, doubling the impact of global climate changes (Diaz and Bradley 1997). A previous study examined data from 1850 to the present and identified a gradual decrease in cumulative annual precipitation. This decrease amounts to approximately − 5% per century, and it has become more noticeable in recent decades, indicating a reduction of about $2.0 \pm 2.4\%$ compared to the overall average for the entire study period (Todeschini 2011). Snow coverage analysis is a necessity in this region, given that 40% of the area is mountainous. Between 1991 and 2003, the region experienced a 25 km^2 reduction in snow cover, primarily due to rising temperatures rather than changes in precipitation (Diolaiuti et al. 2012). Satellite observations of snow cover records indicate a consistent trend of decline, particularly during the Spring season (Kunkel et al. 2016). Studying climate parameter trends till a recent date helps to better understand the local climate and identify signs of climate change in the region.

Precipitation, temperature, and snow cover are essential climatic factors that have a significant impact on various aspects of human health, ecological systems, and the diversity of organisms. Changes in these patterns can have significant effects on the complex relationships within (Önöz and Bayazit 2003). Studying precipitation patterns is essential because they impact drought and flood risks, affecting water resources, infrastructure, economies, and ecosystems (Tabari 2020; Faquseh and Grossi 2023). On the other hand, the variation in temperatures in metropolitan areas mostly has an impact on residents, health, finances, and quality of life (Leal Filho et al. 2022). Moreover, SWE variation matters because it affects water supply, ecosystems, and various activities like Winter sports and tourism (Żemła 2021). These shows the importance of carrying the study on the region as Lombardy holds importance for its economic, cultural, historical, and agricultural significance, as well as its contributions to education, tourism, and political influence in Italy. The study aims to analyze the climate change indicators in Lombardy, focusing on precipitation variations and temperature trends over the years and seasons from 1990 to 2020. Additionally, it will analyze the total yearly and monthly SWE in the region during the snow melting and accumulation periods which comes from eight mountain basins in Lombardy, specifically Adda Lacuale, Adda Prelacuale, Serio, Brembo, Chiese, Mera, Mincio, and Oglio, from 2006 to 2019. Analyzing these parameters works as indicators of the region's climate change and shows the essential need for collaboration in addressing both local and global climate issues. The scientific approach uses various statistical tests to analyze hydrological and hydrometeorological trends over time,

including both parametric and non-parametric methods. The Mann–Kendall test and the Sen's slope estimator test were employed in this study to identify and analyze trends. These statistical methods are widely recognized for their effectiveness in detecting and quantifying trends in time series data (Dahmen and Hall 1990; Chen et al. 2007). The Mann–Kendall test is a method used to identify consistent trends in data, even when the data's distribution is uncertain. Sen's slope estimator is a reliable way to measure the strength and direction of these trends.

Study area

Lombardy region, located in the northwest of Italy, consists of twelve provinces and is home to a population of 10,060,574 people. The region covers approximately 238,623 km^2, with mountains making up 40.5% of the land, followed by plains at 47.1%, and hills at 12.4%. The region is located between the Alps Mountain range and the Po River's tributaries. The highest point in Lombardy is the secondary peak of Piz Bernina, reaching an elevation of 4020 m. Lombardy has a temperate continental climate, with cold winters and hot summers. The average daily high temperature in Lombardy is 16 °C. July is the warmest month, with an average temperature of 29 °C, and January is the coldest, with an average temperature of 4 °C. The region records an annual precipitation of 947 mm (Fazzini et al. 2020). Figure 1 shows the location of region within Italy. The analysis of the precipitation and temperature of this study was carried out on the whole region.

Lombardy's hydrography is complex, given the presence of various basins. The region has experience rapid climate change since the beginning of the industrial age, characterized by increased temperatures, shifts in precipitation patterns, decreasing in snow cover and a greater frequency and severity of extreme weather events, including heatwaves and droughts (Choler 2015). The main water resources come from the lakes, rivers (including the Po River), groundwater reservoirs, and seasonal snowfall, which contributes to its SWE (Regione Lombardia 2015). The mountainous area in the northeastern region significantly contributes to the SWE. This study focuses on analyzing the total SWE in the region, specifically from the eight basins shown in Fig. 2.

Methodology

Data

The study used monthly precipitation and temperature data from 1990 to 2020, obtained from ERA5. ERA5, which is the fifth edition of the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis, provides
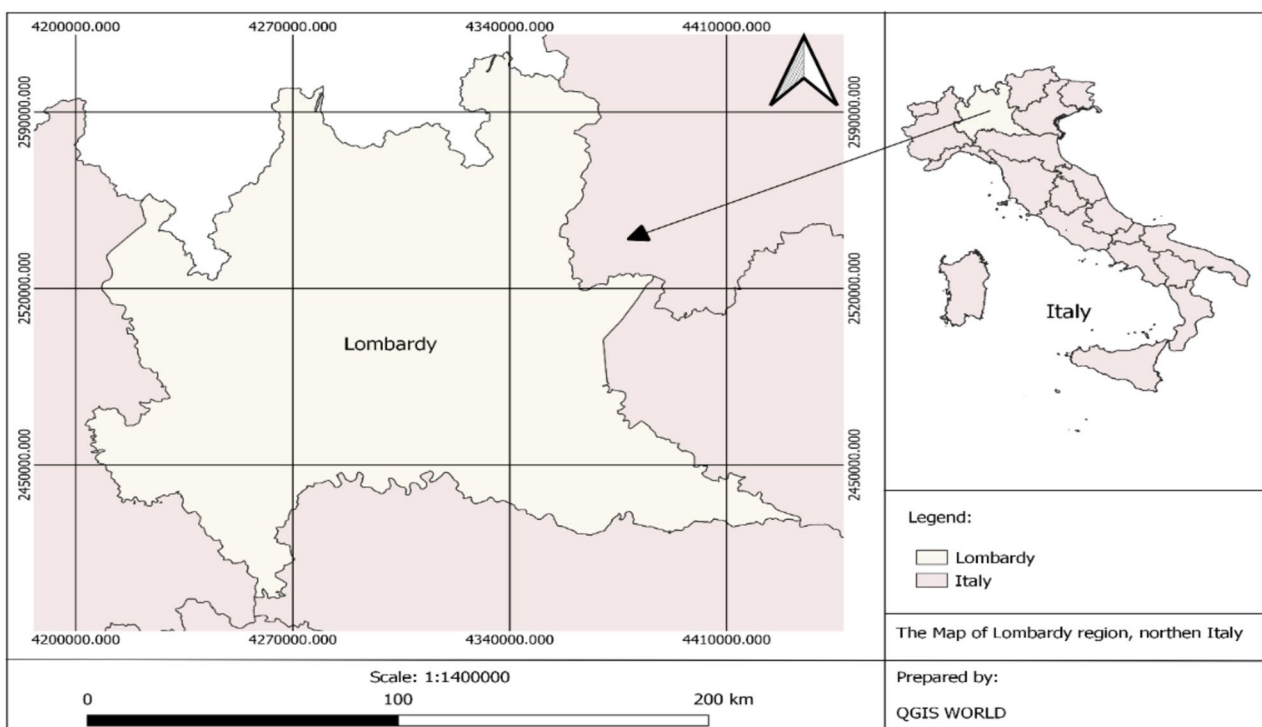

Fig. 1 The location and the boundary of Lombardy region
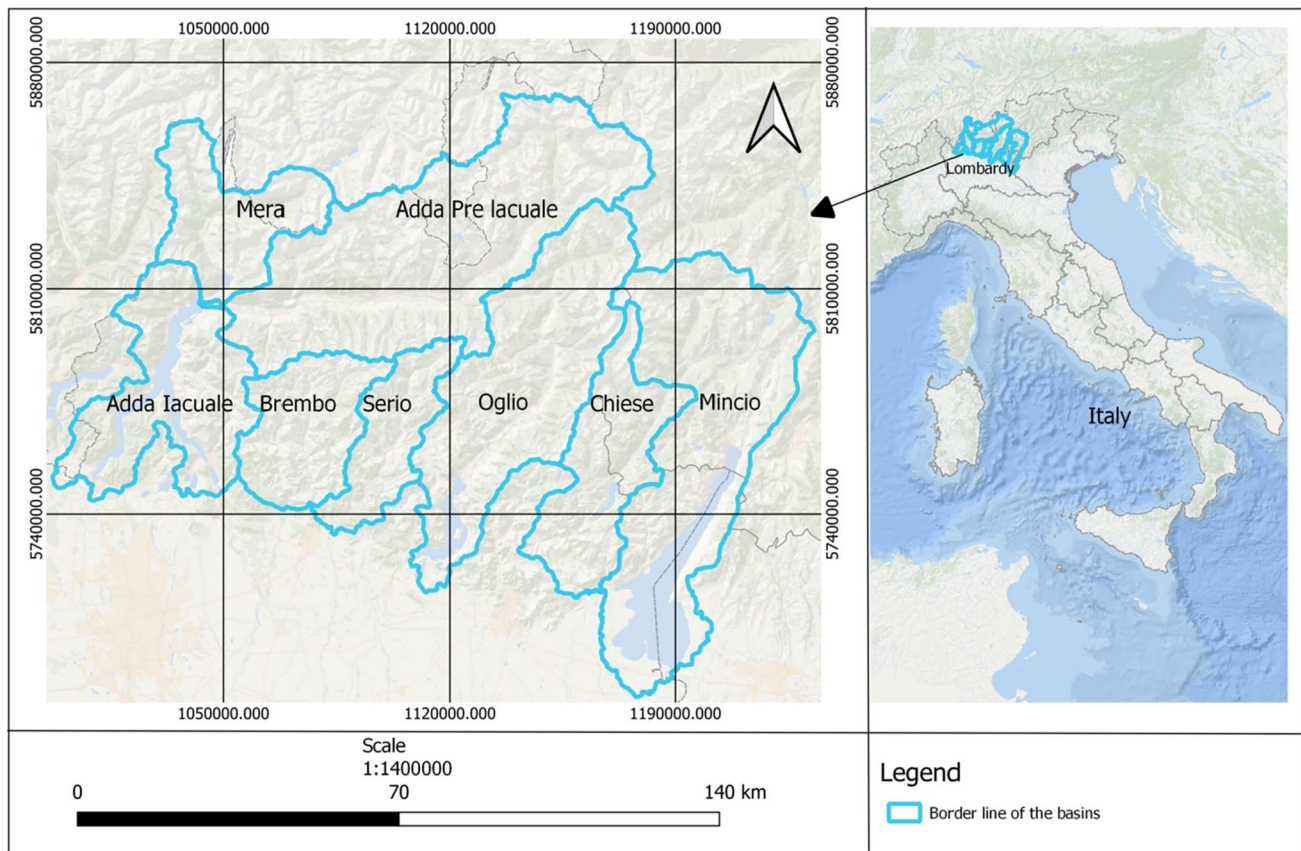
Fig. 2 The basins boundaries in Lombardy region considered for SWE analysis

information about the global climate over the past 8 decades (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form). Since 2004, the Regional Agency for Environmental Protection of Lombardy (ARPA Lombardy) has been responsible for monitoring the basins to assess water resource availability. ARPA uses a simplified approach to estimate SWE in each basin within the region. This approach considers snow melting and accumulation and provides weekly measurements on a 100×100 m grid (Bellingeri et al. 2006). ARPA publishes weekly bulletins on their website (https://www.arpalombardia.it/) of SWE data for the studied basins. These bulletins provide data starting from either November or December of the previous year and continue through June or July of the current year. The data are expressed in millions of cubic meters. This study is analyzing the total SWE in the region that are coming from the eight basins.

Climate parameter trend analysis

Climate parameters trend analysis, a widely used method in previous research, involves the examination of long-term data to identify patterns, changes, and shifts in various climate-related parameters (Mudelsee 2019; Jaiswal et al. 2015). Statistical techniques are commonly used in climate parameters trend analysis to quantify and visualize these trends. These techniques help to identify whether there are statistically significant shifts in the data, whether it is an increase or decrease in temperature, changes in precipitation patterns, or variations in snowpack accumulation and melting. In the study of the Lombardy region, the focus was on analyzing seasonal and yearly precipitation and temperature data. Additionally, the analysis covered the total monthly SWE during the snow accumulation and melting period, which was from December to June. In this study, statistical techniques like the Mann–Kendall test, Pettitt's change point detection test, and Sen's slope estimator test were used to identify and analyze the trends. These methods helped understand climate variable evolution and detect significant changes over time.

Mann–Kendall test

The Mann–Kendall test is a statistical tool created by statisticians Mann and Kendall in the 1940s and 1950s commonly used to identify upward trends, downward trends, or the

absence of trends in time series data (Kendall 1975; Mann 1945). The test is widely applied in various fields, including climate science, hydrology, environmental monitoring, economics, and more (Yue and Wang 2004). It analyzes data without assuming a specific distribution, making it a good choice for datasets that do not follow a normal distribution (Tabari et al. 2011). The Mann–Kendall test can be easily applied to time series data in Python using libraries like SciPy. These libraries offer functions that compute Kendall's Tau and provide p values, streamlining trend analysis. In this study, the Mann–Kendall test was calculated using the Python programming, the test functions use common inputs: data, an alpha value that shows the significance of the trend (in this study is 0.05), and a period, which can be monthly, seasonal, or yearly. The presence and the characteristics of the trends within the dataset are evaluated by computing Kendall's Tau (τ), a measure that quantifies the alignment of data point pairs in either a concordant or discordant manner. Kendall's Tau (τ) measures both the strength and direction of the relationship between data points. A positive τ indicates an increasing trend in time series data, while a negative τ suggests a decreasing trend. Subsequently, the test statistic (S) is derived from τ in conjunction with its variance (Var(τ)). To ascertain the significance of the observed trend, the standardized test statistic (Z) is computed by dividing S by the square root of Var(τ). The final step involves calculating the p value using the standard normal distribution and cumulative distribution function. The p value helps determine if the observed trend in data is statistically significant or not. A low p value (typically < 0.05) indicates a statistically significant trend (increasing or decreasing), while a large p value suggests no significant trend.

Pettitt's change point detection test

The Pettitt's change point detection test, introduced by Pettitt, is a non-parametric statistical method specifically used for identifying significant changes or breakpoints in time series data (Pettitt 1979). It identifies points in the data where significant shifts occur and it works by calculating a test statistic, comparing it to a critical value, and determining if a change point exists. Pettitt's change point detection test is a valuable tool for pinpointing sudden shifts in climate, precipitation, and temperature data and it has been widely used for this purpose (Drápela and Drápelová 2011; Winingaard et al. 2003). In this study, Python programming language is used to apply Pettitt's Change Point Detection Test on the data. In Python, the test can be performed on time series data using libraries like NumPy and SciPy. The first step is to upload the time series data, then the application of Pettitt's test using the library function to calculate Kendall's tau. The test statistic is compared to a critical value (in this study of 0.05) from the Pettitt distribution, and if it exceeds this value, it indicates a statistically significant change point in the data.

Sen's slope estimator test

Sen's slope estimator is a statistical method for estimating the slope of a linear relationship between two variables. Sen's slope estimator is commonly used in hydrology and climatology for trend analysis in various datasets (Sam et al. 2022; Jiqin et al. 2023). The slope represents the rate of change over time: positive slopes indicate increasing trends, negative slopes suggest decreasing trends, and slopes near zero indicate stability or no significant trend. In this study, the Sen's slope estimator test is applied in Python to identify the trends magnitude. In the Python implementation, the necessary libraries, including NumPy and SciPy, were imported. Following that, a custom function was created to calculate the Sen's slope estimator, which computed all possible slopes between data points and returned the median slope as the estimate. Afterward, the function was applied to the dataset to obtain the trend estimate.

Results

Precipitation trend

The analysis of the yearly precipitation data in Lombardy region suggests a minor upward trend in annual precipitation, indicated by Kendall's Tau (τ) value of 0.1871 and Sen's slope of 5.4214 mm per year. However, it's important to highlight that this trend lacks statistical significance, as evident from the Mann–Kendall p value of 0.1448. Additionally, the Pettitt's Change Point Test with a p value of 2.0 does not identify any significant change point in the dataset. Figure 3 shows the annual precipitation trend in Lombardy from 1990 to 2020. While there is a slight suggestion of an increasing trend in yearly precipitation, the statistical tests demonstrate that this trend lacks statistical significance. Lombardy's seasonal precipitation data shows no significant trends or changes across all four seasons including Autumn, Winter, Spring, and Summer shown in Fig. 4. In the Autumn season, the results show a Kendall's Tau (τ) that suggests a minor negative trend at − 0.0431, but the high Mann–Kendall p value of 0.7339 indicates a lack of statistical significance. Sen's slope at − 0.1175 supports a non-significant trend. Additionally, Pettitt's Change Point Test returns a non-significant p value of 1.9444, confirming the absence of a statistically significant change point. In Winter, there's a minor positive trend with Kendall's Tau value of 0.1613, but it's not statistically significant as the p value is 0.2104. Sen's slope shows a result of 0.7619 aligns with this non-significant trend, and Pettitt's Change Point Test results shows
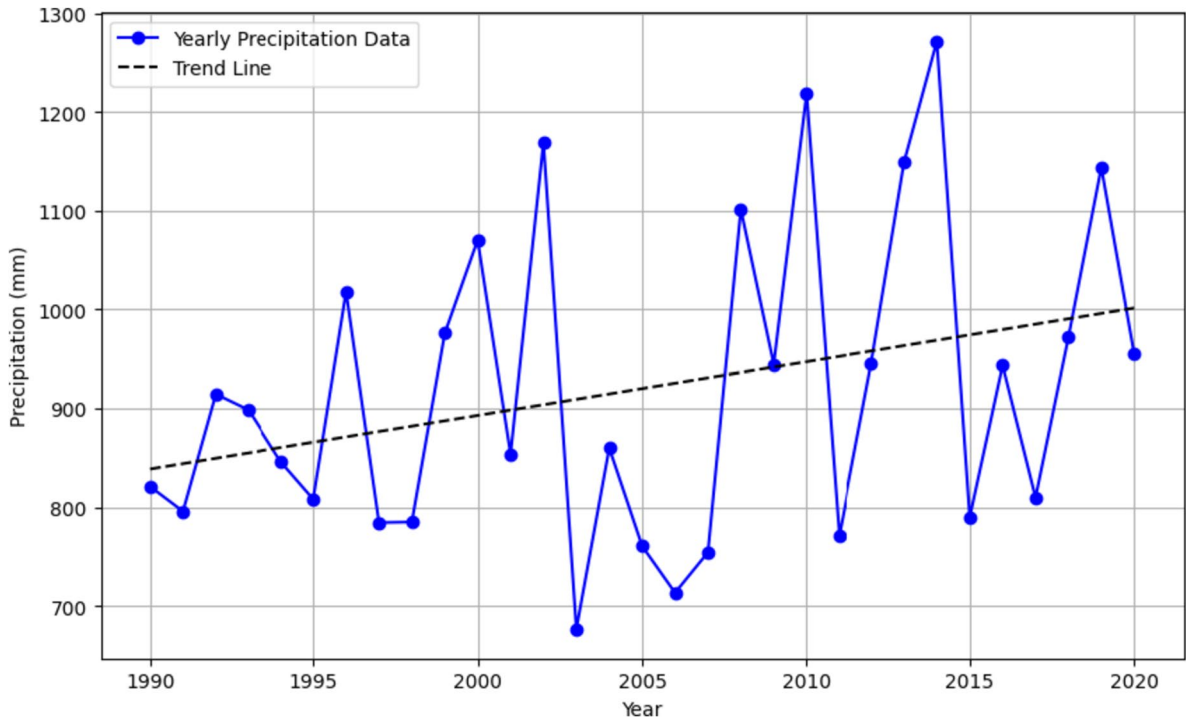
Fig. 3 The annual precipitation trend in Lombardy from 1990 to 2020
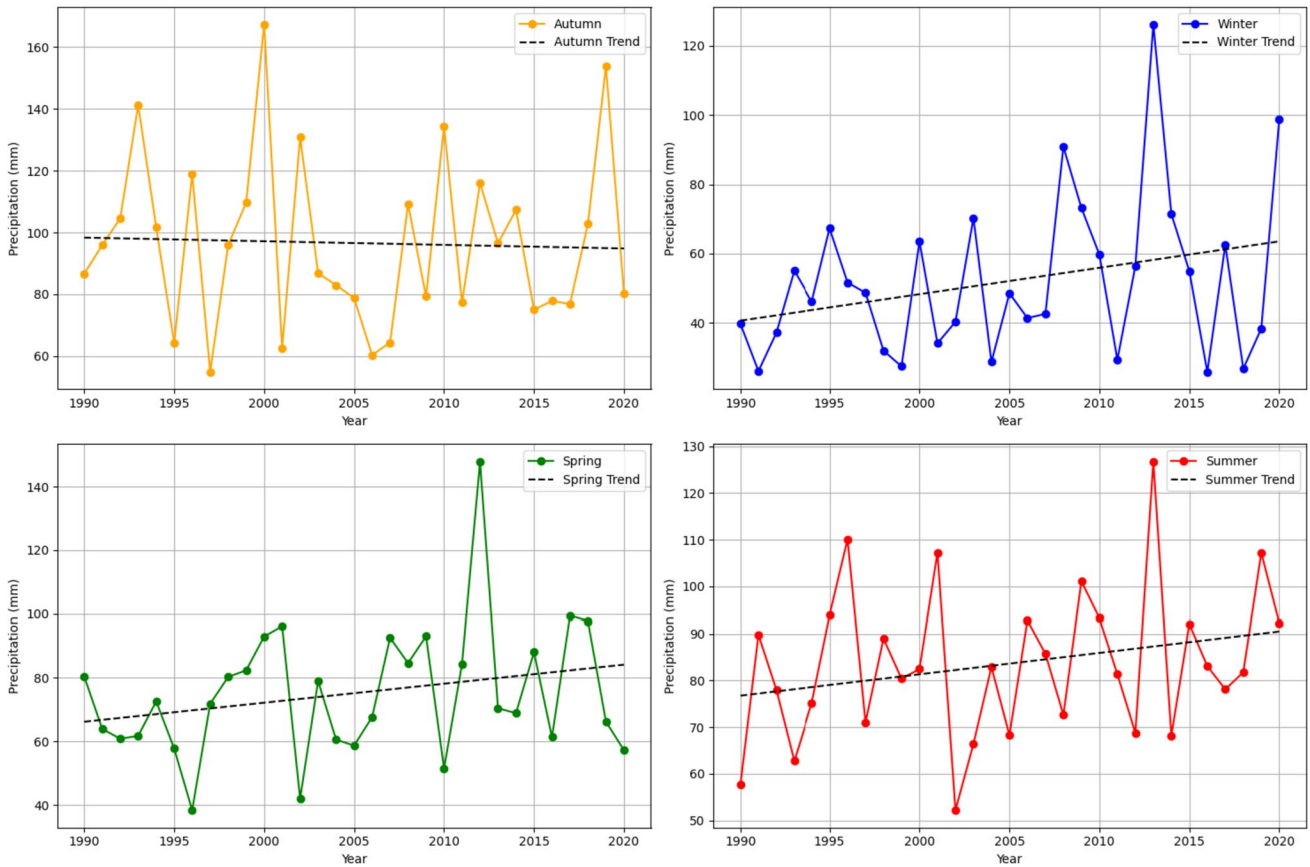

Fig. 4 The seasonal precipitation trend in Lombardy from 1990 to 2020

a *p* value of 1.9118 confirms the absence of a significant change point. In Lombardy's Spring and Summer seasons, the results indicate a lack of significant precipitation trends or change points. For Spring, Kendall's Tau value is 0.1570 that shows a minor positive trend, but it's not statistically significant as the *p* value is 0.2231. Sen's slope shows a result of 0.5990 that supports this non-significant trend, and Pettitt's Change Point Test shows a *p* value of 1.9373 confirms the absence of significant change points. In Summer, the pattern continues with Kendall's Tau of 0.1656, a non-significant Mann–Kendall *p* value of 0.1982, Sen's Slope of 0.4572, and a non-significant Pettitt's Change Point Test with a *p* value of 1.7946. These results indicate that Lombardy's seasonal precipitation patterns have remained constant and without significant changes or trends throughout the study period.

Temperature trend

The trend analysis of the yearly average temperature in Lombardy shows a clear and significant warming pattern shown in Fig. 5. With Kendall's Tau at 0.5182 and a Mann–Kendall *p* value of 0.0001, this trend is both strong and statistically significant. Sen's slope of 0.0436° per year, quantifies the rate of temperature increase, confirming a steady upward trend. However, Pettitt's Change Point Test did not detect a significant change point, as indicated by the *p* value of 1.0285. This means that the temperature

increase appears to be relatively consistent over the analyzed period. The analysis strongly supports that Lombardy is experiencing a significant and statistical annual temperature increase. The trend analysis of mean seasonal temperatures shown in Fig. 6 in Lombardy presents significant scientific observations. During the Autumn season, there is a clear and statistically significant warming trend, with a Kendall's Tau (*τ*) of 0.4065, a low Mann–Kendall *p* value of 0.0015, and Sen's slope of 0.0565, all indicating substantial temperature increases. Winter and Spring show mild positive temperature trends. For Winter, the Kendall's Tau is 0.1737, and the Sen's slope is 0.0485. For Spring, the Kendall's Tau is 0.1761, and the Sen's slope is 0.0245. However, these trends are not statistically significant, with Mann–Kendall *p* value of 0.1733 for Winter and 0.1679 for Spring. The Pettitt's Change Point Test also does not identify any significant temperature changes during these seasons. In Lombardy's Summer season, there is a significant warming trend. Kendall's Tau is 0.3319, with a Mann–Kendall *p* value of 0.0100, indicating a clear upward temperature trend. The Sen's slope is 0.0421, and although Pettitt's Change Point Test does not detect significant changes, the Mann–Kendall result highlights the region's consistent warming during the Summer months. Overall, Lombardy experiences a noteworthy warming trend in Autumn and Summer, while Winter and Spring exhibit milder, non-significant temperature trends.
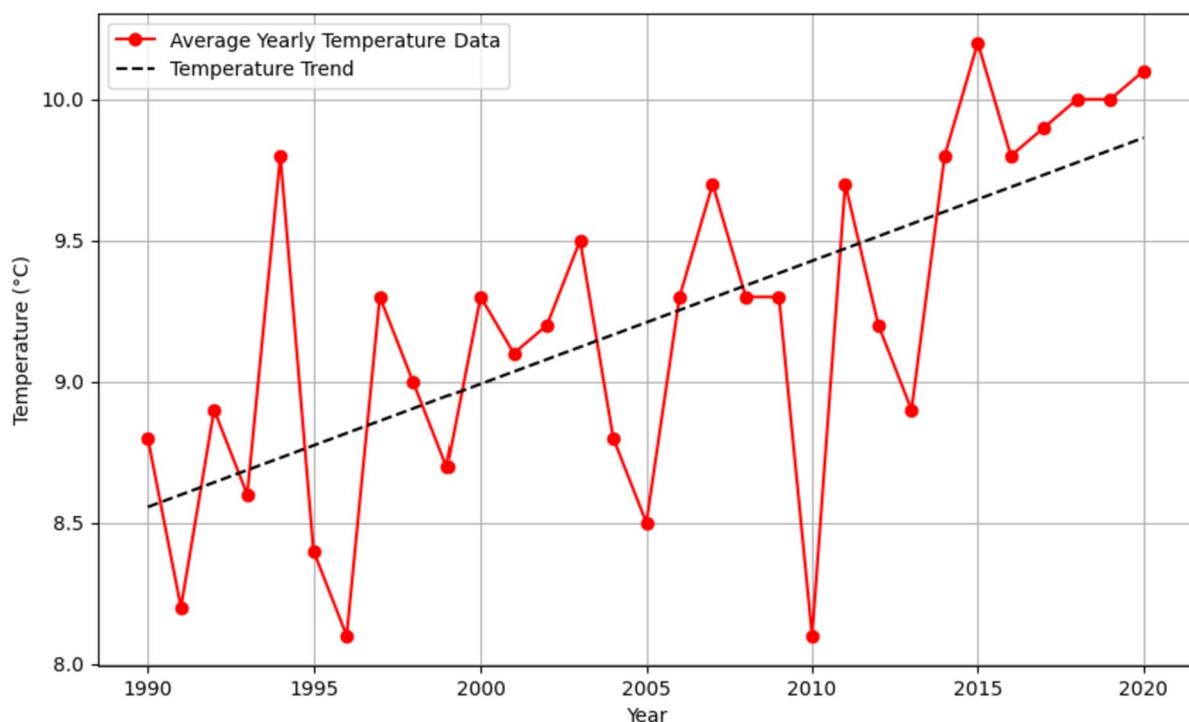

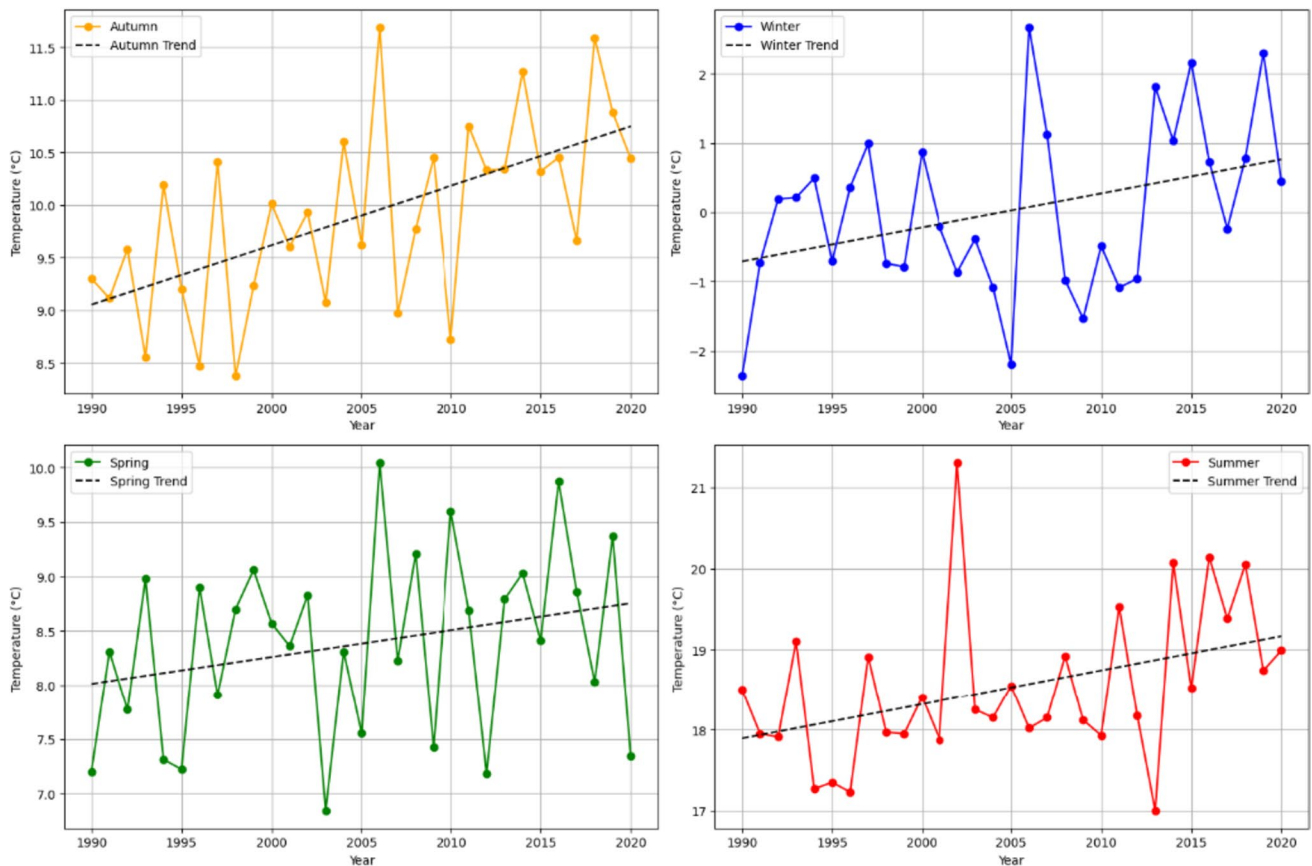**Fig. 5** The Annual temperature trend in Lombardy from 1990 to 2020

Fig. 6 The seasonal temperature trend in Lombardy from 1990 to 2020

SWE trend

The analysis aimed to evaluate the average SWE in the region, considering the period from December to June in the years from 2006 to 2019. Analyzing the mean SWE values during these months clarifies the timing and patterns of snowpack accumulation and melting as shown in Fig. 7. The curves show how SWE values gradually increase starting from December and reach their maximum in between March and April, marking the peak of the accumulation season. Subsequently, these values progressively decrease for the remainder of the reference year during the melting season. SWE curves provide a clear visual representation of snowpack accumulation and melting patterns, helping to check the trend of monthly SWE values.

The trend analysis of SWE values in the Lombardy region has been performed, focusing on a 15-year dataset. It's important to note that the relatively short time span of this analysis introduces some uncertainties into the findings due to the limited data available. Nonetheless, the available data for this region is instrumental for understanding the trends in SWE over the years. The yearly trend analysis indicates a minor positive trend with a Kendall's Tau of 0.0330

and a Sen's slope of 37.5108. However, these findings lack statistical significance, as reflected in the Mann–Kendall p value of 0.9145, suggesting no clear trend. The Pettitt's Change Point Test also fails to identify significant shifts. The monthly trend analysis of SWE suggests a mix of weak and non-significant trends in SWE values in Lombardy. While some months show positive or negative trends, only June exhibits a statistically significant positive trend. Negative Tau values indicate a decreasing trend, indicating a decline in SWE over time, while positive Tau values indicate an increasing trend, indicating a rise in SWE. Notably, in December, January, February, March, and April, Kendall's Tau values range from − 0.0110 to − 0.0989, implying weak negative trends, though none are statistically significant with high Mann–Kendall p value above 0.6. Sen's slope in these months is likewise moderate but lacks significance. The Pettitt's Change Point Test yields non-significant results, indicating no abrupt shifts. In contrast, May, and June present different results. May shows a stronger positive trend with Kendall's Tau of 0.1429 and with a Sen's slope of 18.6106, but it remains non-significant. June stands out as the only month with a significant positive trend with a Kendall's Tau value of 0.4066 and a notable Sen's slope of 28.8195,
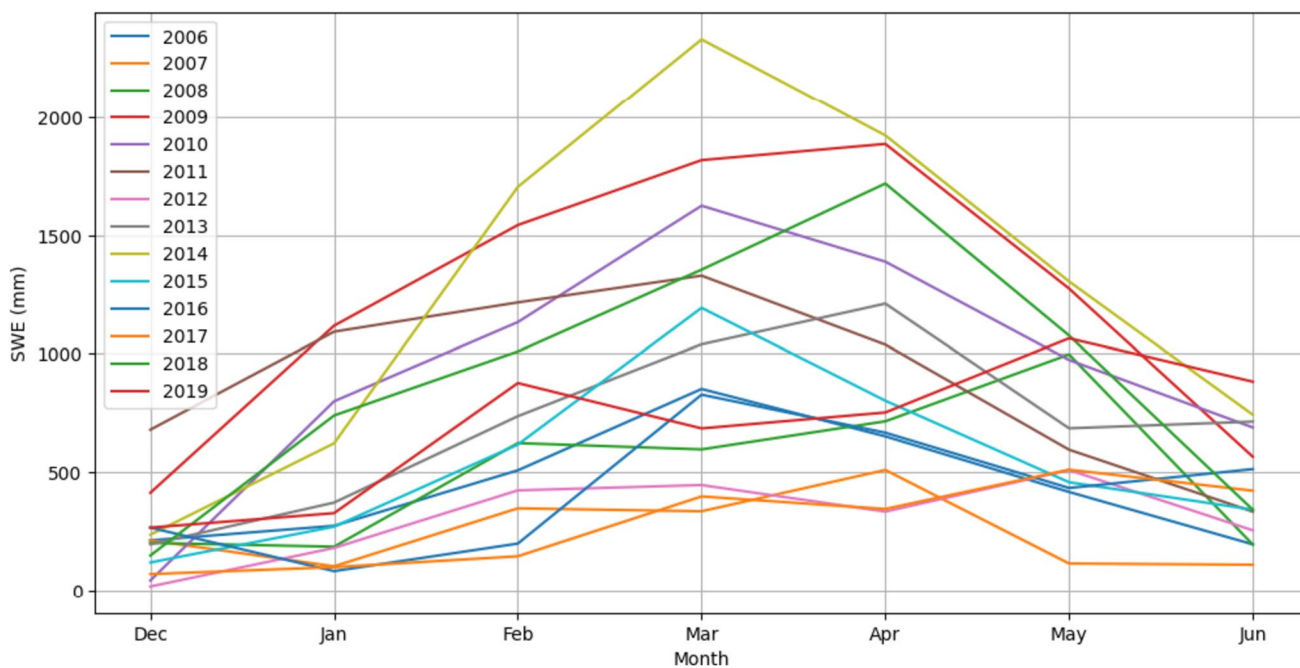
Fig. 7 The mean SWE in the Lombardy region for each month in the period from December to June

supported by a Mann–Kendall *p* value of 0.0472. However, even in June, Pettitt's Change Point Test remains non-significant. The results of the monthly analysis of SWE are shown in Table 1. Overall, December, January, and February exhibit weak negative trends, implying potential delays in snow accumulation. Conversely, March, April, and June demonstrate positive trends, indicating earlier snowmelt, with June showing a significant positive trend. Figure 8 shows the yearly and monthly (Dec–Jun) SWE trends in Lombardy from 2006 to 2019.

Discussion

Studying the climate's impact on the Alps is important to protect this exceptional and environmentally significant area. The Alps shows a stable annual precipitation pattern (Marty 2008), while more significant warming, especially

during summers, since 1970. This warming, consistent with global trends, has become even more clear since the early 1980s, exceeding a 1 °C increase which is twice of the global average (Casty et al. 2005; Bocchiola and Diolaiuti 2009; Diaz and Bradley 1997). Snow cover in the Alps is a critical aspect of study. Past research highlights a substantial decrease in snow cover duration and decline in SWE values (Matiu et al. 2021; Marty et al. 2017). Lombardy, a key region in its area, has been the subject of several research. One study on drought patterns indicates that precipitation in Lombardy remains relatively stable (Gandolfi et al. 2020). Additionally, another research in the Lombardy mountains reveals a notable variation in the average annual temperature, with a range of up to 1.37 °C, compared to the global average of +0.56 °C (Diolaiuti et al. 2012). This study shows that the increase in yearly average temperatures leads to changes in local climate patterns, particularly affecting elements like snow and SWE in the region.

Table 1 The results of monthly (Dec–Jun) SWE trend analysis tests during the period 2006 to 2019

Test	Values	Dec	Jan	Feb	Mar	Apr	May	Jun
Mann–Kendall	Tau	− 0.0556	− 0.0989	− 0.0330	− 0.0110	0.0549	0.1429	0.4066
	p value	0.7837	0.6672	0.9145	1.0000	0.8299	0.5183	0.0472
	Significant	No	No	No	No	No	No	Yes
Pettitt's change point detection	*p* value	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000	2.0000
	Significant	No	No	No	No	No	No	No
Sen's slope	Slope	− 6.5778	− 9.2083	− 5.3756	3.9110	7.3379	18.6106	28.8195

Fig. 8 The yearly and monthly (Dec–Jun) SWE trends in Lombardy from 2006 to 2019

The results of this work show notable trends in precipitation, temperature, and SWE in Lombardy, highlighting the region's changing climate dynamics. An upward trend in annual precipitation is evident, but its statistical significance is lacking, highlighting the need for a careful interpretation of any increase in rainfall in the region. Seasonal analyses further demonstrate the constancy of precipitation patterns across all seasons. While these trends in annual and seasonal precipitation may lack statistical significance, the changing precipitation patterns still have a variety of effects, including droughts, floods, impacts on agriculture, and public health concerns. The increasing trend of precipitation can be addressed with flood preparation, water management, farming and infrastructure adaptation, community education,

ecosystem conservation. Conversely, Lombardy is facing a notable and consistent warming trend, especially in Autumn and Summer. These changes have major local implications, including adjustments in farming and increased energy use in warmer months. To address increasing temperatures, adapt agriculture, improve energy efficiency, manage water resources, protect ecosystems, enhance public health measures, plan resilient cities, invest in renewable energy, and educate about climate change. The SWE trends, although derived from a relatively short dataset, provide observations into the dynamics of snow accumulation, and melt in Lombardy. While the yearly trends indicate minor changes in SWE, the monthly analysis shows the shifts of the different patterns of the snow. During the Winter months, minor negative trends in SWE without statistical significance suggest a delay in snow accumulation. Conversely, in Spring months, non-significant positive trends indicate an earlier snowmelt. During the Winter season, a Pearson correlation analysis was performed to provide a better understanding of the

relationships between these parameters. The results revealed correlation coefficients of 0.520, indicating a moderate positive relationship between SWE and precipitation, and − 0.682, signifying a strong negative relationship between SWE and temperature. These results show that temperature has a more significant influence on SWE than Precipitation during the Winter period. During the Spring season, the same analysis has been done and the results showed a weak positive relationship of 0.300 between SWE and precipitation, suggesting a mild connection. In contrast, there was a moderate negative relationship of − 0.471 between SWE and temperature, indicating that Temperature has a more pronounced influence on SWE during the Spring period. Figure 9 shows the relation between the parameters in the two seasons, and this shows as the temperature increases this will negatively affect the SWE. The change in SWE may have significant effects on water availability, particularly in regions reliant on snowmelt for freshwater resources. Managing these changes involves monitoring SWE trends,
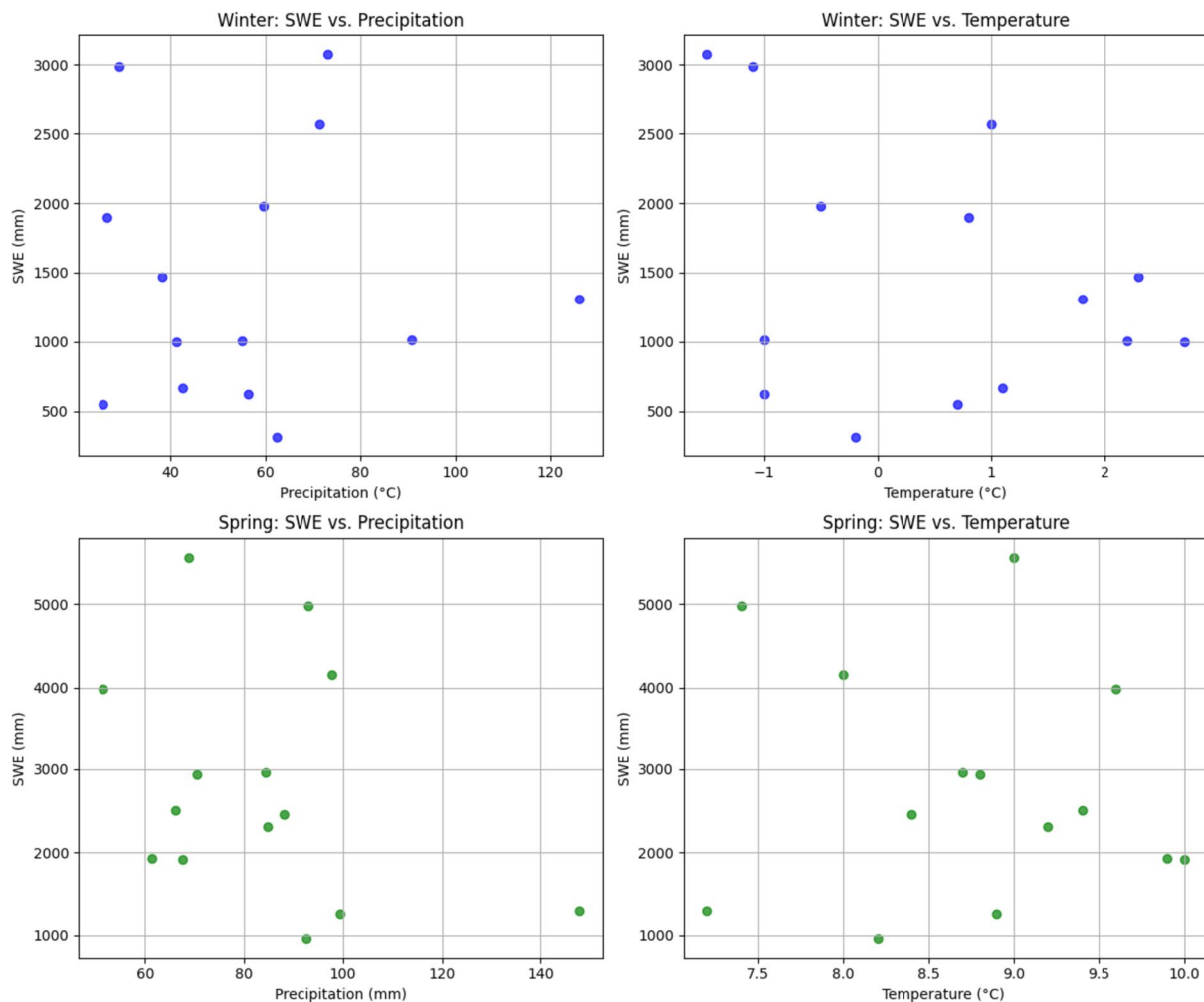

Fig. 9 The relation between precipitation, temperature and SWE for the Winter and Spring seasons from 2006 to 2019

improving water resource management, and planning for potential shifts in water supply timing. Adaptation strategies may include implementing efficient water storage and adjusting agricultural practices.

Conclusion

This study analyzed climate data of Lombardy region, specifically focusing on annual and seasonal precipitation and temperature trends from 1990 to 2020. In addition, it analyzed data about the total annual and monthly SWE from 2006 to 2019. This analysis aimed to provide a clearer understanding of how the climate in the region is changing. Annual precipitation patterns in Lombardy show a slight increase of about 5.42 mm per year. However, it is essential to emphasize that this trend is not statistically significant, as indicated by a Mann–Kendall p value of 0.1448. The seasonal analysis of precipitation trends across all four seasons, including Autumn, Winter, Spring, and Summer, showed no significant shifts. The increased precipitation, with its potential benefits and risks, underscores the importance of effective management and adaptation strategies. Conversely, the region is experiencing a clearer warming trend, with a significant rise in annual average temperatures of 0.0436 °C per year. In Autumn, there is a substantial warming trend, with an increase of 0.0565° per year, indicating a significant shift in temperatures during this season. During the Summer season, there is a significant warming trend, with temperatures rising by 0.0421° per year, confirmed by a Mann–Kendall p value of 0.0100. These trends have important effects, requiring changes in agriculture practices and adaptation measures like sustainable urban planning and renewable energy investments. Over the year, SWE shows minor changes (5–10% variation). Winter exhibits a slight trend of reduced SWE (2–3% decrease), implying delayed snow accumulation. Spring shows minor variations (1–2%). However, June stands out with a significant trend of earlier snowmelt (6–8% increase). Temperature significantly influences SWE, particularly in Winter, with a 5–7% decrease for every 1 °C increase. In Spring, precipitation has a weak impact (1–2% variation), while temperature moderately affects SWE (3–4% decrease for every 1 °C increase). These trends indicate shifts in snowpack and melting patterns, which may affect water resources, and require adaptive water management. Finally, Lombardy requires ongoing climate monitoring and adaptable strategies due to increasing extreme weather events from climate change. Effective water resource management is essential to address these challenges for a sustainable future.

Declarations

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