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Sustainable practices in the chemical industry: Insights from EU Taxonomy reporting

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ABSTRACT: This research looks at the corporate sustainable revenues, operational expenses and capital expenses to understand how they are linked to the broader sustainability strategy of corporations. We look at publicly listed companies in the chemical sector, within the context of the EU Taxonomy regulation. The objective of our research is to gather and examine data on economic activities in accordance with the EU Taxonomy regulation. We specifically concentrate on the revenues, capital expenditures (CAPEX), and operating expenditures (OPEX) associated with eligible and aligned operations. We used Python module to create an automated procedure for obtaining EU Taxonomy data from PDF reports of major corporations. Our findings suggest that aligned activities make up just a tiny portion of the total turnover, CAPEX and OPEX in the chemical industry. We then analyze the challenges faced by the chemical industry in transforming their operations to foster sustainability. Our findings not only provide a detailed view on the economic activities of chemical companies but also enhances the comprehension of how reporting disclosure could provide more information for policy makers to support the implementation of sustainable policies.

KEYWORDS: sustainability, chemical industry, EU Taxonomy, ESG, annual reporting

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1. INTRODUCTION

The chemical industry plays a crucial role in the global markets by producing raw materials that are requested by a wide range of companies operating in different industries and sectors. Despite this, the chemical industry is also a significant contributor to the greenhouse gas emissions generated in the atmosphere. With the increase concerns on climate change impacts and the need to have more stringent climate-oriented regulations such as COP27 and the EU taxonomy, the chemical industries need to undergo significant transformation to adjust their operations towards more sustainable practices. This needs to be seen on the wider perspectives as chemical companies will have to make some tradeoffs between protecting the environment and responding to changing market demands. Chemical companies need to lower their environmental footprint while simultaneously increasing profitability and preserving a competitive edge in the market by focusing on innovative and sustainable products and technologies. In this area, we mention notable developments in circular economy (Wiprächtiger & Hellweg, 2024), technical advancements, calculating the product carbon footprint for their chemical products (Solvay, 2023) or blockchain tracking of raw materials (Bacchetta et al., 2021).

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In light of the new EU Taxonomy regulation, companies face a new compliance regulation in order to asses if their economic activities are sustainable. The regulation, part of the EU efforts to fulfill the European Green Deal has as objective the creation of a shared common classification for sustainable activities. Moreover, it cans also be used as a tool for companies and investors to make sustainable decisions. Using key performance indicators like turnover, capital expenditures (CapEx), and operational expenditures (OpEx), chemical businesses are required to reveal their efforts to promote sustainability in accordance with the regulation. Companies are able to demonstrate their alignment with sustainability goals and promote transparency to stakeholders if they adhere to these reporting requirements and make them a part of their operations. At the core of the regulation, a sustainable economic activity needs to contribute to at least one of the six environmental objectives and do no significant harm to the other states objectives. Among the Taxonomy objectives we remind of climate change mitigation, climate change adaptation, protection of water and marine sources, circular economy, prevention and management of pollution and restauration of biodiversity.

The aim of this article is to assess the level of green revenues and investments of companies operating in the chemical sector and how they fit in the long-term strategy linked to sustainability. We look at multinationals active in the chemical sector, within the context of the EU Taxonomy legislation. We specifically concentrate on revenues, CAPEX and OPEX associated with eligible and aligned operations. To this extent, we employ data science technologies like Python to create an automated procedure for obtaining EU Taxonomy data from PDF annual reports. With this research we intend to close the gap and provide more insightful information on the activities the chemical companies decide the invest and their level of sustainability. We delve into the literature on corporate investments and ESG reporting to understand the major trends in the chemical industry. We then proceed to the description if the tools used in the data collection and processing. Results explore the different KPIs on which the companies report, their eligibility and alignment to the EU Taxonomy criteria. We present detailed information related to the objectives tackled and the activity sector to which the activities are linked to. We then look at the drivers and causes that are linked to the development of sustainable practices in the chemical industry.

2. LITERATURE REVIEW

The literature review has the objective to provide insights into the efforts of chemical companies to integrate sustainability in their long-term strategy of development. Recent studies reveal that the chemical companies face a complex landscape in their attempt to remain competitive but also in producing more eco-friendly products and reduce in the same time the hazardous waste generated by the chemical products (Song & Han, 2014). The term of "green chemistry" is becoming more and more relevant as there is an increasing concern for the chemical companies to operate more sustainable and to create green products by eliminating their footprint on the environment (Kidwai, 2006). Furthermore, as chemical companies are part of a wider and complex supply chain, their environmental footprint has repercussions on the entire value chain (Rajeev et al., 2019). By the same token, circular economy has gained traction as it can be an important driver in manufacturing more sustainable products and reduce waste by revalorizing waste as raw material (Mohan & Katakojwala, 2020). However, to incorporate circular economy in the daily operations of a chemical company requires a set of clear guiding principles and changes in the operational process.

Another important aspect to take into consideration is the increase in regulatory pressures and their impact on the economic activities of chemical companies. A study by Mady et al. (2024) showed that regulatory compliance on sustainability and the market pressures foster eco-innovation on the analyzed companies, becoming thus, more competitive. This is in line with other studies (Amara & Chen, 2022; Jun et al., 2019) that concluded environmental regulation as one of the main drivers for eco-innovation among manufacturing companies. As the European ESG compliance system becomes more transparent, European companies are faced with other regulatory burden along with the ones already existent. The Global Reporting Initiative (GRI) standards or the Sustainability Accounting Standards Board (SASB) were already exerting pressure on companies to disclose their data on sustainable practices. With the enforcement of the Corporate Sustainability Reporting Directive (CSRD) and the EU Taxonomy, the European companies are faced with additional disclosure requirements raising concerns on the cost of compliance and their effect on the overall development strategy of the companies. Materiality assessment has become a requirement as part of the CSRD disclosure that European chemical companies need to undergo every year. A study conducted on chemical companies' disclosure in 2021 and 2021 found that the industry is having impacts on energy consumption, pollution prevention, health and safety in the workplace and waste and water management (Papafloratos et al., 2023). Among other aspects that were found to be of interest for the chemical industry are human rights issues, reducing GHG emissions and community investment (Liew et al., 2014). Materiality assessment and disclosure it is not sufficient if it lacks clear and transparent methods stated in the annual reports of multinationals. A study done on more than 100 annual reports published by 30 companies listed on the German Stock Exchange found that companies do not reveal the steps taken into the materiality assessment (Beske et al., 2019).

With the new EU Taxonomy regulation as part of the CSRD disclosure, companies need to canalize more resources to make sure they comply with the requirements. This means that they need to asses their economic activities according to the eligibility and alignment criteria stated in the regulation. A study conducted in 2023 by PWC found that 46 % of the companies surveyed needed to employ additional resources to comply with the regulation while more than 60% of the companies stated that they rely on external service providers for this task (PWC, 2022). The same study was carried out in 2023 and 2024 to assess the evolution of the EU Taxonomy reporting. The findings suggest that companies from all industries need to incur higher costs directly linked to the disclosure, do not have a standardized process in collecting the data needed while the most common tool used in excel. In 2023, more than 90% of the analyzed companies report their EU Taxonomy data. The majority use the template provided by the European Commission. With respect to the eligibility and alignment criteria the study found that the shares of economic activities increased in both groups suggesting the European companies are willing to invest in sustainable activities from where they can also generate green revenues (PWC, 2024). Although there are more than 500 companies included in the study conducted in 2024, there is no detailed information on the breakdown of activities by type, sector or industry. Moreover, there is no focus on industries or the specific activities from which the generate revenues or undertake green investments.

3. RESEARCH METHODS

Our research focuses on the data reported by nonfinancial companies in line with the EU Taxonomy regulation. As already specified previously, the regulation aims at providing a clear, transparent and comparable classification of sustainable economic activities. Under the EU Taxonomy, companies that are already subject to the NFRD (Non-Financial Reporting Directive) would need to report data on Turnover, CAPEX and OPEX that are eligible and aligned to the technical screening criteria set out in the regulation. In addition to the NFRD regulation, companies subject to the EU taxonomy are also those that fall under the CSRD (Corporate Sustainability Reporting Directive) regulation. These KPIs show to the investors but also to the wider public the level of commitment of the reporting company towards sustainability. Turnover refers to the revenues generated from the sales of products or services created by the company. CAPEX or Capital Expenditures refer to tangible and intangible assets that a company is willing to make investments in to further support its operating business. OPEX refer to operational expenditures and include expenses linked to the daily business operation of a company like research and development or maintenance. For the purpose of this research, we collected data on these three KPIs from companies that fulfilled at least two out of the three criteria set up in the CSRD regulation. In particular, targeted countries that need to have for the financial year 2023 1) more than 250 employees, 2) a balance sheet of more than 25 mil EUR and 3) turnover more than 50 million EUR. The main focus of this research is to understand what is the level of sustainability of the chemical companies and in what economic activities they decide to investment as part of their long-term strategy. To be able to answer these questions we need to:

- collect the data reported by chemical companies under the EU taxonomy;
- process the collected data to structure it for further analysis;
- assess what is the level of revenues and green investments for the analyzed chemical companies according to the EU Taxonomy guiding principles;
- draw insights on how the chemical industry is adapting to the European ESG compliance framework and what is the impact on the value chain, stakeholders and society.

3.1. Data collection

To be able to collect reported data we would need first to identify the companies targeted by the EU Taxonomy. We use Euronext to find public listed entities with more than 250 employees and that have at least 50 mil EUR in turnover or balance sheet of 25 million EUR for the year 2023. Euronext provides an exhaustive list of companies that are publicly listed belonging to different industries like technology, the financial sector, the healthcare industry, the energy sector, and many more. It offers information related to the company's profile in terms of the economic activities that it operates, the country where the headquarters of the company are located, its financial performance, and other key metrics like revenues, employees, and market capitalizations. Then, we consult the website of targeted companies to extract the EU taxonomy data published in their annual report. Some companies prefer to publish these data in their annual report under the non-financial report while other companies prefer to publish EU taxonomy data in the sustainability report.

We have identified 770 companies that are subject to the EU taxonomy. Out of these, only 26 companies are operating in the chemical sector. For the purpose of the industry classification, we used Euronext level II. We take this as a base for our data collection process. Out of the 26 companies identified, only 19 reported their EU taxonomy data. For the 7 companies remaining either we could not identify the report where the data was published either the reporting was not made using the templates provided by the European Commission. We use Python programming language, to be able to automate the process of data collection from PDF files and save the information that was extracted in an organized Excel format. The methodology employs Python and Jupiter Notebooks as software to write the code necessary for data extraction and collection. Python is an adaptable, high-level, interpreted programming language that has risen to prominence in computer science and academia. Python is fairly easy to use it an excellent choice for both novice and experienced programmers. Alongside Phyton we employ Jupyter Notebook, an open-source platform that is built upon the Python project. It facilitates interactive and exploratory analysis, visualization, and documentation of data. It provides a single environment where code, text, and visualizations may be easily integrated.

Within Phyton we use two types of libraries: pandas and tabula. Pandas is a Python library that is widely recognized for its significant impact in the field of data manipulation, analysis, and organization. It provides a comprehensive technical toolkit for efficiently managing both structured and unstructured data. It has the ability to read and write data from different file formats including PDF, CSV, Excel, SQL databases, and JSON. It employs algorithms that can recognize table borders, rows, and columns included inside PDF files. It has the ability to accurately distinguish table cells, text, and numerical values, making it easy as process of data extraction from a variety of tabular forms. On the other side, pandas library is crucial in the code as it helps with organizing, manipulating, and analyzing the extracted data from PDF files. This library ensures that the data is presented in a structured format that allows us to easily extract insights from the data. It is worth mentioning that the output file generated by the Phyton code contained some unstructured data that makes it difficult to make further analysis. Some manual manipulations of the data were required to be able to get some insights from the reported data.

3.2. Data processing

Data processing is the essential first step in transforming unprocessed data into usable insights. Following the data collection step, it is important to organize, clean, and analyze the data in order to guarantee that it fulfills the objective of collecting EU taxonomy data derived from annual reports of significant corporations. It is worth mentioning that the libraries used in conjunction with Phyton were able to read data from PDF tables and transpose them into excel files. However, since the taxonomy reporting is still new, some companies choose to report their data in a different table structure than the template provided by the EU Commissions. When putting all this data together in one single file, there is a risk that data is not perfectly aligned in rows and columns under the same data field or attributes that could be further used for descriptive statistics and analysis. Therefore, for the purpose of this report, data needed some manual manipulation to make sure that it could be used for further analysis. This meant, rows and columns rearrangement, transformation from units to millions or adding additional columns in order to be consistent across the dataset. Furthermore, in some instances, the values for the listed economic activities were missing.

To ensure that we capture the correct reporting of companies we also keep those activities even if there is no associated value. Given that the source is mostly composed of PDF files, there is the potential for mistakes to occur throughout the extraction process. To counteract any possible errors linked to the data extraction we have compared the data extracted with the source data in the pdf files. Some of the reported data needed rectification following this check. For the majority of data points collected, we kept the abbreviations employed provided in the EU Taxonomy reporting template: Eligible Activities (A), Aligned Activities (A1), Non-Aligned Activities (A2), Non-eligible Activities (B) and Total Activities (A+B). In addition, processing data on individual activities was more difficult as there is always an associated code and name of the reported activity. To keep things simple, we have only kept the codes and then we map them with the codes found in the Taxonomy regulation along with the targeted objective. Data was collected and processed during July and August 2024 and it refers to the latest available information on the companies selected up until this point in time.

4. RESULTS

The scope of this research includes 19 chemical companies[1] that have reported KPIs in the context of the EU Taxonomy regulation. It is important to note that more than 70% of the targeted companies have reported their data. This is in line with a PWC (2024) findings that analyses the EU Taxonomy disclosures. Table 1 and Table 2 offers a detailed analysis into the breakdown of economic activities that are associated with taxonomy-aligned and non-aligned operations. These metrics include turnover, CAPEX, and OPEX for the 19 companies included in our dataset. We look at the mean of reported activities in terms of percentage from the total of activities and their standard deviations. Table 2 depicts the total activities reported by the companies in the data sample for each category of activity, its mean and standard deviation. It is important to mention that companies need to disclose the total of aligned, not aligned, eligible and not eligible activities as part of their reporting. Additionally, companies need to disclose the detailed breakdown of aligned vs not-aligned activities according to the EU Taxonomy compass by associating each activity to a sector and objective. From table 1 we see that the standard deviation is low for Non-Eligible B activities for all KPIs reported suggesting that there is low variability in the dataset. Most activities linked to turnover, CAPEX and OPEX reported by the chemical companies are not subject to the EU Taxonomy screening.

Table 1. Breakdown of economic activities according to the EU Taxonomy classification by Turnover, CAPEX and OPEX (mean and standard deviations for activities expressed as percentage of total activities reported).

Taxonomy Activities	No. of obs	Turnover		CAPEX		OPEX	
		Average %	Std. Dev	Average %	Std. Dev	Average %	Std. Dev
Total Aligned A1	19	3.89%	9.87%	7.59%	16.59%	5.91%	13.52%
Total Non-Aligned A2	19	9.15%	12.58%	17.16%	19.86%	14.78%	16.75%
Total Eligible A1+A2	19	12.85%	15.48%	24.73%	23.35%	18.27%	17.29%
Non-Eligible B	19	87.14%	15.48%	71.03%	27.38%	81.73%	17.29%
TOTAL A+B	19	100.00%	0.00%	100.00%	0.00%	100.00%	0.00%

Source: Author's own calculation with R software based on data collected from annual reports of chemical companies.

In terms of eligibility, we observe that only a small percentage of activities are subject to the EU Taxonomy with CAPEX having the largest share, almost 25%, while turnover has the largest amount among the three KPIs reported with almost 26 billion EUR in total. Turnover also has the largest share of non-eligible activities with 87% of economic activities not suitable to be subject to the technical screening criteria.

[1] The chemical companies included in the data sample are: AIR LIQUIDE, AKZO NOBEL, AQUAFIL, AZELIS GROUP, BASF, BORREGAARD, BRENNTAG, COVESTRO, ELKEM, IMCD, K+S, LANXESS, OCI, ROBERTET, SAES GETTERS, SOL,, SOLVAY, TESSENDERLO, YARA INTERNATIONAL

Table 2. Breakdown of economic activities according to the EU Taxonomy classification by Turnover, CAPEX and OPEX (mean and standard deviations for activities expressed as mil EUR).

Taxonomy Activities	No. of obs	Turnover			CAPEX			OPEX		
		Total (mil EUR)	Average %	Std. Dev	Total (mil EUR)	Average %	Std. Dev	Total (mil EUR)	Average %	Std. Dev
Total Aligned A1	19	5,668	298	676	1,379	72	137	1,038	54	144
Total Non-Aligned A2	19	20,252	1,063	2,025	3,190	180	245	1,945	133	215
Total Eligible A1+A2	19	25,915	1,363	2,240	4,569	240	314	2,984	155	227
Non-Eligible B	19	167,143	8,797	14,164	13,249	697	1,205	13,267	698	1,275
TOTAL A+B	19	192,937	10,154	15,958	17,828	938	1,474	16,222	853	1,425

Source: Author's own calculation with R software based on data collected from annual reports of chemical companies.

In terms of turnover, aligned activities (A1) account for 5,668 million EUR, which is equivalent to 3.89% on average, from the turnover reported by the targeted chemical companies. Significantly more revenue is generated by non-aligned operations (A2), which amount to 20 billion EUR accounting for 9% of the overall turnover. In the realm of corporate finance, capital expenditure, often known as CAPEX, continues to be one of the most important indications of a company's investment strategy, future orientation, and dedication to certain business operations. The analysis of the supplied data on CAPEX related to eligible vs non-eligible and aligned versus non-aligned operations provides profound insights into the goals and foresight of the chemical sector. In terms of investment patterns related to capital expenditure (CAPEX), eligible activities account for almost 25% of the total CAPEX reported. This may be an indication that these businesses are increasing their investments in eligible operations, pointing to the possibility of a shift or expansion in this area in the near future. Within the eligible activities, the non-aligned activities (A2) get a substantially larger investment (17%) than their aligned counterparts (A1), which only account for 7% of CAPEX. Given these numbers, we can state that there is still room for improvement for chemical companies to shift their investments towards more sustainable activities according to the EU taxonomy. It is worth mentioning that chemical businesses are one of the most difficult industries to transform because of its extensive processes, complex supply networks, and established operating models. As a result, the chemical industry is one of the least likely to see significant changes in their processes and operations towards more sustainable activities. During their existence on the market, chemical businesses have made significant investments in the infrastructure or perfecting the chemical processes necessary to be competitive. Plants, refineries, and factories are often planned long term and tend to be rigid in face of new challenges and regulations on the market. In certain situations, the switch to more environmentally friendly business practices, could require the modernization of their current facilities, change the operation model or simply undergo a digital transformation to be able to measure and follow up on their sustainability strategy. The resources engaged in this process are complex and often requires a change in mindset and organizational culture of the company.

Operational Expenses (OPEX) offers a glimpse into the continuing expenditures that are connected to the day-to-day operations of a business. It provides an overview of how companies manage their day-to-day operations and the many directions in which resources are being directed. With an operational cost that only accounts for almost 6% of the overall OPEX, the operational expenses for aligned activities appear to have the same pattern as turnover and OPEX. Almost 6% are reported as aligned while non-aligned activities account for almost 15%, more than double compared to the ones considered sustainable.

The share of non-eligible activities accounts for a staggering 80% of the total OPEX. This suggests that these processes continue to serve as the fundamental basis for the day-to-day operations of the chemical industry. Even while non-eligible operations dominate the operational landscape of today, organizations are likely going to feel increased pressure from regulatory authorities, stakeholders, and market dynamics to optimize the OPEX of eligible activities even more. Businesses might make investments in technology and procedures that reduce the ongoing costs of operating in a sustainable manner, so making their operations not only more beneficial to the environment but also more economically competitive. One important aspect to mention is that the share of aligned, non-aligned and not eligible will not always sum up to 100% as during the data extraction and processing the percentages associated to low levels activities will not reflect the accurate decimals in the percentages. This is also due to the unit in EUR used in the Taxonomy tables which varies from millions to thousands.

We have looked at the share of eligible, aligned and not aligned activities for each KPI for the entire data sample od companies analyzed. The EU Taxonomy regulation mandates the companies to assess each activity individually and report on their alignment or eligibility. The regulation has clear guidelines on the technical screening criteria to evaluate if an activity is sustainable or not, it is always linked to an objective and to an activity sector.

Table 3. Breakdown of activities by objective and reported KPI in EUR absolute value.

Activity	Objective	Turnover	CAPEX	OPEX
Aligned A1	Climate Mitigation	5,667,559,799	1,378,984,186	1,038,088,791
	Water		4,600	
Non-Aligned A2	Biodiversity		16,641	
	Circular Economy	15,700,000	4,324,499	5,900,000
	Climate Mitigation	20,197,702,485	3,183,239,006	1,897,934,321
	Pollution Prevention	38,500,000	831,645	41,160,305
	Water		258,574	

Source: Author's own calculation based on annual reports of chemical companies.

Table 3 details the breakdown of activities linked to the objective that is targeting. Most activities reported by the chemical companies are mitigating against climate change and a large share are not aligned according to the EU Taxonomy principles. In particular, the highest amount is accounted for Turnover with 20 billion EUR that is not aligned vs 5 billion EUR aligned activities. It seems that chemical companies are investing heavily in climate related projects to reduce their impact on the environment and reduce their carbon footprint. CAPEX and OPEX activities are lower in amount but still are not aligned. On the other end, Water and Biodiversity account for the smallest share in terms of tackled objectives. This might be due to the fact that these activities are not directly generating revenues and companies are not making them a priority in their sustainability strategy. Circular Economy and Pollution Prevention have relatively modest shares for the three KPIs reported, accounting for more than 54 million EUR for Turnover, 5 million EUR for CAPEX and 47 million EUR for OPEX for both aligned and not aligned activities. This shows that chemical companies are willing to explore the different solutions linked to circular economy and potentially to be aligned to the EU Taxonomy principles.

The European Commission provides an indicative mapping of the economic activities reported and how these could be linked to NACE activity codes. We have used the indicative mapping of these activities to understand in what sectors the chemical companies chose to deploy their activities. Figure 1 depicts the aligned and not aligned activities that are linked to turnover. Most of the activities are concentrated in the manufacturing sector, followed by energy, water and waste management systems and transportation. As already seen from the previous data insights, most activities are not aligned according to the EU Taxonomy criteria. Table 4 provides more detailed information related to the aligned activities that are linked to Turnover. Most chemical companies generate their sustainable revenues in 2023 from the manufacturing of soda ash, manufacture of low carbon technologies and manufacture of batteries. Although the share of these activities is not high compared to the total of activities reported, we can see that chemical companies have started exploring other markets from where they can generate green revenues and where the demand for more sustainable products is increasing. As chemical companies act as suppliers for other industries, we could see an increase in green revenues in the upcoming years as market trends shifts and consumers become more aware of the impact on environment.

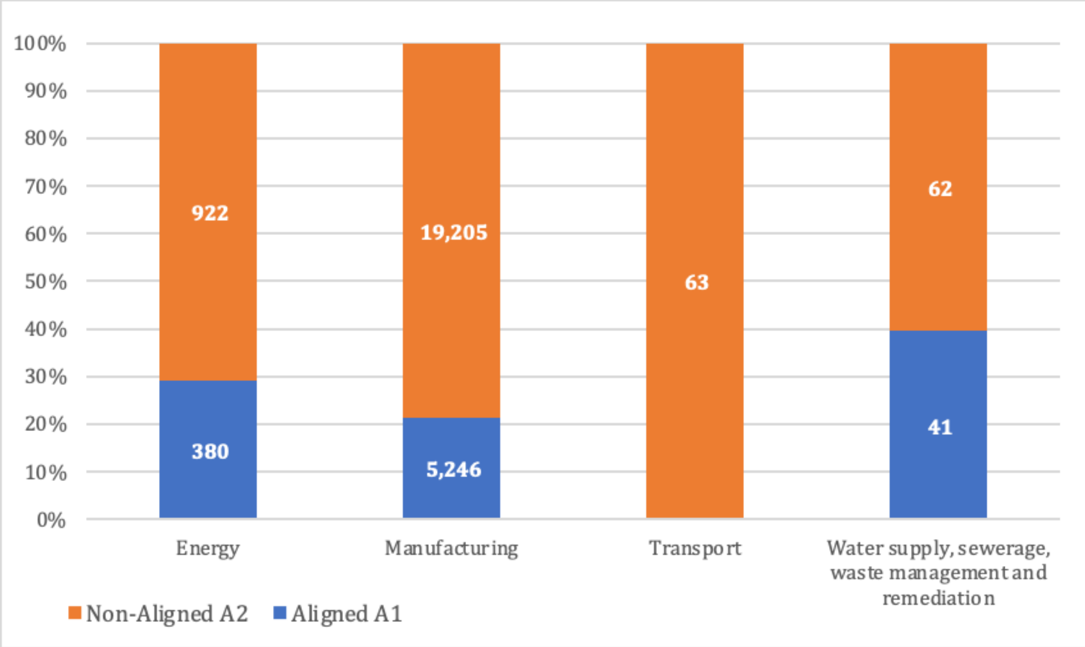

Figure 1. Aligned and Not Aligned activities linked to Turnover reported by chemical companies (absolute value in mil EUR and percentage of Eligible activities).
Source: Author's own calculation based on annual reports of chemical companies.

Table 4. Breakdown of Aligned activities by sector and reported Turnover (expressed in EUR absolute value and as a percentage of Eligible activities).

Activity Sector and Activity Code and Name	EUR	%
Energy	**380,479,000**	**1.47%**
4.13 Manufacture of biogas and biofuels for use in transport and of bio-liquids	377,500,000	1.46%
4.5 Electricity generation from hydropower	2,979,000	0.01%
Manufacturing	**5,246,380,799**	**20.24%**
3.10 Manufacture of hydrogen	68,800,000	0.27%
3.12 Manufacture of soda ash	2,113,000,000	8.15%
3.13 Manufacture of chlorine	80,000,000	0.31%
3.14 Manufacture of organic basic chemicals	200,000,000	0.77%
3.16 Manufacture of nitric acid	21,620,000	0.08%
3.17 Manufacture of plastics in primary form	162,503,926	0.63%
3.2 Manufacture of equipment for the production and use of hydrogen	31,800,000	0.12%
3.3 Manufacture of low carbon technologies for transport	52,300,000	0.20%
3.4 Manufacture of batteries	861,956,873	3.33%
3.5 Manufacture of energy efficiency equipment for buildings	32,000,000	0.12%
3.6 Manufacture of other low carbon technologies	1,622,400,000	6.26%
Water supply, sewerage, waste management and remediation	**40,700,000**	**0.16%**
5.10 Landfill gas capture and utilization	13,200,000	0.05%
5.7 Anaerobic digestion of bio-waste	27,500,000	0.11%

Source: Author's own calculation based on annual reports of chemical companies.

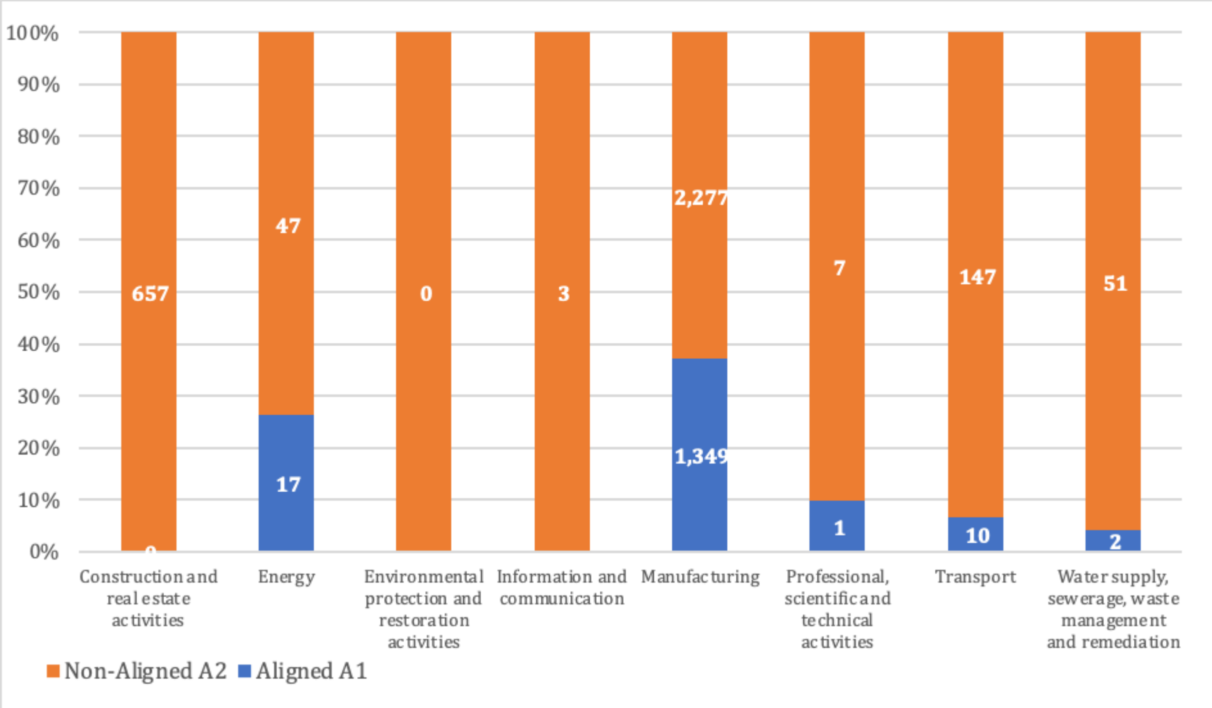

Figure 2. Aligned and Not Aligned activities linked to CAPEX reported by chemical companies (absolute value in mil EUR and percentage of Eligible activities).
Source: Author's own calculation based on annual reports of chemical companies.

With respect to CAPEX, we see more sectors in which the companies are willing to concentrate their investments. The largest share is represented by the manufacturing sector accounting for more than 3.5 bn EUR, followed by construction and real estate activities with 657 million EUR and transportation with 157 mil EUR. As depicted in Figure 2, most of the activities reported are not aligned and they do not fulfill the criteria set out in the EU Taxonomy regulation. In terms of aligned activities, we notice that companies were willing to make green investments in low carbon technologies (395 million EUR), manufacture of hydrogen (327 million EUR) and manufacture of batteries (244 million EUR). This is consistent with the data reported on turnover. Chemical companies increased their investments in 2023 especially in the manufacturing of hydrogen to develop their operations and generate additional revenues in the following years. Apart from the manufacturing activities, Table 5 shows companies invested in the renovation of existing buildings and in the manufacturing of biogas and storage of hydrogen. These green investments in energy accounted for more than 16 mil EUR at the end of 2023 for the companies in the data sample. We also notice investments in low carbon road transport accounting for more than 9 million EUR and in the water and waste management systems for more than 2 million EUR. It seems that sustainable R&D activities were intensified as companies are willing to invest in IT technologies that would help them reduce their carbon footprint.

Table 5. Breakdown of Aligned activities by sector and reported CAPEX (expressed in EUR absolute value and as a percentage of Eligible activities).

Activity Sector and Activity Code and Name	EUR	%
Construction and real estate activities	**23,722**	**0.00%**
7.2 Renovation of existing buildings	23,722	0.00%
Energy	**16,550,000**	**0.36%**
4.12 Storage of hydrogen	4,500,000	0.10%
4.13 Manufacture of biogas and biofuels for use in transport and of bio-liquids	10,700,000	0.23%
4.16 Installation and operation of electric heat pumps	50,000	0.00%
4.25 Production of heat/cool using waste heat	1,300,000	0.03%

Manufacturing	**1,349,205,078**	**29.53%**
3.10 Manufacture of hydrogen	327,600,000	7.17%
3.12 Manufacture of soda ash	260,000,000	5.69%
3.13 Manufacture of chlorine	23,000,000	0.50%
3.14 Manufacture of organic basic chemicals	13,000,000	0.28%
3.15 Manufacture of anhydrous ammonia	21,620,000	0.47%
3.16 Manufacture of nitric acid	47,940,000	1.05%
3.17 Manufacture of plastics in primary form	13,035,078	0.29%
3.2 Manufacture of equipment for the production and use of hydrogen	2,600,000	0.06%
3.4 Manufacture of batteries	244,210,000	5.35%
3.5 Manufacture of energy efficiency equipment for buildings	1,000,000	0.02%
3.6 Manufacture of other low carbon technologies	395,200,000	8.65%
Professional, scientific and technical activities	**707,386**	**0.02%**
9.2 Research, development, and innovation for direct air capture of CO2	700,000	0.02%
9.3 Professional services related to energy performance of buildings	7,386	0.00%
Transport	**10,340,000**	**0.23%**
6.10 Sea and coastal freight water transport, vessels for port operations and auxiliary activities	940,000	0.02%
6.15 Infrastructure enabling low-carbon road transport and public transport	9,400,000	0.21%
Water supply, sewerage, waste management and remediation	**2,158,000**	**0.05%**
5.10 Landfill gas capture and utilization	300,000	0.01%
5.4 Renewal of waste water collection and treatment	258,000	0.01%
5.7 Anaerobic digestion of bio-waste	1,600,000	0.04%

Source: Author's own calculation based on annual reports of chemical companies.

In terms of OPEX, companies reported most activities linked to the manufacturing sector as this is their main domain of activity. Transportation related activities, energy and water supply account for the majority of eligible activities according to the EU Taxonomy.

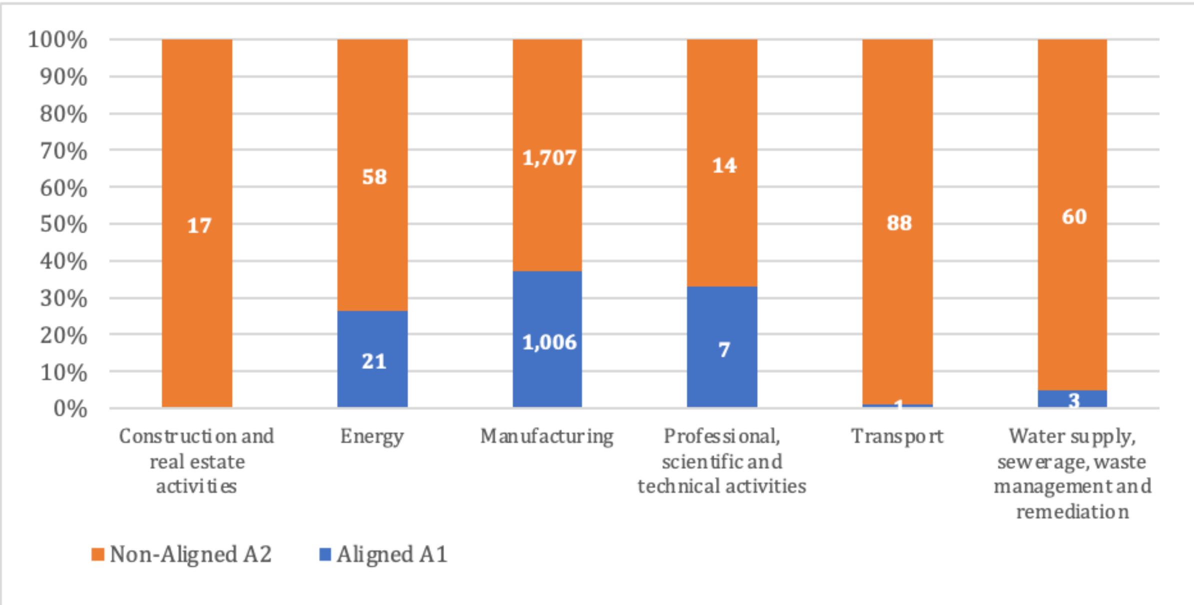

Figure 3. Aligned and Not Aligned activities linked to OPEX reported by chemical companies (absolute value in mil EUR and percentage of Eligible activities).
Source: Author's own calculation based on annual reports of chemical companies.

Table 6. Breakdown of Aligned activities by sector and reported OPEX (expressed in EUR absolute value and as a percentage of Eligible activities).

Activity Sector and Activity Code and Name	EUR	%
Energy	**20,720,000**	**0.69%**
4.13 Manufacture of biogas and biofuels for use in transport and of bio-liquids	20,300,000	0.68%
4.5 Electricity generation from hydropower	420,000	0.01%
Manufacturing	**1,006,228,791**	**33.72%**
3.10 Manufacture of hydrogen	9,300,000	0.31%
3.12 Manufacture of soda ash	610,000,000	20.44%
3.13 Manufacture of chlorine	19,000,000	0.64%
3.14 Manufacture of organic basic chemicals	41,000,000	1.37%
3.16 Manufacture of nitric acid	35,720,000	1.20%
3.17 Manufacture of plastics in primary form	22,308,791	0.75%
3.2 Manufacture of equipment for the production and use of hydrogen	38,500,000	1.29%
3.3 Manufacture of low carbon technologies for transport	8,700,000	0.29%
3.4 Manufacture of batteries	27,000,000	0.90%
3.5 Manufacture of energy efficiency equipment for buildings	3,000,000	0.10%
3.6 Manufacture of other low carbon technologies	191,700,000	6.42%
Professional, scientific and technical activities	**7,000,000**	**0.23%**
9.2 Research, development, and innovation for direct air capture of CO2	7,000,000	0.23%
Transport	**940,000**	**0.03%**
6.10 Sea and coastal freight water transport, vessels for port operations and auxiliary activities	940,000	0.03%
Water supply, sewerage, waste management and remediation	**3,200,000**	**0.11%**
5.10 Landfill gas capture and utilization	700,000	0.02%
5.7 Anaerobic digestion of bio-waste	2,500,000	0.08%

Source: Author's own calculation based on annual reports of chemical companies.

Related to the specific activities depicted from the annual reporting, we gather that companies continue on their strategy to manufacture sustainable soda ash, a product used mostly in the production of glass, powdered detergents and soaps, cleaning and water treatment. Around 20% of reported soda ash manufacturing are aligned and account for more 600 million EUR for the entire data sampled analyzed. The same picture applies for OPEX breakdown. Operational expenses of chemical companies refer to the production of biogas and biofuels, manufacture of hydrogen and low carbon technologies.

5. DISCUSSION

Through this research we attempted to have a first insight into the EU Taxonomy reporting of chemical companies. The objective was to understand where sustainability stands from a strategic perspective and how the industry is preparing to reduce their environmental impacts. The findings suggest that the industry has started a transformation process fostering sustainability but there is still a long way to achieve maximum results. Our findings can be coupled with the PWC reports (PWC, 2023; PWC, 2024) in terms of reporting as most of the chemical companies in the data sample report their data using the template provided by the European Commission. Our data analysis reflects that a low share of activities is eligible and even a lower one is aligned according to the principles of the EU Taxonomy. This is observed across the three indicators reported, turnover, CAPEX and OPEX. As it was expected, the majority of activities are linked to manufacturing but we also observed that some revenues are generated by the sustainable manufacturing of soda ash, low carbon technologies and biofuels. The percentage is still small compared to the amount of eligible activities that could be sustainable if sufficient efforts are made towards improving their processes. We next expose and analyze the reasons why a higher degree of sustainability is difficult to achieve among the chemical companies.

5.1. Operational complexities

The difficulty in achieving a higher share of alignment raises from the fact that the chemical sector tends to be more complex and specific than other industries. Chemical processes have been established and perfected over the course of many years as a consequence of extensive study, specialized knowledge, and repeated experimentation (Wangthong & Rojniruttikul, 2023). Altering these processes so that they are less harmful to the environment is not as simple as exchanging one component for another or rearranging the order in which certain steps are carried out. It may need a complete rethinking of the procedure, which brings with it a wide range of technical obstacles as well as the possibility of a lower production or lower overall product quality. Here comes in play, the dependence of chemical companies on raw materials. Many different chemicals are produced from non-renewable raw materials such as petroleum, which creates a dependency on these resources. To successfully make the switch to bio-based or more environmentally friendly raw materials, it is not enough to just identify a suitable alternative. The company also needs to establish that this alternative can be acquired on the required scale and without lowering the quality of the final product. Despite the fact that most chemical companies are research oriented, this does not mean that they can easily modify their recipe to include biobased raw materials.

Furthermore, even if a chemical firm is completely dedicated to the concept of sustainability, it frequently operates inside a complex network of processes and products that are dependent on one another. It is possible for a single primary product to generate many by-products, which can then be used as raw materials in other processes. Altering one process or input in the interest of sustainability can throw off the production of another essential good. Therefore, establishing sustainability is not a step-by-step process but rather a complex process with many dimensions. Moreover, it is possible that the company's suppliers and distributors are not aligned on sustainable practices or do not have the resources necessary to maintain sustainable operations. For instance, a business that is interested in acquiring environmentally friendly raw materials may discover that there are just insufficient vendors that satisfy the requirements. Given the possible negative effects that its operations might have on both the environment and people's health, the chemical industry is one of the most strictly regulated industries. When new procedures or materials are utilized, it is possible that they may require re-certification, re-approval, or rigorous testing in order to guarantee that they are in accordance with both local and international standards. This not only mean that the shift to more sustainable raw materials or commercial products might take longer, but it also adds another degree of complexity and an additional expense. By the same token we could also argue that companies are more incentivize to rethink their long-term strategy in the light of the EU taxonomy and the future CSRD compliance. This is coupled with the financial sector legal incentives to connect their lending strategies with sustainable practices because to the EU Taxonomy and other efforts of a similar nature that are being implemented throughout the world.

Although the majority of the analysed companies declare and state on their website that they are committed to decrease emissions, focus on circular economy and empower local communities with new skills, the findings of this research tell us otherwise. It seems that there is a significant gap between these declarations and the actual activities performed. More than half of the eligible activities are not aligned. This disparity highlights the difficulties that have been encountered by businesses in the process of putting their sustainable aspirations into action. The absence of alignment in key activities shows that either the execution of these strategies is trailing behind or that the requirements of the taxonomy are regarded as being too difficult or restrictive for firms to completely comply with. One possible solution to close this gap is for them to start measuring their real impact on the environment and based on the results to set up realistic objectives that are in line with their capacity of implementation. For these reasons, data management systems and data governance can become extremely important for their long-term sustainability strategy. Multinationals, especially renowned chemical companies can have complex data architecture and find it difficult to have accurate data important for decision making process.

5.2. Regulatory pressures

Other difficulties for chemical companies to transform their daily operations include regulations and the perception of the public. Regulations controlling the production of chemicals have gotten more stringent in response to the growing environmental awareness across the globe. Although these restrictions are necessary for moving the sector in the direction of sustainability, they may also provide difficulties, particularly for businesses that operate in a number of different jurisdictions, each of which has its own set of laws. Because of the fluid nature of the regulatory environment, staying ahead of the curve or even just being compliant may be an expensive endeavor, particularly for more novice competitors in the market. There is evidence that heavy polluting chemical companies may feel less prone to make green investments in face of enforced environmental regulations (Zou et al., 2022). While there is an increasing demand for environmentally friendly products, there is also a consistent market sector that places a higher priority on cost than sustainability. Chemical businesses need to find a middle ground between meeting the needs of the current customer base and developing products with an eye towards the future. Completely changing their business model might turn off a substantial number of the customers they already have. In addition, the general public frequently has an unfavorable impression of the chemical industry due to the sector's tendency to be stereotyped. The problem at hand is not just one of a technical or financial nature, but also one of reputation. The process of transforming operations to be more sustainable can help in redefining this impression, but the path is a lengthy one, and throughout this transformation, the industry is frequently subjected to more criticism than praise.

Another finding is related to the use of significant capital expenditures (CAPEX) in the manufacture of hydrogen, soda ash, batteries and low carbon technologies. Hydrogen production is a leading renewable energy alternative because it can decarbonize heavy industries, transportation, and power generation. These might be the reasons why chemical corporations decided to undergo considerable investment in this alternative. Green or blue hydrogen produced from renewable energy or carbon capture has clean fuel properties. By investing in hydrogen manufacture, chemical firms can address the expanding need for hydrogen in fuel cells, industrial heating, and ammonia production. This is in line with the evidence that more companies want to position themselves on the hydrogen market (Eltweri et al., 2024). Moreover, our findings also suggest that green investment in the production of batteries and low carbon technologies are evidence that chemical industries are not only addressing an increasing market demand for these new technologies but also fostering the development of new capabilities like better efficiency, capacity of storage and sustainability. This evidence is supported by other studies like Chen (2024) where Chinese companies are actively working to be competitive in the batteries market with the support of policy incentives and continuous investment in the development of the technology. The investment of chemical corporations in the manufacture of batteries implies that these businesses are investigating the possibility of diversification. Even if many of the activities reported do not fit with the EU taxonomy criteria, high CAPEX linked to the investment in batteries can indicate a shift towards technologies that are more environmentally friendly.

Apart for the increased demand of batteries the automotive industry also needs lighter materials to cut high emissions, improve the energy efficiency of their vehicles and keep up with the market demands of consumers. In this area chemical companies should make a priority the manufacture of sustainable plastic products that would lead to lower footprint and increased demand from the automotive industry. This is backed up by Kamińska-Witkowska and Kaźmierczak (2024) and Carvalho et al. (2024) research as the automotive industry is interested in using more sustainable raw materials in their production process. To keep encouraging diversification within the chemical sectors, public policies should strive for developing a clear regulatory framework for growing businesses that prioritizes sustainability and green sources of energy. From our findings we see that companies lack CAPEX and OPEX in regenerable sources and incentives from governments would foster development towards these activities. Another idea would be to increase financing for public-private research partnerships that are focused on sustainable chemical processes, waste minimization, and the concepts of circular economies. The establishment of innovation hubs (Sgroi & Marino, 2021; Egessa & Mwadzogo, 2024) or clusters is one way to further encourage cooperation between existing chemical industries, newly founded businesses, and academic institutions. Our results indicate that there is still room for improvement in incurring CAPEX in the field of research and development in carbon capture technologies that would foster the development of new green products with a lower carbon footprint. The activities related to the manufacture of soda ash seems to account for high level of aligned CAPEX and could possibly be linked to its increased demand in the production of energy efficiency glass.

Among the lowest share of aligned activities, we remind of the renovation of existing structures belonging to chemical companies. This is an indication that companies are willing to modernize their facilities but there is still room for improvement in order to have higher alignment according to the EU taxonomy principles. To this end, public policy initiators should focus on providing financial assistance in the form of grants or interest-free loans to businesses who invest in the renovation of their existing properties in order to increase the energy efficiency of their operations or to include renewable energy sources. These kinds of proposals would lower the environmental footprint that chemical factories leave behind, and it may lead to considerable reductions in greenhouse gas emissions, and align to the EU's climate objectives and SDGs. Regulators should also consider the cost of disclosure as companies need to incur important costs in external consultancy to understand how the EU Taxonomy needs to be implemented. Coupled with future CSRD disclosure, these regulatory pressures might deter companies from focusing on their competitiveness and innovation as important resources might be focused on compliance rather on the core business of the company. By this token, the European Commission should assess whether the cumulative load of disclosure obligations has a negative influence on the performance of European firms. In fact, this may result in a reduction of their competitive advantage in comparison to overseas competitors that are not subject to equivalent regulatory demands. The complexity of these regulations could undermine the existence of European companies in industries that are essential to the growth and sustainability of the economy. In this particular setting, the Draghi report on European competitiveness suggests that the EU Taxonomy should be simplified, this given the fact that the technical screening criteria might evolve in the future. Simplification can be the key to produce more positive results. If the framework were simplified, it would minimize the administrative complexity and the expenses associated with compliance, which would allow businesses to better concentrate their resources toward innovation and market performance. A balance needs to be achieved between environmental transparency and maintaining the competitiveness of European companies.

6. CONCLUSIONS

The data collected on a limited sample chemical companies subject to EU taxonomy presents a non-exhaustive overview of the financial operations, that are aligned or not aligned to the EU taxonomy criteria. Our findings provide a glimpse into the economic goals and strategic investments of the chemical sector. Our research shows that sustainable activities make up just a tiny portion of the total turnover and capital expenditure (CAPEX) in the chemical industry. This emphasizes the need for considerable progress in aligning investments with sustainable practices. This study not only enhances the comprehension of how business actions within the EU Taxonomy might impact sustainable development but also demonstrates the significance of technology in enhancing data collecting and analysis procedures for improved compliance and reporting.

Despite the good trend, the move to sustainable practices faces major obstacles. These problems include budgetary restrictions, the complexity of legal requirements, and operational impediments. It is common for businesses to confront significant expenses associated with the adoption of new technology and processes, in addition to the fact that regulatory frameworks are always growing and requiring rigorous compliance efforts. In addition, the possibility of greenwashing, which is the act of misrepresenting efforts to promote sustainability, creates reputational concerns in a market that is becoming increasingly dubious. The complexity of the regulatory disclosures adds another layer of difficulty to the whole process. The EU Taxonomy includes stringent screening requirements that companies are required to fulfill in order to be allowed to identify their operations as sustainable. The navigation of this framework requires a large amount of administrative effort and skill, despite the fact that it gives clarity and uniformity in the definition of sustainable activities. Adapting to ever-changing rules is a must for businesses, since these requirements frequently necessitate the modification of internal procedures, systems, and reporting methods. These adjustments may be both expensive and time-consuming. Additionally, operational constraints are a barrier to advancement. A significant number of chemical businesses are active in industries that have long-standing procedures and infrastructure that are difficult to modify in order to conform to sustainability recommendations. Redesigning manufacturing lines, locating new resources, and reevaluating supply chains are frequently associated with the process of transitioning to activities that are more environmentally friendly. Existing workflows may be subject to disruption as a result of this, which may necessitate significant personnel retraining and organizational reorganization.

In addition to these problems, there is a growing worry around greenwashing. This occurs when businesses may exaggerate or misrepresent their efforts to save the environment in order to satisfy the expectations of the market or of stakeholders. In a market that is becoming more suspicious, investors, consumers, and regulators are demanding genuine and demonstrable contributions to sustainability. This generates reputational concerns, particularly in a market that is becoming increasingly skeptical. By this token, transparency and accountability are becoming more important than they have ever been, and businesses that fail to support their assertions with trustworthy data may be subject to criticism. In order to effectively address these difficulties, it is necessary for politicians, corporations, and other stakeholders to collaboratively develop strategic solutions. Policymakers at both the EU and member state levels are tasked with the responsibility of formulating and refining policies that strike a balance between fostering economic growth and maintaining environmental guardianship. Companies can be encouraged to engage in environmentally friendly technology and practices by providing them with financial incentives such as grants, subsidies, and tax cuts. At the same time, laws that are both clear and consistent may offer businesses with the direction they require to make decisions that are well-informed without being overpowered by the uncertainty that comes with regulatory compliance.

Partnerships between the public sector and the commercial sector can also speed up the transition to sustainability. The integration of renewable energy sources, carbon capture and storage and the generation of hydrogen are all examples of large-scale initiatives that might benefit from collaborations involving governments, research institutions, and industry partners. These collaborations serve to stimulate innovation, share risks and concentrate efforts and resources. Additionally, these types of alliances may facilitate the exchange of information and best practices, allowing businesses to gain insight from the achievements and difficulties of one another. In addition, the incorporation of sustainability measures into the culture of a company is very necessary for long-term success. When it comes to strengthening brand reputation, attracting investment, and appealing to consumers who are environmentally sensitive, businesses need to grasp the strategic importance of sustainability. This goes beyond simply complying with regulations. There is the potential to cultivate a culture of creativity and dedication to sustainable growth through the implementation of internal training programs, leadership that is focused on sustainability, and clear communication of goals.

As a conclusion, despite the fact that the chemical sector has made tremendous progress in conforming to the standards of the EU Taxonomy, major hurdles still exist. Progress is hampered by a number of obstacles, including financial limits, the complexity of legal requirements, operational obstacles, and the possibility of greenwashing. On the other hand, these difficulties also create chances for creative partnerships and cooperative endeavors. Accelerating the transition toward sustainability in the chemical sector may be accomplished via the utilization of technology, the cultivation of partnerships, and the alignment of legislative frameworks with the aims of sustainable development. This will ensure both economic resilience and environmental responsibility in the years to come. As future research topics one might investigate if the the EU Taxonomy regulation has the intended purpose of increasing sustainable growth or it affects negatively the revenues generated by companies and the prosperity of the European countries long term. Studies of this nature might investigate the dual impact on the regulation, which includes its efficiency in directing money toward activities that are environmentally sustainable as well as the possible trade-offs that it may have in terms of performance, innovative power and competitiveness. Additionally, one can analyse the comparative advantage or disadvantage that European companies subject to the EU Taxonomy have in the international market, particularly when competing against other companies operating in countries that have less severe regulations for sustainability reporting. By the same token, one could investigate if the regulation encourages the development of new green technologies or it restricts the dynamic nature of the economy by imposing rigid policies. By addressing these aspects, future research might give significant insights into improving the balance between legislative aims and economic realities, ensuring that sustainability goals are accomplished without sacrificing the long-term resilience and profitability of European economies.

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The author declares they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflicts of interest
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RETRACTED ARTICLE: Long term climate variability, trend and drought occurrence: the case of Loka Abaya, Ethiopia

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ABSTRACT: This study investigates the variability and trends in rainfall and temperature, as well as drought patterns in the Loka Abaya district of Ethiopia, over a 42-year period (1981-2022). The Coefficient of Variation (CV), Mann-Kendall trend test, and Standardized Precipitation Evapotranspiration Index (SPEI) were employed to examine variability, trends, and drought occurrences, respectively. Results indicate that the annual rainfall exhibited low variability (CV: 17.54%), while seasonal rainfall showed higher variability: Belg (spring) at 28.3%, Kiremt (summer) at 26.6%, and Bega (dry season) at 37.8%. Although the annual rainfall trend declined over time, it was not statistically significant ($p > 0.05$). Seasonal trends revealed a significant decrease in Belg rainfall, whereas Kiremt rainfall increased slightly but without statistical significance. The annual minimum and maximum temperatures showed an increasing trend, with the minimum temperature increase being statistically significant. The minimum temperatures during the Kiremt and Belg seasons also showed significant increases, whereas the maximum temperatures did not significant trend. Drought occurrences were assessed using the SPEI at 3-month and 12-month time scales. Severe to extremely severe droughts were identified in the years 1984, 1986, 1987, 1993, 2002, 2004, 2009, 2012, 2015, 2016, and 2022. These findings highlight the increasing frequency and intensity of droughts, as well as significant temperature increases and variability in rainfall patterns. The insights provide critical guidance for policymakers and stakeholders to develop effective adaptation and mitigation strategies, enhancing resilience to climate variability and its associated risks in the region.

KEYWORDS: rainfall, temperature, Mann-Kendall test, coefficient of variation, anomalies.

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1. INTRODUCTION

Climate change is one of the most significant challenges facing the world today, impacting ecosystems, economies, and human societies on a global scale (Abidoye & Odusola, 2015; Intergovernmental Panel on Climate Change - IPCC, 2023). While climate change results from both natural processes and anthropogenic activities, the latter has driven more frequent and severe climate extremes, with far-reaching consequences (Belay et al., 2021). In particular, human-driven climate change has led to disruptions in weather patterns, contributing to adverse impacts such as droughts, flooding, and rising temperatures (IPCC, 2023).

Ethiopia, like many regions in sub-Saharan Africa, is particularly vulnerable to the effects of climate change, especially in climate-sensitive sectors such as agriculture, forestry, fisheries, energy, and tourism

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(IPCC, 2023; Ware, 2022). Recent studies indicate noticeable shifts in Ethiopia's climate over the past few decades, with some showing declining rainfall trends and others suggesting an increase in certain regions (Belay et al., 2021; Benti & Abara, 2019). For example, Cheung et al. (2018) found a significant reduction in Kiremt (June–September) rainfall, particularly in the southwestern and central Rift Valley areas. Additionally, research by Gashaw et al. (2023) in Southern Ethiopia revealed a decline in annual rainfall and a rise in temperatures, along with severe drought events in 2009 and 2015. The Standardized Precipitation Evapotranspiration Index (SPEI) has become a valuable tool for assessing drought conditions and temperature-induced precipitation deficits (Kourouma et al., 2022).

Despite these findings, there remain gaps in understanding the specific climate dynamics in certain regions of Ethiopia, particularly in the Loka Abaya area. This region is known for its vulnerability to droughts, but there is limited information on seasonal and long-term variations in rainfall and temperature trends. Previous studies have not fully addressed how these factors interact and influence drought severity in the region. A comprehensive analysis of these trends is essential for improving climate prediction models and developing effective mitigation strategies.

This study focuses on the Loka Abaya area in Southern Ethiopia, aiming to examine trends in rainfall and temperature variability, as well as the occurrence and severity of droughts over the past four decades (1981–2022). The study addresses the following research questions: have rainfall and temperature trends changed in the Loka Abaya region between 1981 and 2022? what is the distribution of rainfall anomalies in the area? And how do seasonal and annual rainfall patterns vary, and what are the characteristics of drought in this region? By filling these gaps, this research seeks to contribute to a better understanding of the region's climate dynamics, providing valuable insights for adaptation and mitigation strategies.

2. LITERATURE REVIEW

Climate change and variability encompass both natural and anthropogenic influences on climate patterns over extended periods. Natural variability arises from dynamic interactions within the climate system, including ocean-atmosphere processes such as El Niño and La Niña events, which significantly impact global and regional weather patterns. Additional natural factors, such as volcanic activity and variations in solar radiation, also contribute to fluctuations in the Earth's climate. These processes are fundamental drivers of climatic conditions and play a pivotal role in shaping weather patterns and climate systems over time. In contrast, anthropogenic activities have considerably intensified climate change and variability, creating unprecedented challenges for global systems. The burning of fossil fuels, large-scale deforestation, and industrial processes has dramatically increased greenhouse gas (GHG) concentrations in the atmosphere (IPCC, 2023). These processes are fundamental drivers of climatic conditions, shaping weather patterns and climate systems over time; however, the rise in GHG levels has accelerated the greenhouse effect, leading to global warming and its associated consequences, such as rising temperatures, melting ice caps, and shifting weather patterns.

Climate trends refer to the consistent and directional changes in climate variables, such as temperature and rainfall, observed over extended periods. These trends provide critical insights into how climate systems evolve over time and their implications for various sectors. Understanding both long-term climate variability and trends is essential for assessing the impacts of climate change. The effects of these changes are widespread, influencing ecosystems, agriculture, water resources, and human livelihoods (IPCC, 2023). The Intergovernmental Panel on Climate Change, (2014) reported a clear and measurable upward trend in global temperatures. Over the period of 2006–2015, global temperatures rose approximately 0.87°C compared to the late 19th century. This warming has been accompanied by notable changes in rainfall distribution and patterns, as well as shifts in the timing and frequency of extreme weather events, including heatwaves, floods, and droughts. These changes underscore the need to study climate variability and trends on both global and regional scales to fully understand their potential consequences.

Regional climate trends exhibit distinct patterns that are influenced by various factors such as geographic location, altitude, and proximity to large bodies of water (Serreze & Barry, 2011; Yamanouchi & Takata, 2020). The tropical regions are experiencing a rise in the frequency and intensity of extreme weather events, including hurricanes, floods, and droughts. These changes are largely driven by increasing sea surface temperatures, which influence atmospheric circulation and intensify storm patterns (Bolan et al., 2024). The contrasting trends between the tropical and Arctic regions highlight the complex ways in which climate change manifests at a regional scale, underscoring the need for targeted climate mitigation and adaptation strategies (Bolan et al., 2024).

Droughts are prolonged periods of abnormally low precipitation, leading to water shortages and significant socioeconomic impacts, particularly in agriculture-dependent regions. Drought occurrence has been a subject of extensive research, as changes in climate are expected to alter both the frequency and intensity of droughts (Bharambe et al., 2023). Recent studies have shown that long-term climate variability and trends have significantly affected the occurrence of droughts worldwide (Kendon et al., 2019; Mera, 2018). Some regions, particularly the tropics and subtropics, are experiencing more frequent droughts due to reduced rainfall, others may experience increased drought intensity as temperatures rise, accelerating evaporation (Bolan et al., 2024; IPCC, 2023).

Statistical approaches to analyzing droughts. To assess long-term climate variability and drought occurrences, researchers employ a range of statistical methods, including trend analysis and drought indices. One of the widely used methods for identifying trends in temperature and precipitation is the Mann-Kendall test, which is employed to determine whether there is a significant upward or downward trend in climate variables over a specific period (Mann, 2013). Additionally, Standardized precipitation evapotranspiration index (SPEI), Standardized Precipitation Index (SPI) and the Palmer Drought Severity Index (PDSI) are frequently used to quantify and monitor drought severity over time (Burka et al., 2023; Mckee et al., 1993; Vicente, 2010). These indices, when used alongside temperature and rainfall data, help in evaluating the long-term behavior of droughts and the role of climate change in their frequency and intensity.

3. RESEARCH METHODS

3.1. Description of study area

The study was conducted in Loka Abaya, located on the western border of the Sidama Regional State in Ethiopia, at coordinates 6°17′25″ N latitude and 37°49′44″ E longitude (Figure 1). The area is situated 325 km southwest of the capital, Addis Ababa, and 50 km southwest of the regional city of Hawassa. The study area is located in a major agroecological zone characterized by hot to warm submoist lakes and great rift valleys with a total area of 119,000 ha. It experiences a bimodal rainfall pattern, with a short rainy season from March to May and the main rainy season from June to September. Mean annual rainfall in the region ranges from 636.5 mm to 1,320 mm, with an average of 967.1 mm. The mean annual temperature ranges from 27.4°C to 31.2°C. The mean seasonal maximum temperatures were recorded as 30.5°C for Belg (February–May), 27.5°C for Kiremt (June–September), and 30.12°C for Bega (October–January), respectively. The mean seasonal minimum temperatures were recorded as 12.62°C for Belg, 12.53°C for Kiremt, and 12.06°C for Bega, respectively. The area is also characterized by erratic rainfall, moisture stress, and high temperatures during the different seasons. Specifically, rainfall during the Belg season exhibited a statistically significant decreasing trend ($P < 0.05$), leading to increased moisture stress (Table 2). This season is particularly critical for farmers, as it dictates the timing of land preparation and planting activities, which are essential for agricultural productivity. The altitude varies from 1,178 m to 1,851 m above sea level. Agriculture is the primary livelihood source for most of the population, and the predominant soil type is grey sandy loam, which is prone to erosion. Based on the 2007 Census conducted by the CSA, this woreda has a total population of 99,233, of whom 50,603 are men and 48,630 women; 1,059 or 1.07% of its population are urban dwellers. The district is endowed with forest vegetation that is dominated by species such as Acacia species, Erythrina brucei, Commiphora africana, Albizia gummifera, Balanite eagyptiaca, Ficus species, Cordia africana, Calpurnia aurea, Croton macrostachyus, and others. Exotic plant species such as Grevillea robusta, Pinus patula, and Eucalyptus and Cupressus lusitanica occupy the plantation forest of the district.

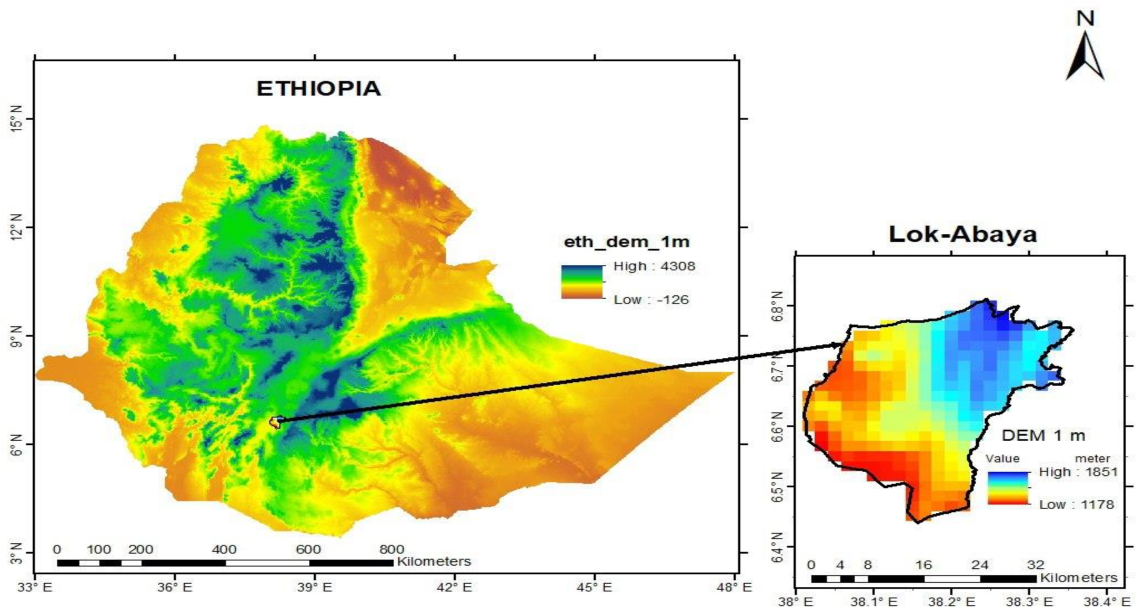


Figure 1. Map of the study area.
Source: Author analysis.

3.2. Data type and sources

The climate data used in this study were obtained from the Ethiopian Meteorological Institute (EMI). The dataset included daily temperature and rainfall data, which were gridded by merging station data with satellite data. The data had a grid cell size of 0.0375 degrees (approximately 4 km × 4 km) and covered the period from 1981 to 2022. The Ethiopian Meteorological Institute used the latest type of instruments installed at stations for ground observations, including Raingauges for rainfall and Thermometers for temperature.

3.3. Data analysis

Different techniques were employed to analyze rainfall and temperature, typically falling under the categories of variability and trend analysis. The data were analyzed using the Coefficient of Variation (CV), Mann-Kendall (MK) test, percentage departure from the mean (anomalies), and the Standardized Precipitation Evapotranspiration Index (SPEI). Data analysis was conducted using XLSTAT software. The Coefficient of Variation (CV) was used to assess the variability of rainfall. A higher CV value indicates greater variability, while a lower CV suggests less variability. The CV is calculated as follows:

$$CV = \frac{\sigma}{\mu} \times 100\,, \tag{1}$$

where σ is the standard deviation and μ is the mean precipitation. CV is used to classify the degree of rainfall variability as follows: low variability (CV < 20), moderate variability (20 < CV < 30), and high variability (CV > 30). Additionally, the standardized anomaly of rainfall was calculated to examine the nature of the trends, identify dry and wet years, and assess the frequency and severity of droughts (Asfaw et al., 2018; Dad et al., 2021; Mihiretu et al., 2021) as:

$$Z = \frac{(Xi - \overline{\overline{Xi}})}{s}\,, \tag{2}$$

where Z is the standardized rainfall anomaly, X_i is the annual rainfall for a particular year, $\overline{Xi}$ is long term mean annual rainfall over a period of observation, and s is the standard deviation of annual rainfall over the same period. The drought severity classes are extreme drought (Z < _1.65), severe drought (_1.28 > Z

> _1.65), moderate drought (_0.84 > Z > _1.28 and no drought (Z > _0.84) (Burka et al., 2023; Mckee et al., 1993; Vicente, 2010).

Mann-Kendall (MK) trend test is a non-parametric method commonly used to detect monotonic trends in environmental, climate, or hydrological data. In this study, the MK test was applied to identify the presence of monotonic (increasing or decreasing) trends in the climate data for the study area and to assess whether these trends were statistically significant. Since the dataset may contain outliers, the non-parametric nature of the MK test makes it particularly useful. This is because the MK test statistic trusts on the signs (+ or -) of the data points, rather than their actual values. As a result, the trends identified by the MK test are less sensitive to outliers (Asfaw et al., 2018; Birsan et al., 2005). The MK test is widely used to detect trends in meteorological variables (Adnew & Woldeamlak, 2013; Kiros et al., 2016; Willems, 2015). Trend analysis was conducted on an annual basis, as well as for the Belg and Kiremt seasons. Given that the Kiremt rainfall occurs from June to September in the study area, monthly trends for these four months were also analyzed separately.

The MK test statistic 'S' is calculated based on Mann, (2013) and Yue & Wang, (2002) using the formula (3):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \tag{3}$$

The application of trend test is done to a time series x_i that is ranked from i 1, 2...n-1 and x_j, which is ranked from j ¼ i þ 1, 2.... n. Each of the data point x_i is taken as a reference point which is compared with the rest of the data point's x_j so that:

$$sgn(x_j - x_i) = \begin{cases} +1 \; if \; (x_j - x_i) > 0 \\ 0 \; if \; (x_j - x_i) = 0 \\ -1 \; if \; (x_j - x_i) < 0 \end{cases}, \tag{4}$$

where X_i and X_j are the annual values in years i and j (j > i) respectively.

It has been documented that when the number of observations is more than 10 (n ≥ 10), the statistic 'S' is approximately normally distributed with the mean and E(S) becomes 0. In this case, the variance statistic is given as:

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{t=1}^{m} t_1(t_1-1)(2t_1+5)}{18}, \tag{5}$$

where n is the number of observation and t_i are the ties of the sample time series. The test statistics Zc is as follows:

$$Z = \begin{cases} \frac{S-1}{\sigma} & if \;\; S > 0 \\ 0 & if \;\; S = 0 \\ \frac{S+1}{\sigma} & if \;\; S < 0 \end{cases}, \tag{6}$$

where Z follows a normal distribution, a positive Zc indicates an upward trend, while a negative Zc indicates a downward trend over the given period. Sen's Slope Estimation method computes both the slope (i.e., the linear rate of change) and the intercept. The magnitude of the trend is predicted using Theil's and Sen's (1968) (Sen et al., 2016) slope estimation methods. A positive value of β indicates an upward trend (increasing values over time), while a negative value of β indicates a downward trend. In this method, the slope β for all data pairs is computed. Generally, the slope β between any two values in a time series x can be estimated using the following formula (7):

$$\beta = \frac{x_j - x_i}{j - i} \tag{7}$$

Let x_j and x_i represent data values at times j and k (j > i) correspondingly. A positive value of β indicates an increasing trend, while a negative value of β indicates a decreasing trend. The sign of β reflects the direction of the trend, while its magnitude indicates the steepness of the trend. One key advantage of this method is that it reduces the influence of missing values or outliers on the slope compared to traditional linear regression. Additionally, the coefficient of variation (CV) is used to evaluate the variability of rainfall data in relation to its standard deviation, and it is typically expressed as a percentage.

Standardized precipitation evapotranspiration index (SPEI) is a multiscalar/meteorological drought index, and it responds to weather conditions that have been abnormally dry or abnormally wet. The severity of drought is influenced not only by precipitation deficit but also by the increased atmospheric evaporative demand. Evaporative demand plays a particularly significant role during periods of low precipitation. We describe here a simple multiscalar drought index (the SPEI) that combines precipitation and temperature data. The SPEI is very easy to calculate, and it is based on the original SPI calculation procedure. The SPEI uses the monthly (or weekly) difference between precipitation and PET (Vicente, 2010). Calculating the Standardized Precipitation-Evapotranspiration Index (SPEI) requires long-term, high-quality datasets of precipitation and atmospheric evaporative demand (Mckee et al., 1993). In order to estimate the value of SPEI, the difference of the water balance is normalized as log- logistic probability distribution. The following equation (8) expresses the probability density function:

$$f(x) = \frac{\beta}{\alpha}\left(\frac{X-Y}{\alpha}\right)\left[1+\left(\frac{X-Y}{\alpha}\right)\right]2\,, \tag{8}$$

where parameters α, β, and γ represent scale, shape and origin, respectively. Therefore, the probability distribution function can be expressed as:

$$f(x) = \left[1+\left(\frac{\alpha}{x-y}\right)\beta\right]^{-1} \tag{9}$$

Vicente–Serrano (Vicente et al 2009) calculated the SPEI as follow:

$$SPEI = W - \frac{C_O + C_1W + C_2W^2}{1+d_1w+d_2w^2+d_3w^3}\,, \tag{10}$$

when P is the probability of exceeding a determined D value $P \leq 0.5$ W = _−2 in (P), and when $P \geq 0.5$, W = −2 ln (1 − P), The constants are $C_0 = 2.5155$, $C_1 = 0.8028$, $C_2 = 0.0203$, $d_1 = 1.4327$, $d_2 = 0.1892$, $d_3 = 0.0013$.

The average value of SPEI is 0, and the standard deviation is 1. The SPEI is a standardized variable, and it can therefore be compared with other SPEI values over time and space. An SPEI of 0 indicates a value corresponding to 50% of the cumulative probability of *D*, according to a log-logistic distribution. The categorization of drought classified by the SPEI is show in Table 1.

Table1. Climatic moisture categories for the SPEI classes as per Vicente-Serrano et al. (2010).

Categorization	SPEI Values
Extremely wet	SPEI≥ 2.0
Severely wet	1.5 < SPEI<2
Moderately wet	1< SPEI< 1.5
Mildly wet	0.5<SPEI<1
Normal	-0.5<SPEI<0.5
Mild drought	-1<SPEI<-0.5
Moderate drought	– 1.0 <SPEI< – 1.5
Severe drought	-2<SPEI<-1.5
Extreme drought	SPEI<-2

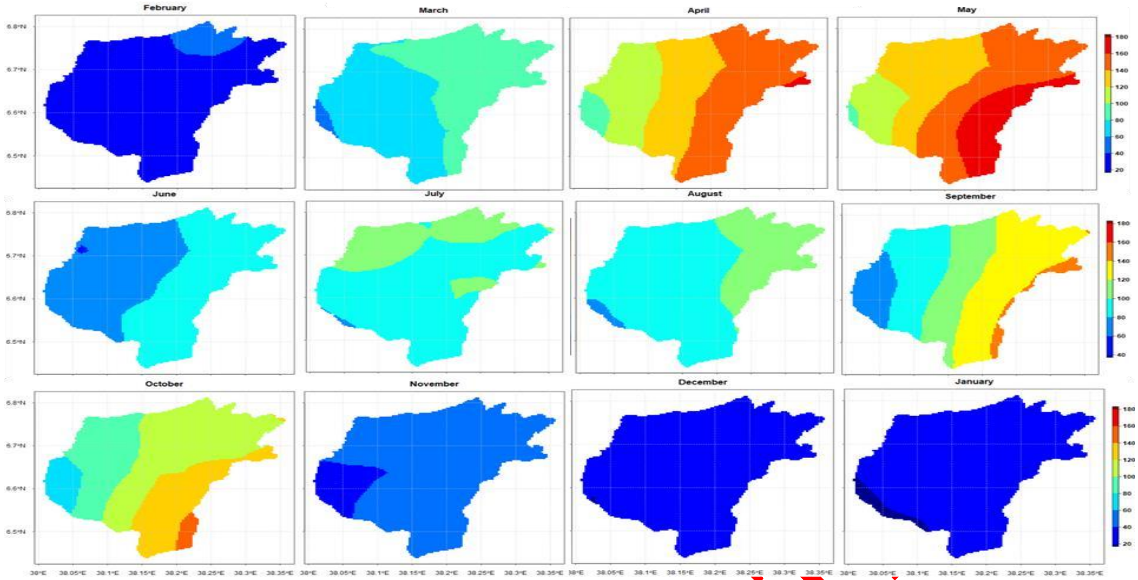
Source: Liu et al., 2021.

4. RESULTS

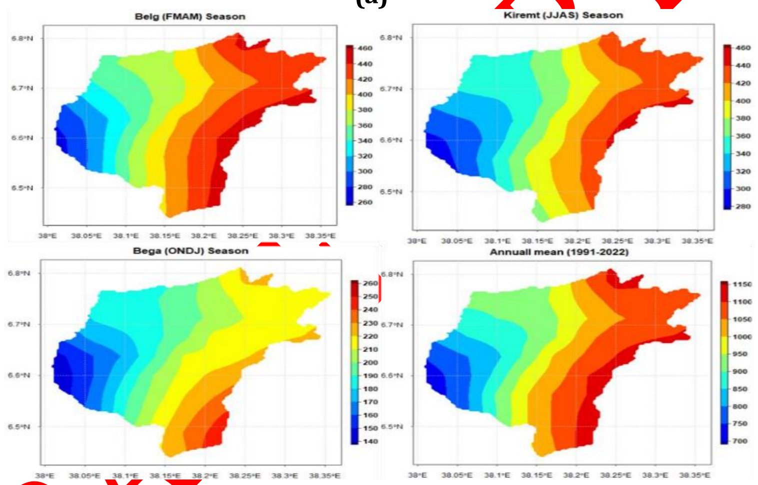
4.1. Rainfall and temperature

4.1.1. Rainfall patterns and trends

Rainfall data spanning 42 years was analyzed for the Loka Abaya district, revealing that the mean annual rainfall ranged from 636.5 mm to 1320 mm, with an overall mean of 967.1 mm. The Belg season (February–May) contributed more to the total annual rainfall than the Kiremt season (June–September), with the mean seasonal rainfall for Belg and Kiremt at 387mm and 379 mm, respectively. Seasonal rainfall showed notable variability: Belg ranged from 138 mm to 614 mm, and Kiremt ranged from 218 mm to 616 mm (Figure 2 a, b).



(a)



(b)

Figure 2. Monthly rainfall distribution climatology (**a**); Seasonal rainfall distribution climatology (**b**).
Source: Author analysis.

Table 2. Basic statistics and MK trend analysis of rainfall in Loke Abaya.

Variables Rainfall	Mean(mm)	SD (mm)	CV (%)	Sen.'s (β)	MK Test (P-Value)	RF Trends Contribution (%)
Belg	387.123	109.65	28.3	-2.525	0.046*	40.03
Kiremt	379.808	100.96	26.6	0.589	0.618	39.27
Bega	200.212	75.72	37.8	0.811	0.488	20.7
Annual	967.127	169.6	17.54	-2.178	0.448	100

MK is the Mann–Kendall trend test, β = Sen's slope, SD = Standard Deviation; CV = coefficient of variation.
*= indicate significant at $p < 0.05$.
Source: Author analysis.

Annual rainfall variability was low, with a coefficient of variation (CV) of 17.54%. However, seasonal rainfall exhibited higher variability, with Belg showing 28.3% CV, Kiremt at 26.6%, and Bega at 37.8%. Statistical analysis indicated a significant decreasing trend in the Belg season's rainfall ($P < 0.05$) (Table 2), while the overall annual rainfall showed a non-significant decreasing trend, with a slope (β) of -1.713

(Figure 3). This decreasing trend in rainfall was also evident in decadal analyses, where rainfall from 2000 to 2020 showed an average deficit of about 82.3 mm annually (Figure 5).

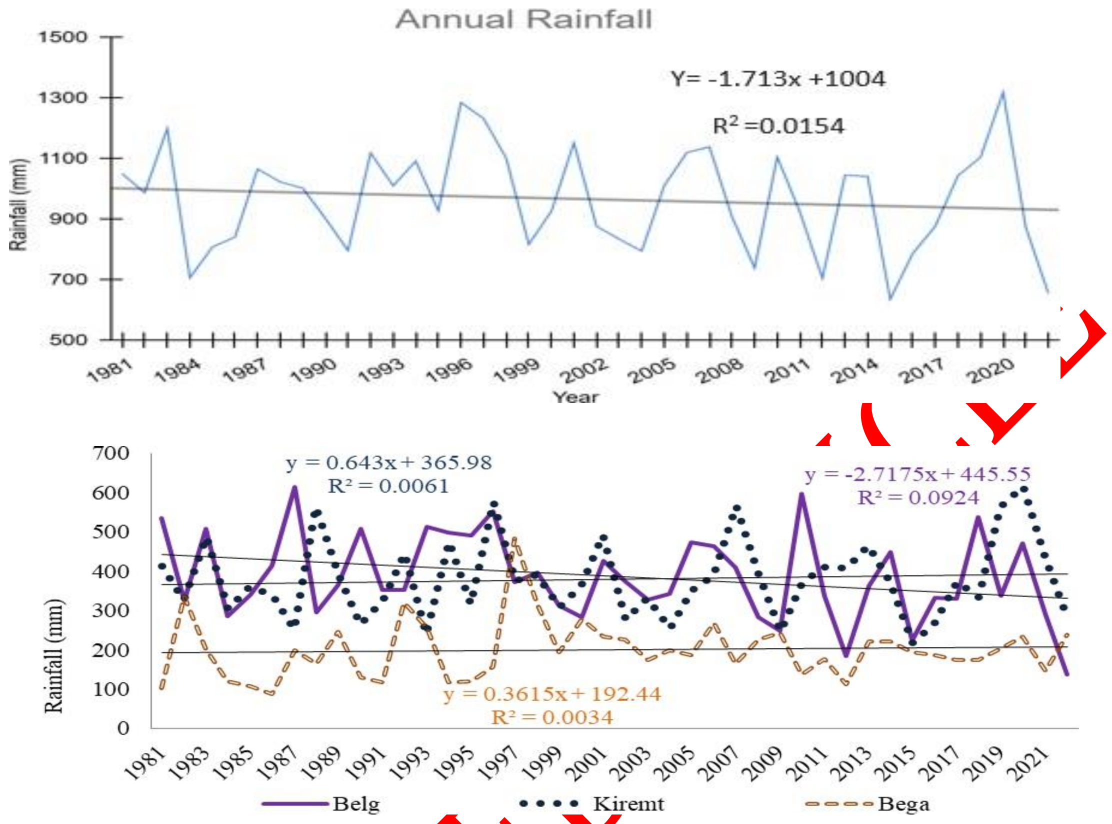


Figure 3. Long-term annual and seasonal rainfall variability of Loka Abaya (1981–2022). Source: Author analysis.

To assess deviations in rainfall from the established average for the period 1981–2022, the anomaly of the rainfall variables was calculated, with results shown in Figure 4. Any deviation from the baseline annual mean rainfall indicates variability. The baseline is represented by the zero, corresponding to the total mean rainfall value of 967.13 mm. Annual rainfall fell below the average in the following years: - 1984, 1985, 1986, 1991, 1999, 2003, 2004, 2005, 2008, 2009, 2013, 2015, 2016, 2017, 2021, and 2022 (Figure 4).

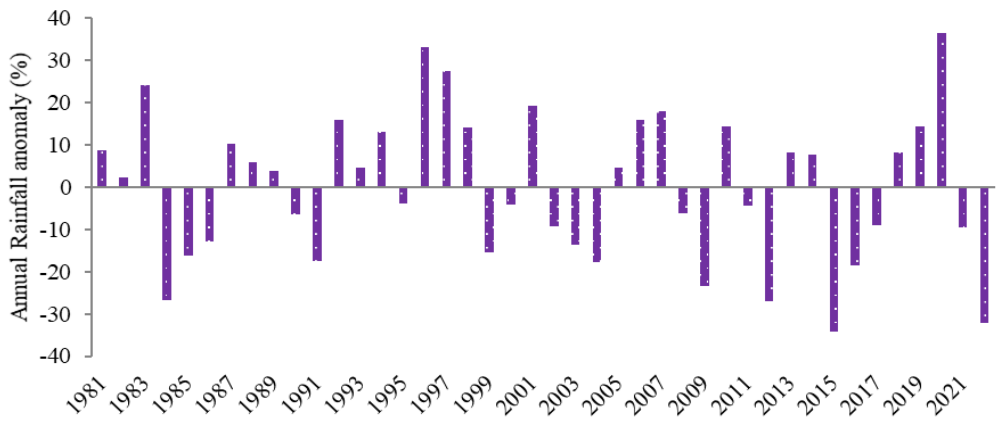


Figure 4. Long-term annual rainfall anomaly of Loke Abaya (1981–2022). Source: Author analysis.

The decadal mean annual rainfall for the periods 1981–1990, 1991–2000, 2001–2010, and 2011–2020 were recorded as 959.54 mm, 1031.51 mm, 968.68 mm, and 949.21 mm, respectively (Figure 5). This shows that, over the last two decades, the rainfall pattern has exhibited a decreasing trend, with an average rainfall deficiency of about 82.3 mm per year from 2000 to 2020. These results are consistent with findings from recent studies conducted in Ethiopia and the broader East Africa region (Belay, et al., 2021; Fink & Knippertz, 2019).

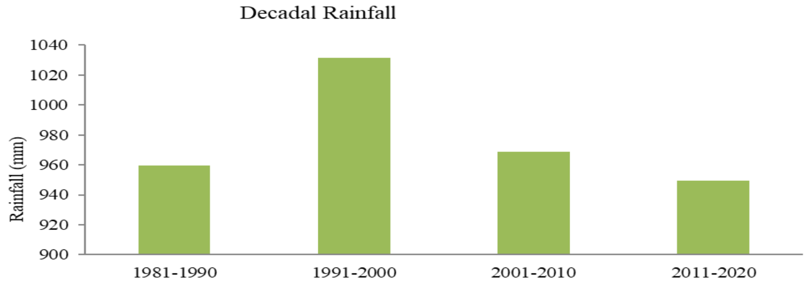


Figure 5. Average decadal annual rainfall trend analysis of Loke Abaya (1981–2022).
Source: Author analysis.

4.1.2. Temperature variability and trends

Analysis of temperature data for the past 42 years revealed an increase in both minimum and maximum temperatures. The mean annual minimum temperature was 12.41°C, and the maximum was 29.36°C. A statistically significant increase in the minimum temperature was observed over time, with a slope (β) of 0.07 (P = 0.001) for annual data. Seasonal minimum temperatures showed significant increases across all seasons, with the largest rate of increase in the Belg season at 2.7°C. However, the maximum temperatures did not show significant trends (Table 3). These trends are consistent with prior studies in Ethiopia, indicating a warming trend over the past decades (Figure 6).

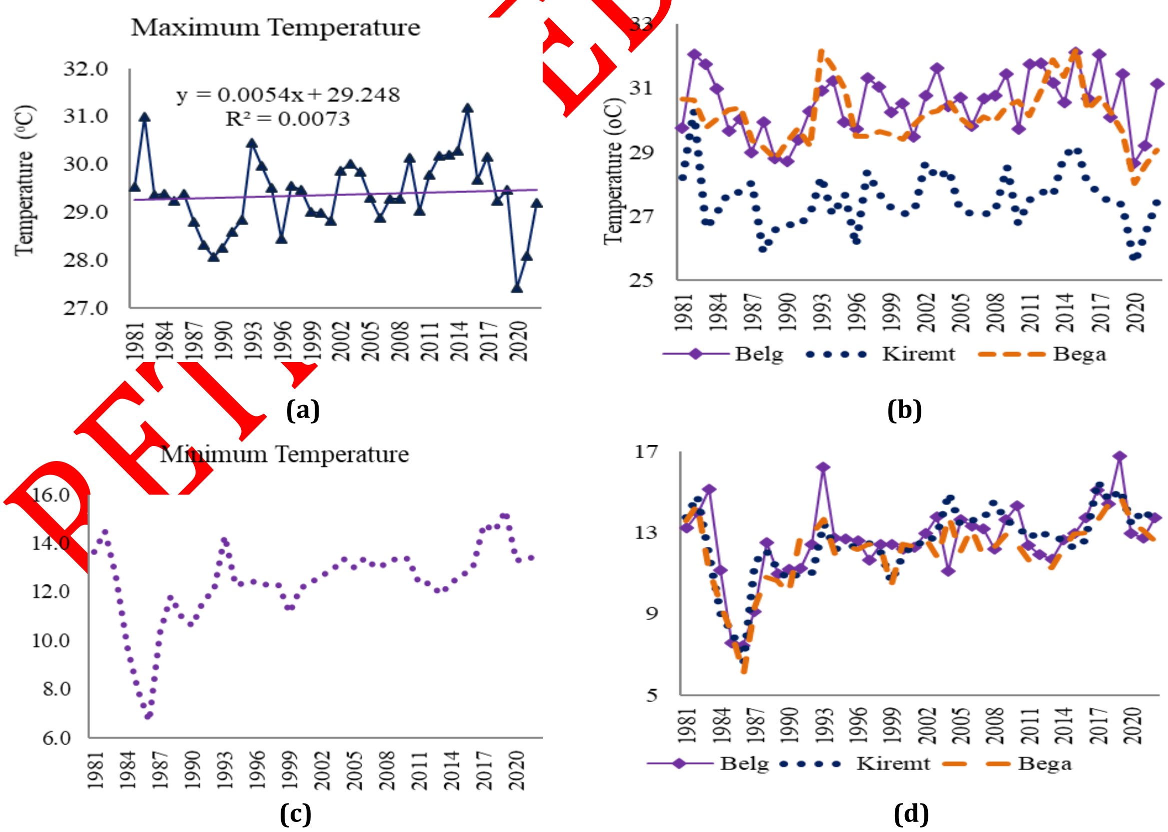


Figure 6. Annual and seasonal Maximum (**a** and **b**) and Minimum (**c** and **d**) average temperature of Loke Abaya (1981-2022).
Source: Author analysis.

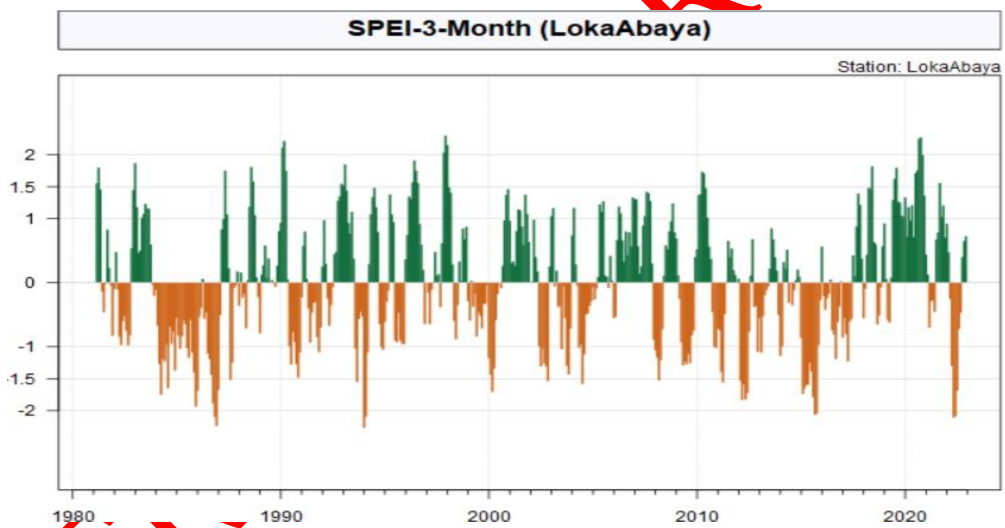
Table 3. Basic statistics and MK trend analysis of temperature in Loke Abaya (1981–2022).

Variable	Mean	SD	CV	Slope (β)	MK test (p-value)
Tmin (Annual)	12.41	1.64	13.18	0.07	0.001*
Tmax (Annual)	29.36	0.775	2.61	0.013	0.308
Tmin (Belg)	12.65	1.76	14.26	0.062	0.002*
Tmin (Kiremit)	12.53	1.78	14.02	0.077	0.0001*
Tmin (Bega)	12.05	1.74	13.89	0.055	0.009*
Tmax (Belg)	30.5	0.95	3.11	0.027	0.119
Tmax (Kiremit)	27.5	0.904	3.25	0.007	0.603
Tmax (Bega)	30.1	1.03	2.98	0.006	0.665

MK is the Mann–Kendall trend test, β = Sen's slope, SD = Standard Deviation; CV = coefficient of variation. *= indicate significant at $p < 0.05$.
Source: Author analysis.

4.2. Drought patterns

The 3-month Standardized Precipitation Evapotranspiration Index (SPEI-3) was used to assess short-term drought patterns from 1981 to 2022. Severe to extreme droughts were recorded in the years 1984, 1985, 1986, 1987, 1993, 2002, 2004, 2009, 2012, 2015, 2016, and 2022 (Figure 7a).



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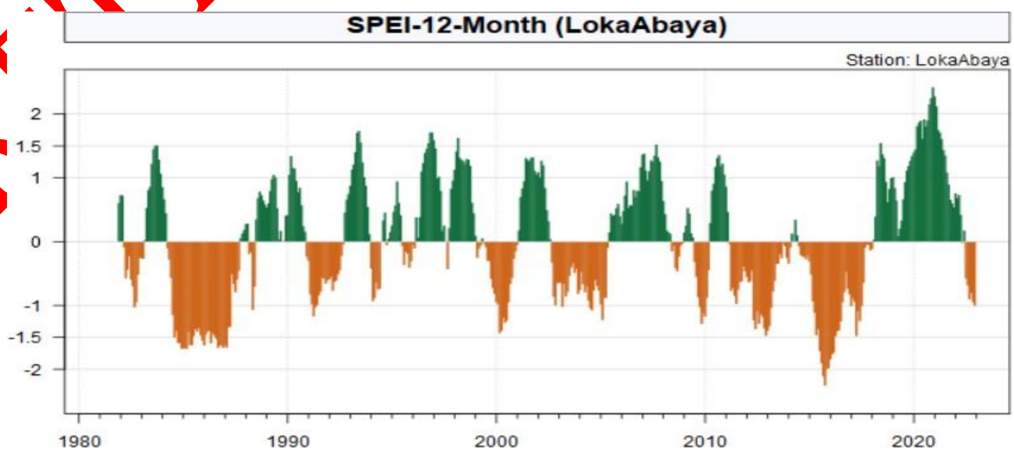

(b)

Figure 7. Three-month (**a**) and annual (**b**) time steps SPEI of Loka Abaya (1981-2022).
Source: Author's analysis.

These droughts were particularly pronounced during the Belg and Kiremt seasons. Over the past decade, the frequency of drought years has increased, leading to challenges for crop production. The 12-month SPEI also showed prolonged droughts, especially in the years 1984, 1985, 1986, 1987, 2009, 2012, 2015, 2016, and 2022 (Figure 7b). These long-term droughts indicate a shift toward more persistent water scarcity in the region, with implications for agriculture and water supply systems.

In addition, the 12-month SPEI from 1981 to 2022 shows us long-term hydrological reflects, groundwater level, and reservoir capacities as it prolonged periods of below-average precipitation. According to 1984, 1985, 1986, 1987, 2009, 2012, 2015, 2016, and 2022, 12-month SPEI showed that a severe to extremely severe drought was observed (Figure 7b). This region is facing longer-term water shortages, which could impact water supply systems, reservoirs, and long-term agricultural productivity.

5. DISCUSSION

The analysis of rainfall and temperature trends in the Loka Abaya district aligns with broader research on climate variability in Ethiopia and East Africa. The findings indicate notable variability and declining trends in rainfall, alongside significant increases in temperature over the past four decades. The study's results reveal an overall declining trend in annual rainfall, with significant variability during the Belg season, important period for agricultural activities in Loka Abaya. The decrease in Belg rainfall (-2.525 mm/year) aligns with findings by Belay et al. (2021) and Advances et al. (2019), Who documented reductions in rainfall during critical growing seasons across Ethiopia. Additionally, the high variability of seasonal rainfall, particularly during the Belg season (CV = 28.3%), reflects the increasing unpredictability of precipitation patterns. This aligns with research by Belay, et al., (2021) which highlights the growing frequency of extreme rainfall events, including droughts and heavy rains, as a hallmark of climate change in East Africa. The declining trend in decadal rainfall from 2000 to 2020 (average deficiency of 82.3 mm per year) further underscores the need for adaptive strategies to mitigate the impacts on agriculture and water resources.

The study's findings on increasing temperatures in Loka Abaya, particularly the significant rise in minimum temperatures during the Belg (0.062°C/year), Kiremt (0.077°C/year), and Bega (0.055°C/year) seasons, are consistent with previous research. Asfaw et al. (2018) and Suryabhagavan (2017) also observed similar trends in Ethiopia, where annual minimum and maximum temperatures have risen gradually over the past century. These temperature increases are linked to global warming and its localized effects, such as higher evapotranspiration rates and reduced soil moisture, which exacerbate drought conditions.

The study's use of the Standardized Precipitation-Evapotranspiration Index (SPEI) reveals an alarming increase in the frequency and severity of droughts, with extreme episodes recorded in 1984, 1999, 2015, and 2022. These findings align with those of Kourouma et al. (2022), who highlighted the intensification of droughts in Ethiopia, attributing this to warming temperatures and reduced rainfall. The observed long-term hydrological droughts, as reflected in the 3-month and 12-month SPEI data, further indicate water shortages, threatening agricultural productivity and water availability. Increasing temperatures and erratic rainfall patterns contribute to the vulnerability of rain-fed agricultural systems, upon which the majority of the population relies. The findings underline the urgency of implementing sustainable land and water management practices, such as soil and water conservation, improved irrigation systems, and climate-resilient crop varieties. Policymakers and stakeholders must prioritize the integration of climate adaptation strategies into regional planning to address the dual challenges of declining rainfall and rising temperatures.

6. CONCLUSIONS

The analysis of rainfall and temperature trends in the Loka Abaya district from 1981 to 2022 highlights significant climatic shifts, underscoring the need for immediate attention to agricultural and water resource management practices. The decreasing trend in Belg season rainfall, combined with rising minimum temperatures, points to heightened vulnerability to droughts and water shortages, particularly during critical agricultural periods. The study underscores the urgency of adaptive strategies, such as improved water resource management and climate-resilient agricultural practices, to address the increasing frequency of droughts and shifting climate patterns.

Despite the absence of statistically significant trends in some seasonal rainfall patterns and maximum temperatures, the overall findings suggest a concerning long-term decline in rainfall, exacerbated by temperature increases. The frequency of severe drought events, particularly in recent years, further reinforces the need for a proactive approach to mitigate the negative impacts of climate change on local livelihoods.

While this study provides essential insights, there are avenues for further research to explore. For example, more detailed studies on the interaction between temperature and evapotranspiration, as well as the potential for climate adaptation strategies tailored to local agricultural practices, would enhance the understanding of climate resilience in the region. Additionally, expanding the scope to include socio-economic impacts on local communities would provide a more comprehensive view of the challenges posed by climate change.

The limitations of this study, such as the reliance on historical data and potential variability in local microclimates, should be acknowledged, but they do not diminish the significance of the findings. The implications of this research are clear: without prompt action to address the adverse impacts of climate variability, Loka Abaya's agricultural productivity and water security will continue to face significant challenges.

Finally, this study emphasizes the importance of timely and targeted interventions to mitigate climate risks, foster sustainable agricultural practices, and ensure long-term water availability for the region. The findings serve as a call to action for policymakers, researchers, and local communities to collaborate in developing effective strategies for climate adaptation and resilience.

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Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Author contributions

All authors contributed equally to this work. All authors read and approved the final manuscript.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Non-rainy cloud cover dynamics and their influence on temperature variability in Chefchaouen, Western Rif, Morocco

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ABSTRACT: Non-precipitating cloud cover plays a significant role in modulating surface temperature by altering solar radiation and longwave heat retention. However, its thermal impacts remain underexplored in Mediterranean mountainous regions. This study investigates the influence of non-precipitating cloud cover on daily and seasonal temperature variability in Chefchaouen, Western Rif, Morocco, over a six-year period (2015–2020). The research classifies non-precipitating cloudy weather into three categories: (1) stable atmospheric conditions, (2) unstable atmospheric conditions, and (3) conditions at the periphery of frontal systems. High-resolution meteorological data, MODIS and NOAA satellite imagery, and synoptic weather maps were employed to analyze cloud-atmosphere interactions. Results reveal that stable cloud cover reduces the diurnal temperature range (DTR) by mitigating daytime heating and enhancing nocturnal warming. In contrast, unstable clouds increase thermal variability due to dynamic atmospheric processes. Seasonal effects were most pronounced in summer and winter, with notable moderation of temperature extremes. The findings highlight the role of synoptic-scale atmospheric structures, including sea-level pressure systems and 500 hPa geopotential height configurations, in shaping temperature variability under non-precipitating cloudy conditions. This study provides critical insights into Mediterranean climate dynamics and emphasizes the importance of integrating cloud-related processes into regional climate models to enhance temperature forecasting accuracy.

KEYWORDS: non-precipitating cloud cover, temperature variability, mediterranean climate, Chefchaouen, synoptic circulation patterns

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1. INTRODUCTION

Chefchaouen, located in the Western Rif Mountains of Morocco, is a distinctive climatic region shaped by its dual influence from the Atlantic Ocean and the Mediterranean Sea. Its unique geographical position, combined with the region's rugged mountainous topography, creates a highly sensitive environment to atmospheric circulation patterns, such as the North Atlantic Oscillation (NAO) and the Azores High (Lionello, 2006; Mashoudi et al., 2024; Trigo & Viterbo, 2003). While the Mediterranean climate is generally characterized by hot, dry summers and mild, wet winters, the Western Rif demonstrates complex climatic behavior driven by interactions between large-scale synoptic systems and localized microclimatic factors (Lennard & Hegerl, 2015; Newton et al., 2014). However, the specific role of non-rainy cloudy weather in shaping temperature patterns remains largely underexplored, particularly in mountainous regions.

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Cloud cover is widely recognized as a critical regulator of the Earth's energy balance, with dual impacts on surface temperatures. It reduces incoming solar radiation during the day and enhances longwave radiation retention at night, thus influencing the diurnal temperature range (DTR) (Zhu et al., 2024). Studies have shown that cloud cover can reduce DTR by 25% to 50% compared to clear-sky days, primarily due to its ability to limit surface solar radiation during the day, while having minimal influence on nighttime temperatures. However, in high latitudes during winter, clouds can increase nighttime temperatures due to their greenhouse effects (Dai et al., 1999; Jiang et al., 2022). This dual role of clouds underscores their significant contribution to surface temperature regulation and their broader implications for climate dynamics. Furthermore, as the atmosphere warms, a shift from ice to liquid-phase clouds introduces reflective and long-lived feedbacks, which reduce the absorbed solar flux and provide negative radiative feedback. Nevertheless, climate models often underestimate these effects due to biases in cloud precipitation-ralated processes (Mülmenstädt et al., 2021). These dynamics emphasize the need for more precise observational studies to improve the accuracy of climate projections.

In mountainous regions like Chefchaouen, the effects of cloud cover on temperature variability are amplified by the interactions between atmospheric dynamics and topographical features (He et al., 2020). Stable cloudy conditions are often associated with reduced DTR due to atmospheric stabilization, whereas unstable cloudy conditions may induce greater thermal variability as a result of dynamic atmospheric processes (Dai et al., 1999; Doan et al., 2022). Despite these well-documented phenomena, limited research has systematically addressed the thermal impacts of non-rainy cloudy weather in Mediterranean mountainous contexts, leaving a significant knowledge gap regarding localized climate dynamics.

This study aims to address this gap by investigating the influence of non-rainy cloudy weather on daily and seasonal temperature variability in Chefchaouen over a six-year period (2015–2020). This timeframe was carefully selected based on the availability of high-resolution meteorological data, ensuring the reliability and robustness of the analysis. The comprehensive datasets collected during this period allow for an in-depth exploration of cloud-atmosphere interactions in Chefchaouen, a region that exemplifies the complex interplay between Mediterranean climatic influences and mountainous topographical dynamics.

Chefchaouen was specifically chosen as the study site due to its climatic complexity and the intricate interactions between synoptic-scale weather systems, localized microclimatic conditions, and mountainous topography. Previous studies have highlighted the region's significant spatial variability in land surface temperature (LST), driven by its heterogeneous topography and land cover, as well as its vulnerability to natural hazards like landslides, which are influenced by geological and climatic factors (El Kharim et al., 2021; Raissouni et al., 2013). These characteristics make Chefchaouen an ideal location for investigating the thermal impacts of non-rainy cloudy weather in a Mediterranean mountainous context.

To analyze the thermal impacts of cloudy weather, this study adopts a well-established classification of non-rainy cloudy weather, originally developed by Vigneau (1985), El Baye (1990) and Arraji (1995). This classification categorizes non-rainy cloudy weather into three distinct types: (1) stable atmospheric conditions, (2) unstable atmospheric conditions, and (3) conditions occurring at the periphery of frontal systems. Building on this framework, the present study examines how cloud cover interacts with atmospheric circulations to regulate surface temperatures in this climatically and geographically sensitive region.Variations in cloud cover significantly influence surface air temperature (SAT) by modulating radiation processes: during the day, clouds block incoming solar radiation, causing cooling, while at night, they trap outgoing longwave radiation, resulting in warming. This diurnal asymmetry in cloud effects has been identified as a key amplifier of surface warming in the context of increasing greenhouse gas concentrations (Luo et al., 2024). Moreover, as the atmosphere warms, the shift from ice to liquid-phase clouds introduces reflective and long-lived feedbacks, although uncertainties remain in climate models due to biases in cloud precipitation-related processes (Mülmenstädt et al., 2021). By focusing exclusively on non-rainy periods, this study seeks to isolate these subtle yet critical dynamics within the unique climatic context of Chefchaouen.

The study adopts an integrated methodology, combining high-resolution meteorological data with synoptic weather maps to identify the atmospheric configurations associated with each cloudy weather type. It tests the hypothesis that non-rainy cloudy weather significantly moderates temperature extremes, particularly in summer and winter, when thermal variability is most pronounced. Preliminary findings suggest that cloudy weather plays a pivotal role in dampening temperature extremes and stabilizing thermal conditions, highlighting its relevance in regional climate modulation.

This research not only contributes to the scientific understanding of Mediterranean climate variability but also has practical applications for improving weather forecasting and guiding climate adaptation strategies. By shedding light on cloud-atmosphere interactions, the findings can inform critical sectors such as agriculture, water management, and urban planning, emphasizing the need for incorporating these dynamics into regional climate models for sensitive and understudied regions like Chefchaouen.

2. LITERATURE REVIEW

The relationship between cloud cover and surface temperature has been widely explored across different climatic zones, particularly in the context of global and regional climate change. Early foundational work by Lamb (1972) and later by Jones et al. (1993) developed weather type classifications that continue to underpin synoptic climatology today. These frameworks have been essential for identifying patterns of atmospheric circulation and their influence on weather dynamics, including temperature variability.

In the Moroccan and broader Mediterranean context, Vigneau (1985) offered significant methodological tools for interpreting synoptic conditions, which were later adapted by El Baye (1990, 1992) and Arraji (1995) to fit local climatic specificities. These classifications remain central to climatological studies in North Africa. However, their application has often been limited to identifying macro-scale weather types, with less emphasis on the thermal implications of non-precipitating cloudy conditions—especially in mountainous regions.

Several international studies have documented the thermal modulation effect of cloudiness, emphasizing its dual role in limiting solar radiation during the day and enhancing longwave radiation at night (Dai et al., 1999; Groisman et al., 2000). These findings are consistent across regions characterized by complex topography and transitional climates (Jiang et al., 2022). In Mediterranean settings, Pyrgou et al. (2019) and Katavoutas et al. (2023) highlighted the role of cloud cover in mitigating summer temperature extremes. Xu et al. (2021), focusing on the Himalayas, demonstrated that increased cloudiness is associated with more stable thermal regimes, a dynamic that may also apply to high-altitude areas in North Africa.

Despite these contributions, limited empirical work has been dedicated to understanding how distinct categories of non-rainy cloudy weather impact temperature variability on a seasonal and daily basis. The present study revisits and applies established classifications (Lamb, 1972; Vigneau, 1985; El Baye, 1990) in a focused regional context—Chefchaouen, northern Morocco—to examine how selected cloud types (fairly stable, quite unstable, and marginal frontal) correlate with temperature variation. Rather than proposing a novel framework, this analysis seeks to deepen the understanding of existing schemes by integrating long-term meteorological data with synoptic interpretation.

This approach aligns with the broader literature calling for more nuanced, location-specific climate diagnostics, particularly in regions marked by orographic and maritime influences. By contributing to this analytical strand, the study supports the growing effort to localize climate impact assessments, providing a reference for regional planning, environmental monitoring, and policy adaptation under evolving climatic conditions.

3. RESEARCH METHODS

3.1. Study area

Chefchaouen, located in the western Rif region of Morocco at 35.1715° N and 5.2697° W (Figure 1), enjoys a distinctive climatic profile shaped by its position between the Atlantic Ocean and the Mediterranean Sea. This unique location, combined with the complex topography of the Rif Mountains—featuring peaks like Jbel Lakrâa (2,159 meters) and Jbel Tissouka (2,122 meters)—creates diverse microclimates. The interaction of steep slopes and deep valleys with atmospheric circulation patterns significantly impacts temperature and precipitation (Hssaisoune et al. 2022; Todaro et al. 2022).

The region's orographic features enhance precipitation at higher elevations through the orographic lifting of moist air masses, while the rain shadow effect causes drier conditions on the leeward side of the mountains (El Alaoui El Fels et al., 2022). These topographical and meteorological interactions generate sharp contrasts in thermal and precipitation regimes over short distances (Camici et al., 2018). Furthermore, the moderating influence of the Atlantic Ocean and the Mediterranean Sea helps stabilize the climate, with the Canary Current along the Atlantic coast dampening daytime heat intensity and maintaining higher humidity levels during summer (Mills, 2024; Semedo, 2018).

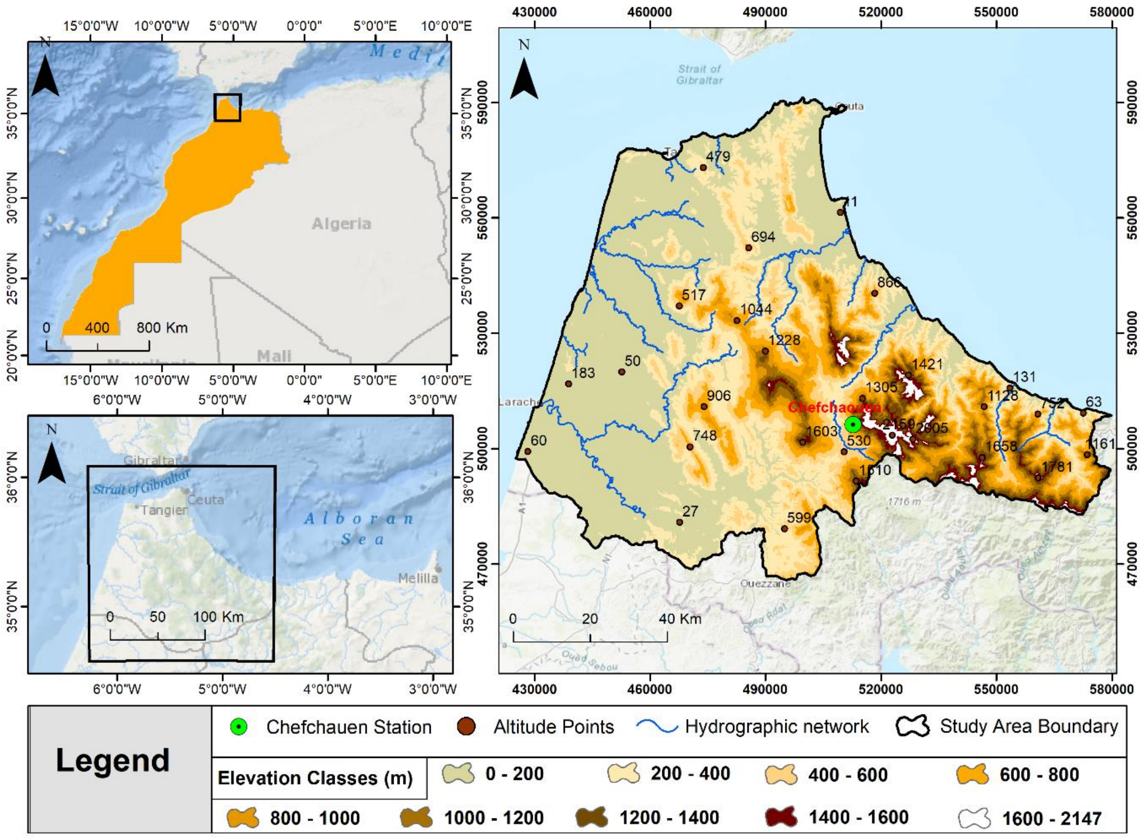

Figure 1. Localization of the study area.
Source: Created by the author (2025).

Over the 1995–2020 period, Chefchaouen's climate exhibited strong seasonal variability. Average monthly temperatures ranged from 4.2°C (January) to 34.3°C (August), reflecting cold, wet winters and hot, dry summers. Rainfall was highly concentrated between November and March, with a monthly peak of 199.9 mm in December, while the summer months, especially July and August, remained virtually dry (less thn 3 mm/month). Annual precipitation averaged around 930 mm, but showed sharp interannual fluctuations, from a minimum of 372.3 mm (2015) to a maximum of 2,422.8 mm (1996). This climatic regime reinforces the region’s sensitivity to hydro-climatic extremes and highlights the importance of understanding seasonal and interannual variability in any environmental or hydrological assessment of the area.

This interplay between maritime and topographical influences establishes Chefchaouen as a region of significant climatic heterogeneity. Detailed investigations into these dynamics are essential for understanding the area's environmental characteristics, including localized wind systems, temperature inversions, and variable precipitation patterns (Dezfuli et al., 2015). Such studies provide valuable insights into the region's hydrological processes and ecosystem dynamics (Bonino et al., 2019; Fang et al., 2010).

3.2. Data

This study utilized a dataset provided by the National Meteorological Office of Morocco (DMN), which included daily temperature records and weather conditions from the Chefchaouen meteorological station (coordinates: 35°10'21" N, 5°18'47" W, elevation: 287 meters). Covering the period from 2015 to 2020, the dataset comprised daily average, maximum, and minimum temperatures, as well as total daily precipitation and cloud cover observations. All data were subjected to rigorous quality control and validation procedures, including cross-referencing with nearby stations and detecting statistical anomaly detection.

To enhance the analysis of cloud cover and atmospheric conditions, satellite imagery from MODIS (Moderate Resolution Imaging Spectroradiometer) and NOAA (National Oceanic and Atmospheric Administration) was incorporated. These platforms offer moderate spatial resolution but high temporal frequency, enabling detailed monitoring of cloud formations, dynamics, and atmospheric structures. By integrating satellite data with ground-based measurements, the study provided a comprehensive framework for cloud classification, as supported by Zhang et al. (2011)

Aerological datasets were also utilized, covering both surface conditions (mean sea level pressure, MSLP) and upper-atmosphere dynamics (500 hPa geopotential height). This multi-level approach allowed for a nuanced understanding of atmospheric behavior. Weather maps from global models, including the Global Forecast System (GFS) and the European Centre for Medium-Range Weather Forecasts (ECMWF), were analyzed to investigate atmospheric patterns. Synoptic charts obtained from the Wetterzentrale platform, which hosts data from Deutscher Wetterdienst (DWD) and NOAA-GFS, provided additional insights into regional and global weather patterns dating back to 1979.

To reconcile the observation periods across these diverse datasets, ground-based, satellite, and aerological, the study adopted a synchronous, case-based selection protocol focused exclusively on the 2015–2020 period. Cloudy weather cases without recorded precipitation were first identified using MODIS and NOAA imagery, and then cross-referenced with local rainfall data from the Chefchaouen station. Only days fulfilling both criteria, visual cloud presence and zero precipitation, were retained. For those same dates, 500 hPa and MSLP fields were extracted from GFS and ECMWF archives to characterize the prevailing synoptic conditions. This strategy ensured full temporal alignment across all datasets and enabled the derivation of consistent weather pattern typologies.

Nevertheless, the use of daily temperature data has inherent limitations. While useful for long-term trend analysis, such data often fail to capture short-term fluctuations and extreme weather events. For instance, daily temperature measurements, typically recorded as maximum and minimum values, cannot adequately reflect rapid changes caused by localized phenomena like thunderstorms or sudden wind shifts (Zhang et al., 2011). Similarly, extreme events such as heatwaves, which are often most intense in the afternoon, are averaged out, thereby underestimating their severity (Perkins et al., 2012). In mountainous regions like the Rif, variations in altitude create significant microclimatic differences within short distances, complicating the use of daily averages for precise climate assessments (Fowler et al., 2007).

3.3. Classification method

3.3.1. Basis and approach

Various classification systems have been developed to study atmospheric patterns and their influence on regional weather. For example, the Grosswetterlagen system (James, 2007) focuses on long-term sea-level pressure patterns, while the Lamb Weather Types (Jones et al., 1993; Lamb, 1972) classify weather based on wind direction and pressure systems. These systems illustrate the diversity of approaches available for categorizing atmospheric dynamics, highlighting the adaptability required for different climatic and geographic contexts. In this study, we adopted a modified version of the classification methodology developed by Vigneau (1985), El Baye (1990) and El Baye (1992), and Arraji (1995), tailored to the subtropical characteristics of Chefchaouen.

To classify cloudy weather patterns, this study utilized Mean Sea Level Pressure (MSLP) data in conjunction with high-resolution satellite imagery from MODIS and NOAA. "Cloudy weather with fairly stable atmospheric conditions," classified with 1-4 octas of cloud cover, reflects weak disturbances or localized convective processes, often with minimal dynamic changes (Appendix I). "Cloudy weather with quite unstable atmospheric conditions" (4-8 octas) typically corresponds to upper-level disturbances or approaching frontal systems, resulting in significant cloud cover (Appendix II). Lastly, "Cloudy weather occurring at the margins of frontal systems" refers to complex synoptic conditions where nearby frontal boundaries influence local weather without dominating it (Hoskins & Karoly, 1981)(Appendix III).

To enhance accuracy, satellite data were integrated with synoptic weather charts to analyze transient phenomena and upper-level disturbances influencing cloud patterns. By combining MSLP data with satellite imagery, this approach captured surface-level dynamics and their connections with upper-atmospheric circulations (Kalisch & Macke, 2008; Philipp, 2009). This combination strengthened the robustness of the classification process

3.3.2. Encoding and categorization

To facilitate detailed daily analysis, atmospheric circulation patterns were classified based on MSLP and upper-level circulation at 500 hPa. These levels are particularly relevant for identifying daily variability due to their role in shaping weather dynamics (Dilling et al., 2017; Hufty, 2005; Liu et al., 2014). Each weather scenario was encoded using a two-letter code system: the first letter indicates the general characteristics of the air masses, while the second letter describes the sky's regional state (Appendix IV). Additional codes represented other non-precipitating weather types (see Table 1 for details).

Table 1. Frequency percentage of non-precipitating weather and its corresponding code.

Cloudy Non-Rainy Weather Types	Frequency (%)	code
Cloudy weather with fairly stable atmospheric conditions	17.5	(1)
Cloudy weather with quite unstable atmospheric conditions	16.0	(2)
Cloudy weather occurring at the margins of the frontal systems	6.5	(3)

Source: Classification adapted from Vigneau (1985) and El Baye (1990); frequency analysis by the author.

Frequencies of weather types were calculated by analyzing occurrences within the six-year dataset, allowing for detailed categorization. For example, code 3 represents weather influenced by nearby frontal systems but not dominated by them, often resulting in variable cloud cover without significant precipitation (Table 1).

3.3.3. Analysis and visualization

The study analyzed the relationship between MSLP and 500 hPa circulations to identify patterns driving non-rainy cloudy weather. Sea-level pressure systems (e.g., cyclones, anticyclones) influence wind patterns and precipitation, while 500 hPa patterns (e.g., Rossby waves) shape regional variability (Hoskins & Karoly, 1981; Peña et al., 2011). By associating recurring atmospheric structures with weather types, average temperatures were calculated for each type over the six-year period. This allowed the study to link atmospheric dynamics to temperature variability.

Figures included in Appendix IV illustrate the methodological framework adopted in this study, detailing the classification of atmospheric circulation patterns and their influence on temperature variability in the Western Rif region. These figures provide a comprehensive representation of high and low-pressure system configurations, with colored lines indicating the relative positions of isobaric structures. Additionally, the two figures presented above will be incorporated into the appendices to further clarify the synoptic conditions affecting the study area. A legend is provided within each figure to facilitate interpretation, ensuring a precise understanding of the atmospheric mechanisms shaping weather patterns in this complex mountainous region.

The study excluded weather types not directly relevant to its objectives (e.g., low stratiform clouds independent of disturbed systems) to maintain focus. Seasonal temperature trends for each weather type were represented visually, with months color-coded (red for summer, blue for winter, etc.), providing an intuitive understanding of the data.

4. RESULTS

4.1. Cloudy weather with fairly stable atmospheric conditions (1)

The "Cloudy weather with fairly stable atmospheric conditions (1)" classification occurred 387 times over the study period, representing 17.5% of all recorded cases (Table 1). This weather pattern demonstrates notable seasonal variations, with the highest frequency observed during the summer months (38.5%), followed by winter (22.4%), autumn (19.8%), and spring (19.3%) (Figure 2).

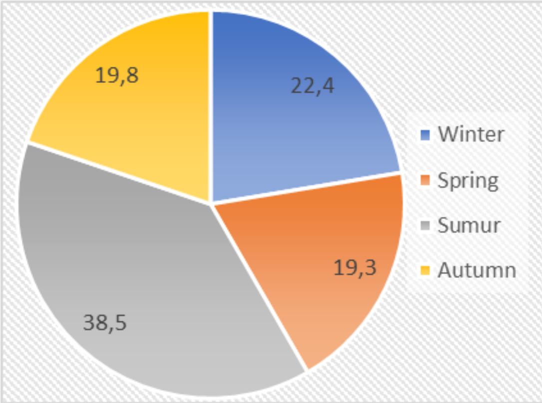

Figure 2. Seasonal Distribution of Cloudy weather with fairly stable atmospheric conditions (1) Occurrences (%).
Source: Created by the author based on seasonally categorized meteorological data.

Building on these seasonal variations, further analysis of sea-level pressure (SLP) configurations provides deeper insights into the mechanisms driving stable, cloudy weather conditions. These configurations highlight the specific atmospheric patterns responsible for the observed variations across seasons.

The seasonal data on sea-level pressure (SLP) configurations reveal significant variation in cloudy weather occurrences under stable atmospheric conditions (1) across different seasons (Figure 3).

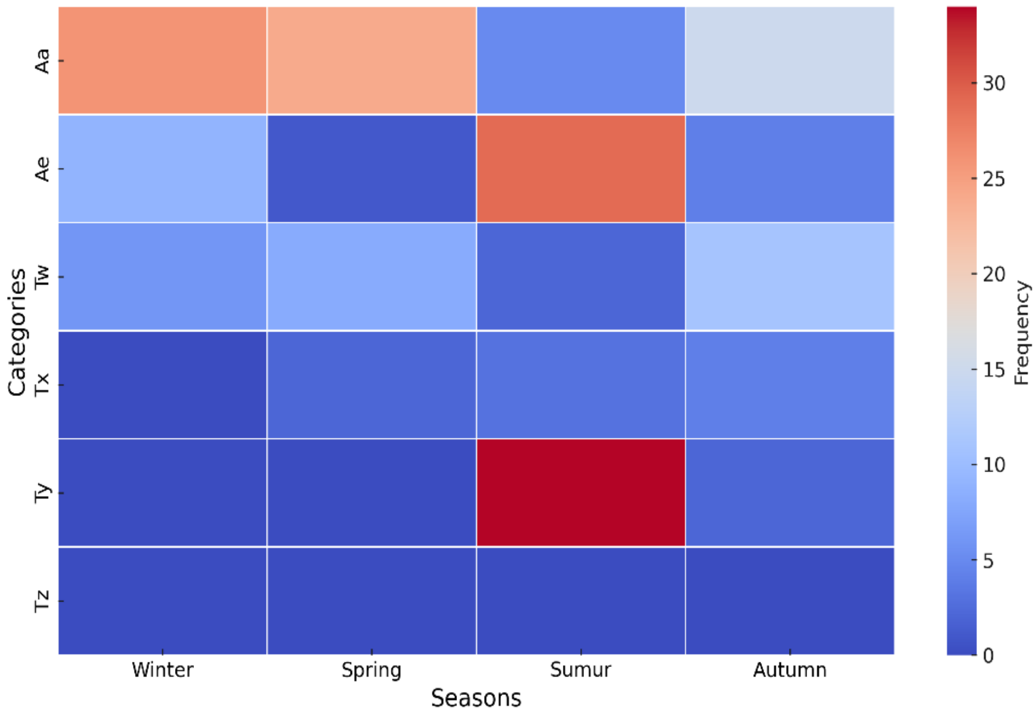

Figure 3. Seasonal distribution of sea-level pressure (SLP) configurations for Cloudy weather with fairly stable atmospheric conditions (1) conditions.
Source: Visualization created by the author based on categorized meteorological data (Chefchaouen Station).

Summer exhibits the highest frequency of these configurations, with Tz being the most prominent, reflecting the influence of stable, high-pressure systems during this period. Despite the general atmospheric stability during (1) conditions, the presence of sufficient relative humidity in the mid-troposphere contributes to the formation of light, intermittent clouds (Groisman et al., 2000; Kolendowicz et al., 2021), particularly during transitional phases such as the Tz configuration in summer. In contrast, winter is marked by the presence of Aa, representing the high pressure centered over the Atlantic Ocean, contributing to stable weather conditions but at a lower frequency compared to summer (Figure 3). Other configurations, such as Tw and Ae, are more evenly distributed during the transitional seasons of spring and autumn, where shifting atmospheric patterns play a critical role in shaping relatively stable cloudy weather. These seasonal variations underscore the importance of different atmospheric configurations in influencing weather stability across the year.

The seasonal data on 500 hPa pressure configurations reveal significant variation in cloudy weather occurrences under stable atmospheric conditions (1) across different seasons (Figure 4). Summer shows the highest frequency, with Sg occurring 18 times and Cd appearing 13 times, reflecting the influence of stable upper-level systems during this period. In contrast, winter is marked by the presence of Ng, which occurs 14 times, associated with northerly currents contributing to stable weather, though less frequently than in summer. Other configurations, such as Vc in autumn with 10 occurrences and Cc in spring with 7 occurrences, are more evenly distributed during the transitional seasons, where shifting atmospheric patterns shape relatively stable cloudy weather. These seasonal variations underscore the importance of upper-atmospheric configurations in influencing weather stability throughout the year.

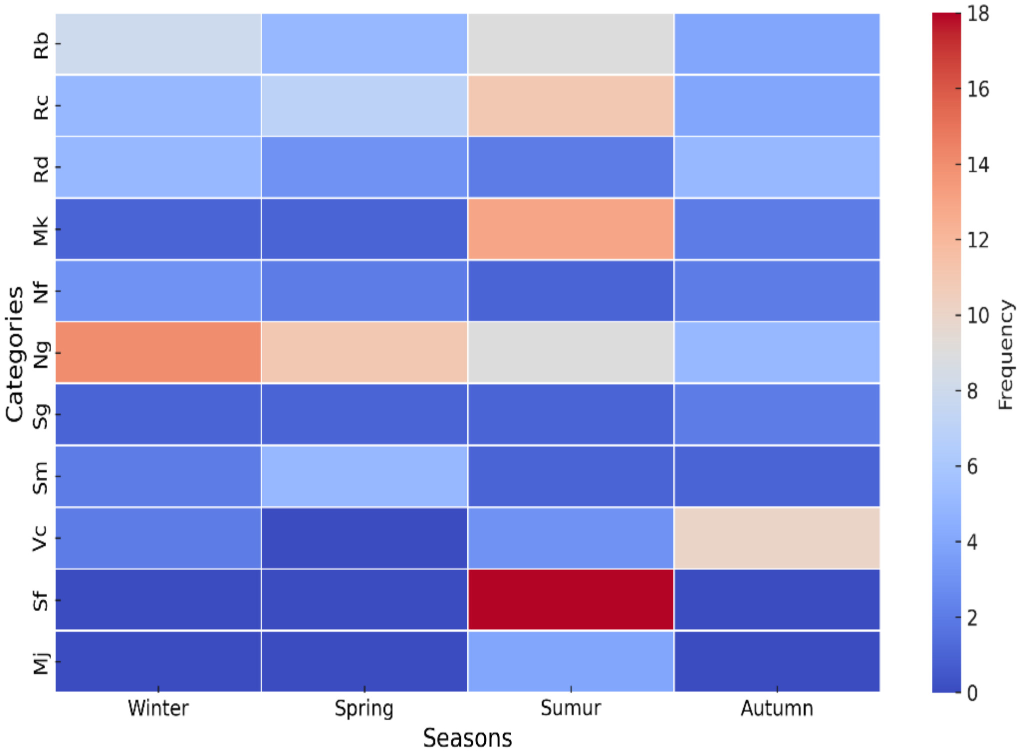

Figure 4. Seasonal distribution of sea-level pressure (500 hPa) configurations for Cloudy weather with fairly stable atmospheric conditions (1) conditions.
Source: Visualization created by the author based on categorized meteorological data (Chefchaouen Station).

The distinction between the roles of surface-level pressure (SLP) and the 500 hPa level in shaping weather patterns is fundamental in meteorology. Surface-level pressure systems, such as high-pressure formations (e.g., Aa and Ae), primarily modulate local temperature variations and wind patterns by regulating the advection and movement of air masses.

At the 500 hPa level, the dynamics of the atmosphere function on a broader scale, governing large-scale circulation patterns. Ridges and troughs at this altitude play a pivotal role in either maintaining atmospheric stability or inducing changes. While these upper-level systems do not directly influence surface temperatures, they set the stage for surface-level pressure systems to exert their influence by creating more stable or unstable atmospheric conditions. Understanding the processes at 500 hPa is essential for interpreting the synoptic-scale mechanisms behind cloud formation, air mass movements, and the broader weather patterns that manifest at the surface (Jabbar & Hassan, 2023; Li et al., 2018; Loikith et al., 2019).

The interaction between upper- and lower-atmospheric systems is what ultimately shapes observable weather conditions. For instance, ridges at 500 hPa influence the persistence of high-pressure systems at the surface, such as Aa and Ae, which in turn regulate local temperature fluctuations and cloud formation. Figure 5 highlights this correlation by illustrating how specific temperature variations align with different atmospheric configurations, showcasing the interdependence between upper-level patterns and surface-level weather dynamics.

This temperature classification, ranging from 28.3°C to 19°C, encompasses approximately 46.5% of the overall cases (Figure 5). Notably, high temperatures are predominantly associated with ridges (Teng & Branstator, 2017) in various branches, including Ca, Cb, and Cd. This relationship is crucial for understanding heatwaves and climate anomalies (Li et al., 2018; Loikith & Kalashnikov, 2023). Additionally, a "no gradient configuration" or "uniform field" (Mk) contributes to these elevated temperatures by making weather conditions homogeneous. This leads to a stable weather pattern without significant changes or movements. Such uniform atmospheric conditions often contribute to partly cloudy skies, especially cirrus clouds. This setup, characterized by minimal variations in pressure and temperature, allows for stable conditions that can lead to the formation of scattered clouds. These conditions are typical in high-pressure systems, where limited vertical air movement results (Wang et al., 2020). At the surface level, these high temperatures correlate with transitional situations, specifically the barometric swamp (Tw), followed by scenarios where the pressure equals 1015 hPa (Tz).

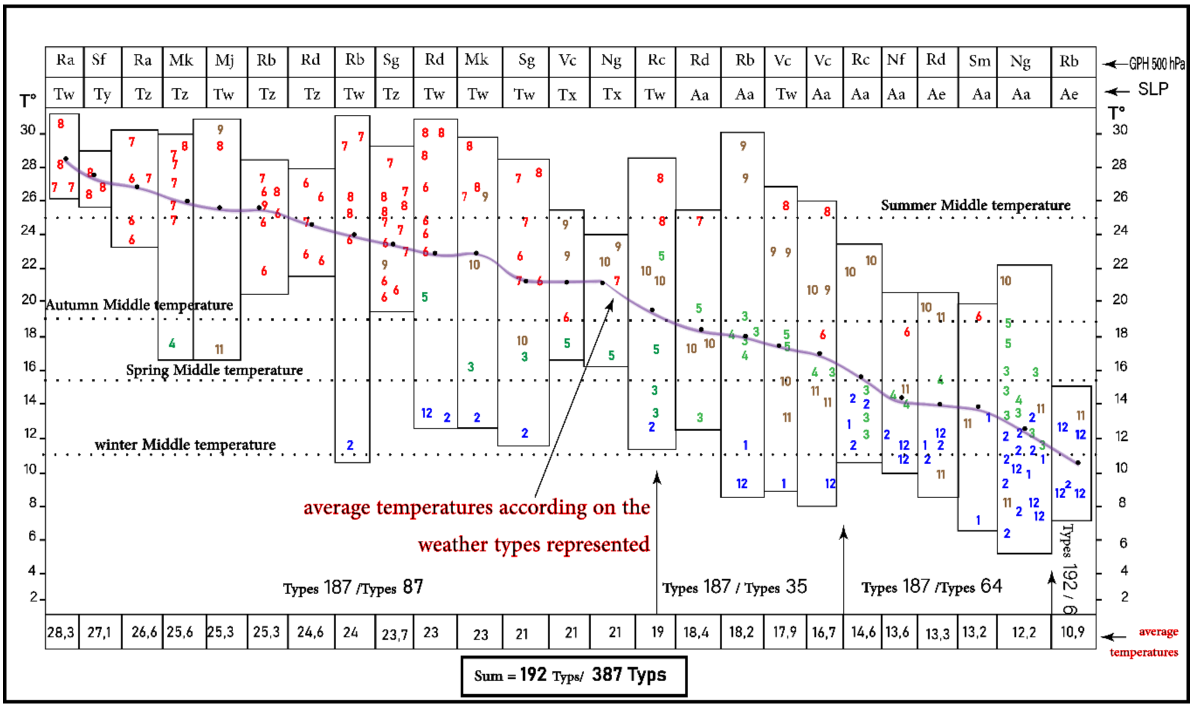

Figure 5. Impact of cloudy weather under relatively stable atmospheric conditions on average temperatures at Chefchaouen Station, based on the analysis of atmospheric structures at 500 hPa and sea level. This figure represents approximately 50% of all recorded weather cases of type (1). The highest average temperature observed was 28.3 °C, associated with the Ca-Tw atmospheric structure, while the lowest average temperature, 10.9 °C, was linked to the Cb-Ae structure. These conditions were most frequently recorded during the summer season, as shown by the predominance of red-shaded months corresponding to summer.

Source: Created by the author based on processed meteorological data.

The classification between 19°C and 16°C comprises approximately 18.8% of the cases. This classification is particularly indicative of the transitional seasons, namely spring and fall, where notable ridges exert significant influence on most circulations at the 500 hPa level, including Cc, Cd, Cb, and Vc. During these two seasons, the atmospheric circulation patterns at the 500 hPa level can lead to substantial shifts in air mass movements, resulting in warmer or cooler than average conditions depending on the prevailing ridge or trough patterns (Gillett et al., 2006; Grimm et al., 2000). This is evident in the noticeable decline in average daily temperatures within this classification, where temperatures shift from 19°C in the Cc configuration to 16°C in the Vc configuration (Figure 5).

The temperature continues to drop in the classification between 16°C and 12°C. This classification represents 33.3% of the total cases depicted in Figure 15. Predominantly observed during the winter months (December, January, and February), it extends to certain spring and fall months, contributing to a decline in the average temperature within this classification. Observations at the 500 hPa level show a significant presence of formations from the North Current (Ng and Nf). This indicates a shift in atmospheric conditions, moving from a state dominated by ridges to one potentially governed by troughs. This transition results in the introduction of northern or northwesterly air masses, leading to the development of scattered clouds. At the surface level, prevailing situations involve the Azores High (Aa) and the European High (Ae).

The classification of cases with temperatures lower than 10°C is the least frequent, representing 3.1% of the total cases depicted, primarily observed in December and January. At the 500 hPa level, well-defined ridges (Cb) dominate, indicating that ridges do not always result in higher temperatures (Figure 5). In this scenario, temperatures dropped to approximately 8.5°C, with high pressure at the surface (Ae) over Europe contributing to cold, stable conditions. This suggests that even in the presence of ridges, the movement and positioning of high-pressure systems play a critical role in determining temperature and cloud formation patterns.

4.2. Cloudy weather with quite unstable atmospheric conditions (2)

The classification of "Cloudy weather with quite unstable atmospheric conditions (2)" occurred 349 times throughout the study, representing 16% of the total recorded cases (Table 1) (Figure 6). This weather pattern displays considerable seasonal variation, with its highest frequency in autumn (27.9%), followed by summer (27.3%) and winter (25%), as illustrated in Figure 9. The lowest frequency was recorded in spring, at 19.8% (Figure 6).

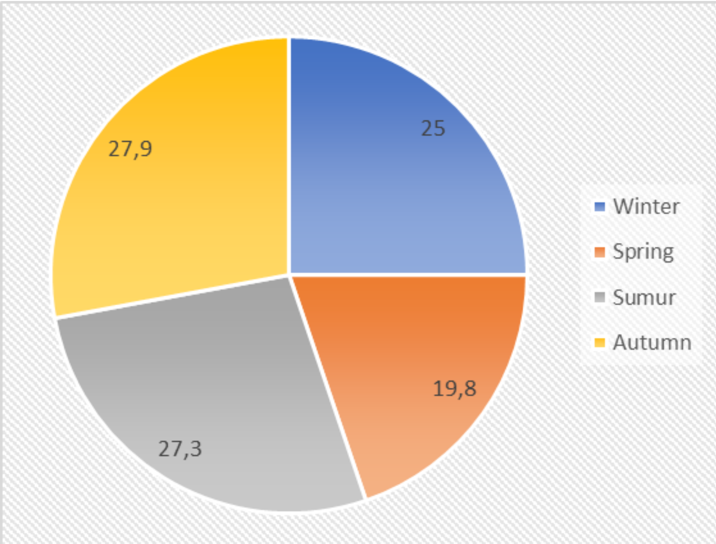

Figure 6. Seasonal Distribution of Cloudy weather with quite unstable atmospheric conditions (2).
Source: Created by the author based on seasonally categorized meteorological data.

The atmospheric configurations at sea level pressure (SLP), depicted in Figure 7, highlight distinct seasonal patterns. For example, the "Aa" structure dominates both winter and spring, whereas the "Tz" structure prevails during summer, correlating with more unstable conditions. This suggests that such patterns have a direct influence on the variability and frequency of cloudy and unstable conditions across seasons.

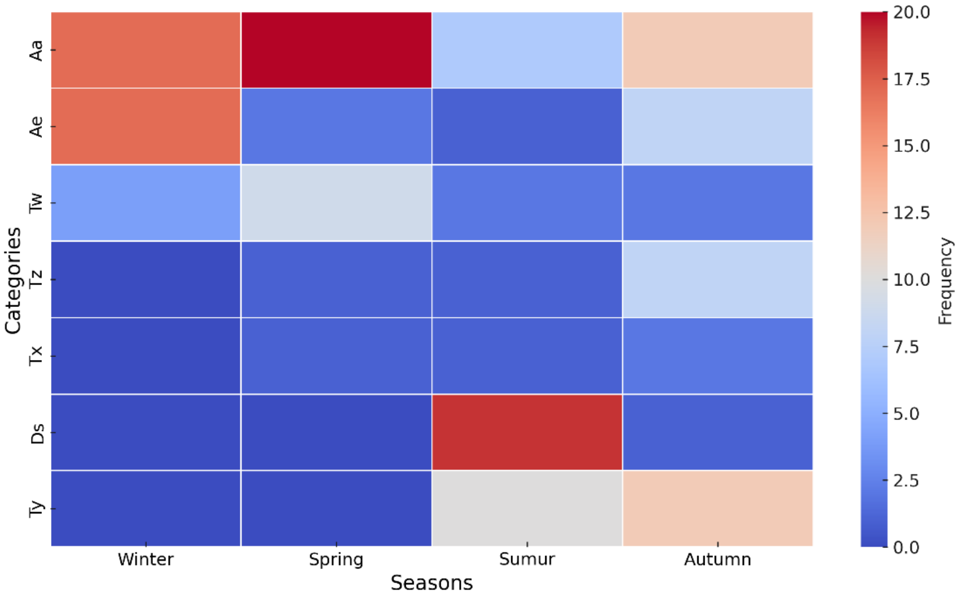

Figure 7. Seasonal distribution of sea-level pressure (SLP) configurations for Cloudy weather with quite unstable atmospheric conditions (2) conditions.
Source: Visualization created by the author based on categorized meteorological data (Chefchaouen Station).

At the 500 hPa level (Figure 8), seasonal variability is further illustrated. The "Cb" structure, representative of Ridge activity, plays a vital role in winter, especially over Western Europe and North Africa. These high-pressure systems block westerly flows, creating prolonged periods of dry and stable weather, notably over the Mediterranean. However, this blocking effect can result in extreme events, such as cold spells, due to the interaction between Ridge and cold air masses from the north (Kautz et al., 2022; Rojas et al., 2013). The "Sg" structure becomes predominant in summer, associated with increased occurrences of this weather pattern. It transports warm, moist air from subtropical regions toward North Africa and southwestern Europe, enhancing humidity and cloud formation without necessarily causing precipitation (Akinsanola & Zhou, 2020; Gatzen, 2020; Yang et al., 2023). The interaction between SLP and 500 hPa structures is essential in driving the seasonal dynamics of this weather type.

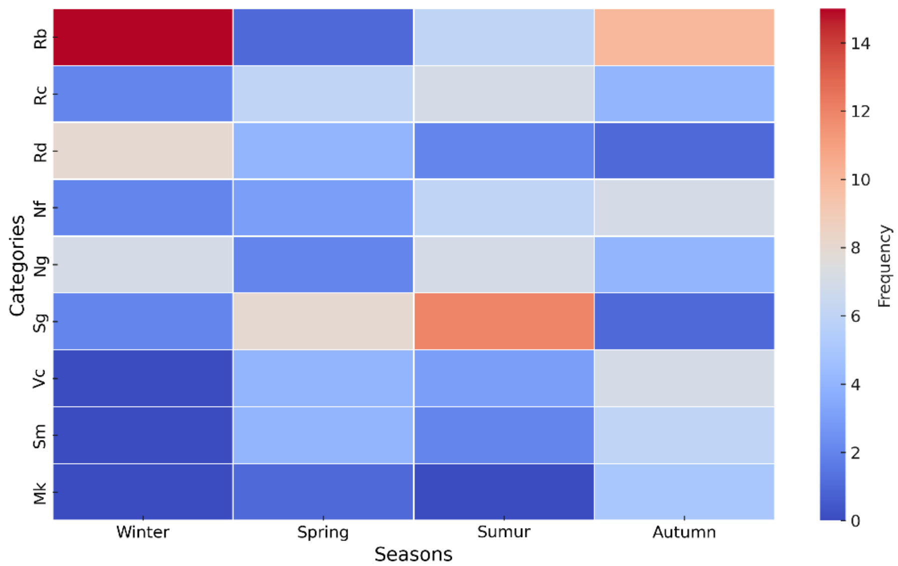

Figure 8. Seasonal distribution of sea-level pressure (500 hPa) configurations for Cloudy weather with quite unstable atmospheric conditions (2) conditions.
Source: Visualization created by the author based on categorized meteorological data (Chefchaouen Station).

Figure 9 illustrates approximately half of these occurrences, with the violet dashed line representing the average temperature, highlighting the thermal variations associated with various atmospheric structures. Notably, there is a significant temperature decline after stabilizing at structures (Mk-Tz), indicating a shift in the atmospheric system that directly affects temperatures. The temperature continues to decrease at a normal rate until the structure (Cc-Tw), where another temperature drop occurs.

The (2) weather condition occurred 349 times, accounting for 16% of all cases. Figure 9 illustrates approximately half of these occurrences, with the violet dashed line representing the average temperature. This line highlights the thermal variations associated with various atmospheric structures. Notably, there is a significant temperature decline after stabilizing at structures (Mk-Tz), indicating a shift in the atmospheric system that directly affects temperatures. The temperature continues to decrease at a normal rate until the structure (Cc-Tw), where another temperature drop occurs. This trend, shown in Figure 9, underscores the dynamic nature of atmospheric changes and their implications for weather patterns (Byrne & Schneider, 2018; Horton et al., 2015; Zappa, 2019).

Temperatures ranging from 29°C to 20°C make up 49.4% of all cases, with the summer months (June, July, and August) being the most represented in this range. Transitional phases are frequently observed at the surface level, particularly through Tz and Tw, with high-pressure conditions notably absent. At the 500 hPa level, ridge movements decline while valleys (Vc) increase, indicating weak polar descents halting over regions such as the Iberian Peninsula or Central Europe. Atmospheric changes often intensify near Morocco (García-Valero et al., 2012; Gonçalves et al., 2023; Pereira et al., 2021). Southern currents, like Sm and Sg, are indicative of imminent weather changes, characterized by dropping temperatures, increased cloud cover, and potential light to moderate winds (Ghassabi et al., 2022; Jabbar & Hassan, 2023; Loikith et al., 2019).

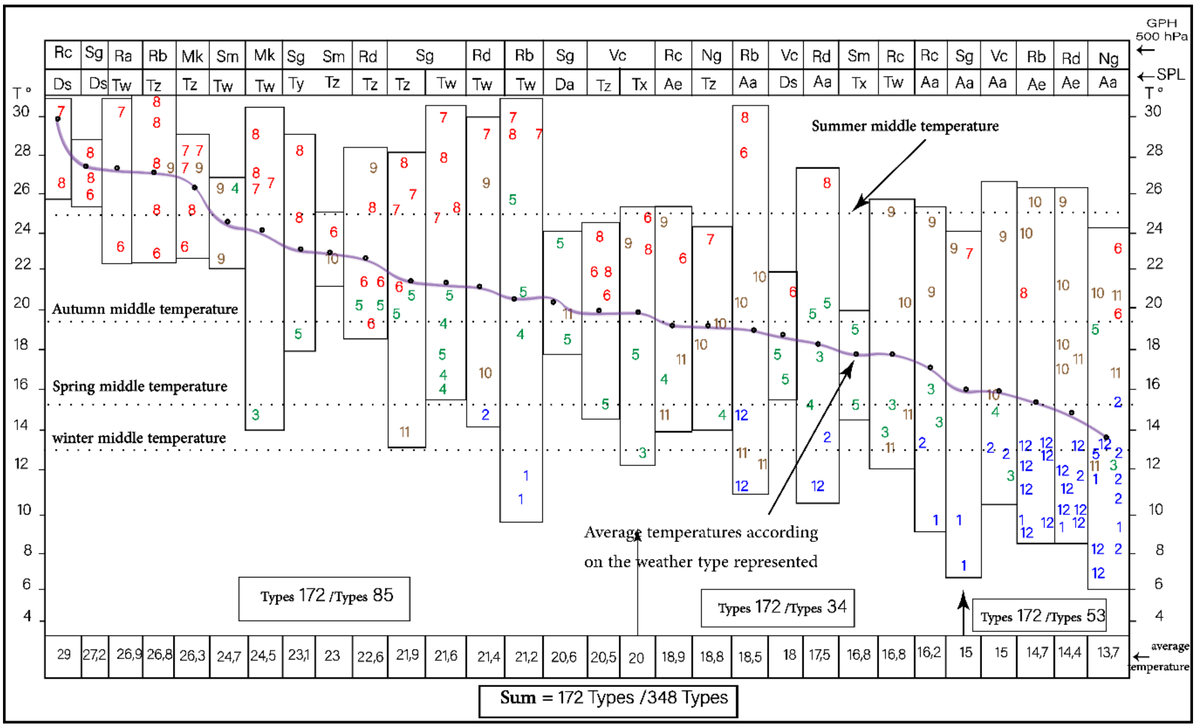

Figure 9. Impact of cloudy weather with notably unstable atmospheric conditions on average temperatures at Chefchaouen Station, based on the analysis of atmospheric patterns at 500 hPa and sea level. This figure represents approximately 50% of the weather cases categorized as type (2-1). Average temperatures exceeded 30 °C under several configurations, including (Ca-Tw), (Cb-Tz), (Sg-Tw), and (Cb-Aa), suggesting that upper-level ridges and transitional conditions at sea level significantly contribute to high-temperature events. Conversely, marked temperature drops were observed under configurations such as (Cb-Ae), (Cd-Ae), and (Ng-Aa), which occurred more frequently in winter. These patterns highlight the seasonal variability and thermal contrast of this weather type, where temperatures can range from over 30 °C to as low as 13.7 °C, characteristic of cloudy and highly unstable atmospheric situations.
Source: Created by the author based on processed meteorological data.

Temperatures between 19°C and 15°C constitute about 20% of all cases (Figure 9). These are mainly associated with Cb and Cc structures, correlating with recurring Aa and Ae states at the sea level. Such conditions create atmospheric consistency within the troposphere, often resulting in stable, cloudy skies, as vertical air movements are minimized (Lu et al., 2019). This phenomenon is particularly common during the winter months, where it recurs more frequently compared to other seasons., as supported by previous studies (Groisman et al., 2005; Kautz et al., 2022; Rojas et al., 2013; Sun et al., 2000). Cloud cover during these periods plays a key role in modulating temperature extremes by blocking solar radiation during the day and trapping heat at night, reducing the diurnal temperature range (Kay et al., 2016).

Finally, temperatures ranging between 15°C and 13.7°C account for 30.8% of cases. These conditions, specific to transitional seasons, show a noticeable and continuous temperature drop, with no stabilization across different atmospheric structures (2).

4.3. Cloudy weather occurring at the margins of the frontal systems (3)

In this study, the term "margin" is used in a geographical sense, as defined by (Keyser 1986; El Baye A 1990; Anand and Pal 2023). The weather condition 'Cloudy weather occurring at the margins of frontal systems (3)' was observed 143 times, constituting 6.5% of all recorded instances during the study period, with notable seasonal variation (Table 1). The highest occurrence was recorded in spring (38.2%), followed by winter (24.5%) and summer (23.5%), while autumn marks the lowest frequency at 13.7%, as shown in Figure 10. Cases (3) depicted in Figure 10 account for over 55% of the total occurrences. This weather condition occurs when a front passes near our study area from the west or north, where the area does not typically experience all the characteristics of the front, particularly precipitation. Instead, the sky is covered with high cumulus clouds, temperatures drop, and wind speeds increase (Beckert et al., 2023; Browning et al., 1982).

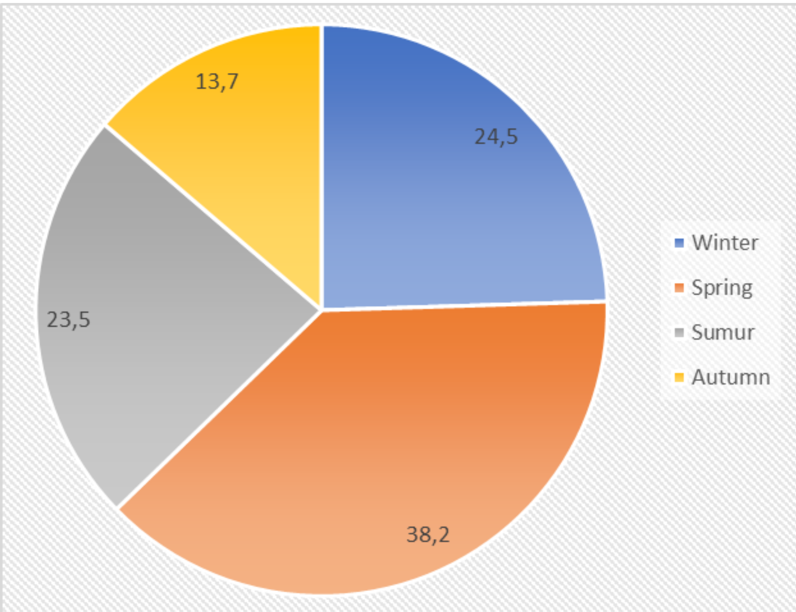

Figure 10. Seasonal Distribution of Cloudy weather occurring at the margins of the frontal systems (3). Source: Created by the author based on seasonally categorized meteorological data.

The atmospheric configurations at sea level pressure (SLP) reveal distinct seasonal variations, as shown in Figure 11. The "Aa" structure is particularly dominant in winter, with 13 occurrences, and remains significant in spring with 7 occurrences. In contrast, the "Tz" structure becomes most prominent during summer, registering 10 occurrences, reflecting more unstable conditions during this period. Additionally, other structures such as "Da" and "Tw" show moderate activity, especially during spring and summer. These patterns clearly illustrate how seasonal variability influences the frequency of cloudy and unstable weather conditions across different times of the year.

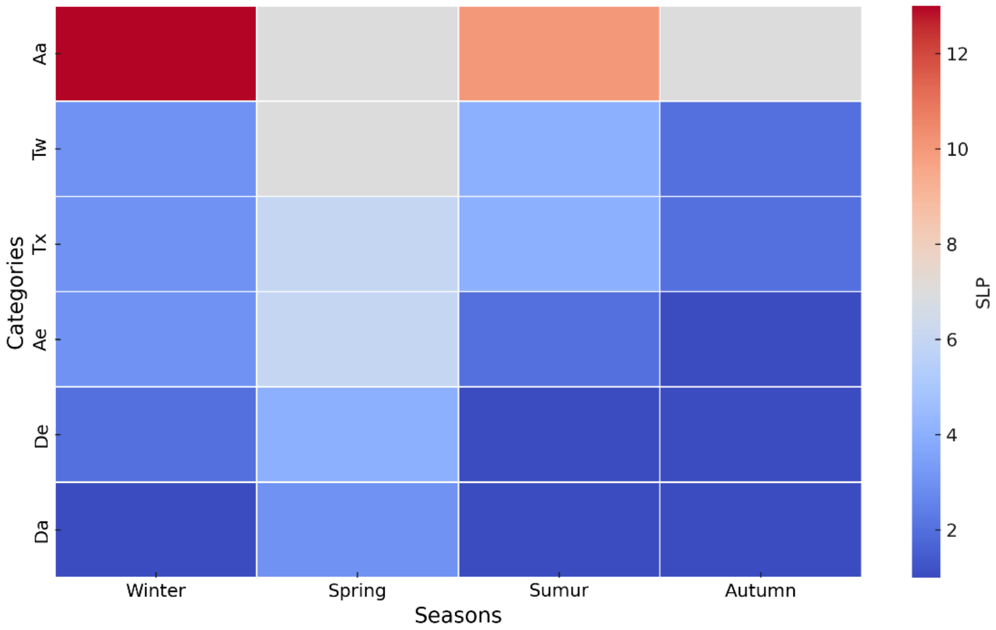

Figure 11. Seasonal distribution of sea-level pressure (SLP) configurations for Cloudy weather occurring at the margins of the frontal systems (3) conditions.
Source: Visualization created by the author based on categorized meteorological data (Chefchaouen Station).

The atmospheric dynamics at the 500 hPa level, depicted in Figure 12, demonstrate notable seasonal variations. The "Ng" structure, representing northern currents, is particularly active in both spring and summer, with 11 and 10 occurrences, respectively. This dominance of northern flows indicates a significant influence of cooler, stable air masses, which can suppress local instability but contribute to cloud formation without precipitation. Such northern currents are known to introduce stable, cold air that suppresses convective activity, leading to cloud formation under stable atmospheric conditions (Kim & Seo, 2023; Spiridonov & Ćurić, 2021). This behavior aligns with the general understanding of northern air masses at mid-level altitudes, where their interaction with warmer surface layers tends to stabilize the atmosphere, preventing major convective developments (Kim et al., 2023).

The atmospheric dynamics at the 500 hPa level, depicted in Figure 12, demonstrate notable seasonal variations. The "Sg" structure dominates during spring and summer, registering 11 and 10 occurrences, respectively, indicating stronger southern flows and an increase in cloud cover and instability. Additionally, the "Rc" structure is particularly active in spring, with 7 occurrences, reflecting the influence of weak ridge formations. During this phase, Chefchaouen lies on the southern margin of the northern jet stream, which predominantly flows over Europe. This positioning allows the jet stream to influence the region indirectly, with increased wind variability and cloud formation due to the interaction between the jet stream's upper-level dynamics and the weak southern ridges. While the jet stream helps contain the movement of these ridges, it also enhances local weather variability, contributing to cloud cover without precipitation. In contrast, the "Rd" structure is most prominent in summer, with 7 occurrences, suggesting increased upper-level divergence and a likely contribution to instability. Structures such as "Vc" and "Ve" show moderate activity, which has begun to increase in frequency compared to previous weather patterns. This shift suggests a complete change in the dynamics producing this weather pattern, compared to earlier ones, primarily in winter and spring, contributing to the seasonal variability in the weather patterns associated with frontal systems.

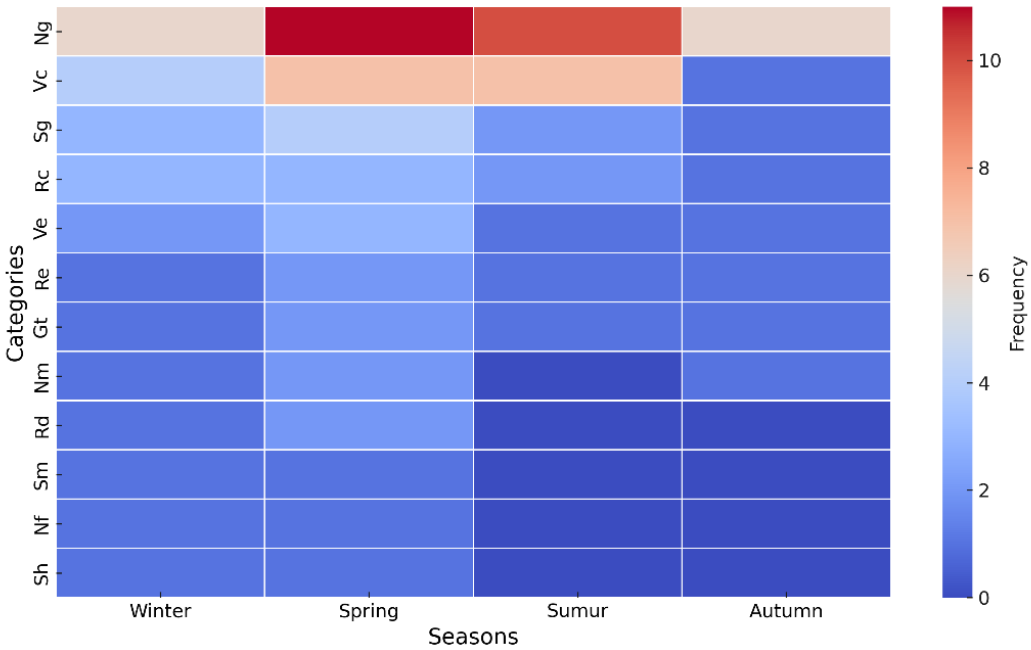

Figure 12. Seasonal distribution of sea-level pressure (500 hPa) configurations for Cloudy weather occurring at the margins of the frontal systems (3) conditions.
Source: Visualization created by the author based on categorized meteorological data (Chefchaouen Station).

These atmospheric configurations not only dictate the specific weather conditions prevalent during each season but also play a significant role in shaping the temperature dynamics associated with the 'Cloudy weather occurring at the margins of frontal systems (3)' pattern. The temperature gradient observed in this weather scenario diverges from previous patterns, as highlighted by a distinctive trend line depicted in violet. This trend shows a rapid decline from temperatures exceeding 30°C to below 8°C, particularly evident between structures (Cc-Im) and (Ve-Da). This pattern is visually illustrated in Figure 13.

The classification of cases with temperatures between 30.8°C and 21.6°C occurs at a rate of 33.6% of the total cases, indicating a relatively low frequency compared to other weather situation (Figure 13). Examining the controlling atmospheric patterns, we observe various branches of the ridge (Rc, Rb, Rd), followed by the southern current (Sg). Regarding mean sea level pressure (MSLP), transitional situations, particularly Situations (Tw) and (Tz), are most dominant and fluctuating.

In contrast, the classification of cases with temperatures between 15°C and 12°C constitutes 13% of the represented cases. At the GPH 500 hPa level, the northern current frequency (Ng) is noticeable, followed by valley forms (Vc, Ve), which significantly control the dynamics in this classification. These forms correspond, at the surface level, with the frequency of situations (Aa and Ae).

The weather system begins to change as the formations producing this type of weather condition shift compared to previous cases. The frequency of valleys fluctuates more, and a similar trend is observed with northern currents (Figure 13). The frequency of valleys (Vc) at the 500 hPa level indicates that polar influences start to prevail, suggesting a decline in hot subtropical influences towards the south. The sky transitions from clear or scattered clouds to being almost completely covered, with increasing wind strength, often from the west or northwest (Loikith et al., 2019; W. Zhang & Villarini, 2019).

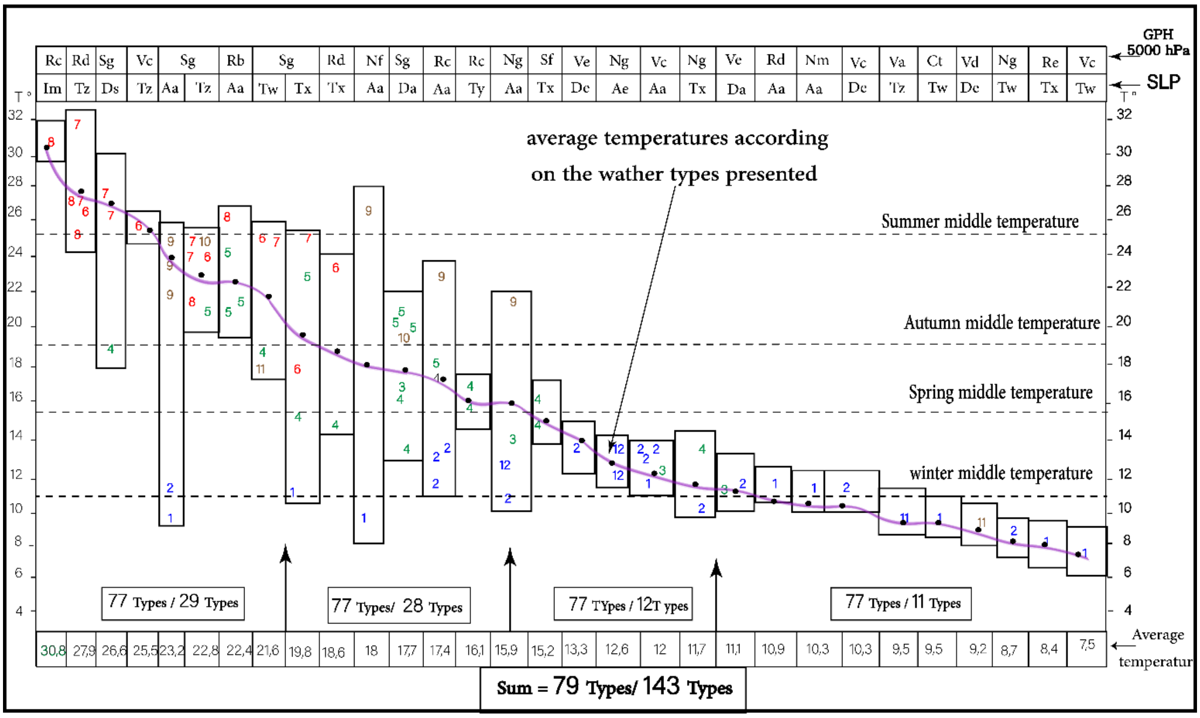

Figure 13. Impact of cloudy weather occurring at the margins of frontal systems on average temperatures at Chefchaouen Station, based on the analysis of atmospheric conditions at 500 hPa and sea level. This figure encompasses over 55% of the weather cases classified as type (3-1). A marked drop in average temperatures is observed, with the highest value reaching 30.8 °C under the (Cc-Im) configuration, and the lowest dropping to 7.5 °C under the (Vc-Tw) structure. This type of weather pattern often reflects a transition from stable to unstable atmospheric conditions, as illustrated by the frequent presence of valleys (Vc, Ve, Vd), southern flows (Sg, Sf), and northern flows (Ng, Nf, Nm) at 500 hPa. At sea level, these cases are commonly associated with low-pressure systems (Ds, De, Da) and transitional patterns (Tz, Tx, Ty), highlighting the dynamic nature of frontal margins in shaping thermal variability. Source: Created by the author based on processed meteorological data.

The classification of weather cases within the temperature range of 20°C to 16°C encompasses approximately 36.3% of the total cases, indicating a frequency close to previous classifications (Figure 13). This range is predominantly influenced by the southern current (S), particularly the movement (Sg), followed by the Ridge (Cc) with eight cases, and then the northern currents (Nf and Ng). These patterns correspond with the frequency of transitional situations (Tx and Tz) at MSLP, as well as a weak frequency of high-pressure systems concentrated over Europe (Ae) and the Atlantic Ocean (Aa).

In the temperature range of 12°C to 7.5°C, which accounts for 14.3% of the cases, most instances exhibit temperatures lower than the average winter temperature of 11°C (Figure 13). The valley forms, particularly (Vc), (Va), and (Vd), significantly contribute to this specific weather state. At the surface level, transitional (T) situations dominate with their various branches. Observations indicate a weak frequency of the Azores high-pressure (Aa) in this classification (Figure 23), primarily due to its southward shift attributed to polar descent. This shift opens the Atlantic gate for polar influences, especially during winter. This aligns with findings from studies on the North Atlantic subtropical anticyclone, documenting changes in the spatial and temporal patterns of the Azores high over the past century. The decline of high pressure in this region, especially during winter, suggests increased meridional flow and a greater prevalence of blocking anticyclones over Europe. Such dynamics have been linked to changes in greenhouse gas concentrations and their impact on atmospheric circulation patterns (Cresswell-Clay et al., 2022; Davis et al., 1997; Sinclair et al., 2020).

5. DISCUSSION

This study investigates the impact of cloudy weather patterns on daily temperature variations in Chefchaouen, located in the Western Rif Mountains of Morocco. By classifying non-rainy weather conditions and analyzing their influence on temperature dynamics, this research provides insights into the role of atmospheric structures in regulating surface temperatures. The analysis identifies three primary categories of cloudy weather: cloudy weather with fairly stable atmospheric conditions (1), cloudy weather with quite unstable atmospheric conditions (2), and cloudy weather occurring at the margins of frontal systems (3). These categories exhibit distinct seasonal variations in temperature responses (see Table 2).

The findings reveal that during winter, category (1) corresponds to an average temperature of 10.6°C, whereas category (2) records 11.6°C, and category (3) exhibits 11.3°C. In contrast, during summer, temperatures rise to 25.4°C, 22.6°C, and 24.8°C for categories (1), (2), and (3), respectively. These variations indicate that cloudy weather with stable atmospheric conditions (1) contributes to greater thermal stability compared to unstable conditions (2), which exhibit more pronounced fluctuations due to atmospheric disturbances.

The observed thermal patterns align with previous findings by Dai et al., (1999), which highlight the dual role of cloud cover in reducing daytime solar radiation while enhancing nighttime heat retention. Furthermore, the presence of high-pressure systems at sea level and specific 500 hPa configurations explains the relatively stable temperature conditions observed during non-rainy periods. These results underscore the importance of synoptic-scale atmospheric structures in modulating local temperature variability.

Table 2. Average seasonal temperatures according to non-rainy weather patterns in Chefchaouen over the period 2015–2020.

weather type	winter C°	spring C°	summer C°	autumn C°
(1)	10,6	15,9	25,4	19,3
(2)	11,6	14,1	22,6	23,7
(3)	11,3	16,3	24,8	19,6

Source: Compiled by the author from classified temperature records at Chefchaouen Station.

This study further demonstrates the influence of cloudy weather patterns on seasonal and diurnal temperature regulation in Chefchaouen. The (2) weather pattern, characterized by unstable atmospheric conditions, results in lower summer temperatures (22.6°C) compared to both stable cloud cover (25.4°C). This cooling effect is particularly pronounced in spring and summer, consistent with findings by Groisman et al., (2000), who showed that dense cloud cover reduces surface solar radiation while increasing surface moisture, leading to overall lower temperatures. Similarly, Pyrgou et al., (2019) demonstrated that cloud cover plays a critical role in minimizing diurnal temperature range (DTR), especially during warm periods, by mitigating excessive daytime heating while preserving nighttime warmth.

These findings align with regional studies highlighting the stabilizing influence of cloud cover on temperature fluctuations. For instance, Xu et al., (2021)found that increased cloud cover in the Himalayas significantly reduces DTR across all seasons, with the strongest effects observed in winter. In Chefchaouen, the (2) and (3) cloud patterns moderate winter temperatures (11–12°C), contrasting with the lower values recorded under clear sky conditions. During summer, the presence of unstable (2) cloud cover results in lower overall temperatures (22.6°C) compared to the significantly higher temperatures observed under clear skies. These findings underscore the essential role of cloud cover in modulating seasonal temperature extremes.

Comparative analyses from European cities such as Athens and Madrid reinforce these conclusions, demonstrating that cloud cover strongly influences DTR during both heatwaves and typical summer days. The reduction in DTR under cloudy conditions in Chefchaouen, particularly during summer and spring, is consistent with results reported for other Mediterranean and mountainous climates (Hamal et al., 2021; Katavoutas et al., 2023; Pyrgou et al., 2019). While these findings corroborate existing research on the temperature-moderating effects of cloud cover, this study expands on previous work by focusing specifically on non-rainy weather patterns in a Mediterranean mountainous environment. This focus allows for a more refined understanding of how specific cloud types influence temperature fluctuations under dry atmospheric conditions.

The results also align with broader research on atmospheric circulation patterns and their influence on local climate dynamics. Studies by Loikith & Broccoli (2012) have demonstrated the relationship between positive geopotential height (GPH) anomalies at 500 hPa and sea-level pressure anomalies, showing their influence on regional temperature variations. Additionally, Connolly et al., (2021) and Yu & Lupo, (2019) highlight the impact of large-scale atmospheric systems on local thermal patterns. However, this study provides a novel contribution by isolating non-rainy atmospheric scenarios, thus refining our understanding of the specific mechanisms regulating temperature variations in Chefchaouen. By distinguishing different non-rainy cloud types, the study advances knowledge on local climate interactions and the thermal impacts of synoptic-scale atmospheric structures.

Despite offering valuable insights into the role of cloud cover in temperature regulation, some limitations should be acknowledged. First, the study is based exclusively on daily temperature data, which may not fully capture short-term fluctuations or transient atmospheric phenomena that influence local climate variability. Future research could incorporate higher-resolution temporal datasets to assess sub-daily temperature variations and detect rapid meteorological transitions. Second, the geographical focus on Chefchaouen limits the generalizability of these findings to regions with distinct topographical and climatic characteristics. Expanding the study to include a broader range of Mediterranean and mountainous locations could enhance the applicability of these results to diverse climate settings. Nonetheless, the robustness of the dataset, combined with detailed weather maps and local climatic analyses, provides a solid empirical foundation for the study's conclusions.

The implications of these findings are significant for practical applications, particularly in understanding the effects of cloudy weather on temperature. This can inform local climate adaptation strategies, urban planning, and natural resource management. For example, recognizing the temperature-modulating effects of cloud cover can guide the design of green spaces and urban layouts to mitigate heat stress (Meng et al., 2022). Additionally, these findings could contribute to the development of more accurate weather forecasting models that account for the specific impacts of cloudy conditions.

Beyond the theoretical contributions, these findings offer several practical implications that can inform decision-making processes in climate-sensitive sectors. The results of this study have practical applications for improving short- and medium-term weather forecasting in mountainous regions, particularly in predicting temperature variations under cloudy weather conditions. Moreover, understanding the influence of stable and unstable cloud conditions on local temperatures could guide the development of climate adaptation strategies for sectors such as agriculture and tourism in regions like the Western Rif. These strategies may include optimized scheduling for planting seasons, improved water resource management, and enhanced planning for tourism activities that are highly dependent on weather conditions.

Future studies should expand this research to include other regions and climatic conditions to verify the generalizability of the results. Furthermore, incorporating higher temporal resolution data and advanced modeling techniques could improve our understanding of short-term weather dynamics.

In summary, this study provides a comprehensive analysis of how cloudy weather types influence temperature patterns in Chefchaouen. The findings contribute to a deeper understanding of local atmospheric and climatic interactions, supporting efforts to improve local climate resilience and sustainable development planning. By highlighting the specific effects of different cloudy weather types, this research offers valuable insights into the broader field of climate and environmental management.

6. CONCLUSIONS

This study has provided a detailed examination of the influence of non-rainy weather patterns on temperature variations in Chefchaouen, located in the Western Rif Mountains of Morocco. By systematically classifying and analyzing daily temperature data in conjunction with atmospheric conditions at both sea level and the 500 hPa altitude, we were able to uncover the significant role these weather patterns play in shaping local temperature regimes.

Our analysis revealed that clear skies were the most dominant non-rainy weather type, representing 27% of all recorded cases. This weather type exhibited substantial temperature variation, especially in summer, where high temperatures were closely associated with anticyclonic systems. Similarly, cloudy weather with fairly stable atmospheric conditions (classification 1), which accounted for 17.5% of the cases, demonstrated a strong link to ridges and barometric depressions, impacting both daytime and nighttime temperatures.

Additionally, cloudy weather with quite unstable atmospheric conditions (classification 2), which represented 16% of the cases, exhibited distinct thermal characteristics, particularly during transitional seasons. The least frequent weather type, cloudy weather occurring at the margins of frontal systems (classification 3), constituted 6.5% of the cases and was characterized by unique temperature gradients influenced by the interplay of polar and subtropical atmospheric systems.

These findings underscore the complexity of local climatic dynamics and emphasize the importance of integrating atmospheric parameters across multiple altitudes to fully understand temperature patterns. The insights gained from this study not only contribute to a more nuanced understanding of non-rainy weather influences but also offer valuable implications for refining regional climate models and enhancing local climate adaptation strategies in response to global climate change.

For future research, incorporating higher temporal resolution data would allow for a more detailed capture of short-term atmospheric events that were beyond the scope of this study. Additionally, extending this analysis to other geographically and climatically similar regions would further validate these findings and broaden their applicability. This research provides a vital foundation for both advancing scientific understanding of atmospheric dynamics and informing practical climate resilience measures.

Use of AI tools declaration

The author acknowledges that he has used AI-assisted tools, specifically ChatGPT, to assist in the organization, refinement, and editing of the manuscript. However, all intellectual contributions, analyses, and interpretations are the sole work of the author, ensuring the scientific integrity and originality of the research.

Author contributions

This work was conducted solely by the author, who has read and approved the final manuscript.

Conflicts of interest

The author declares no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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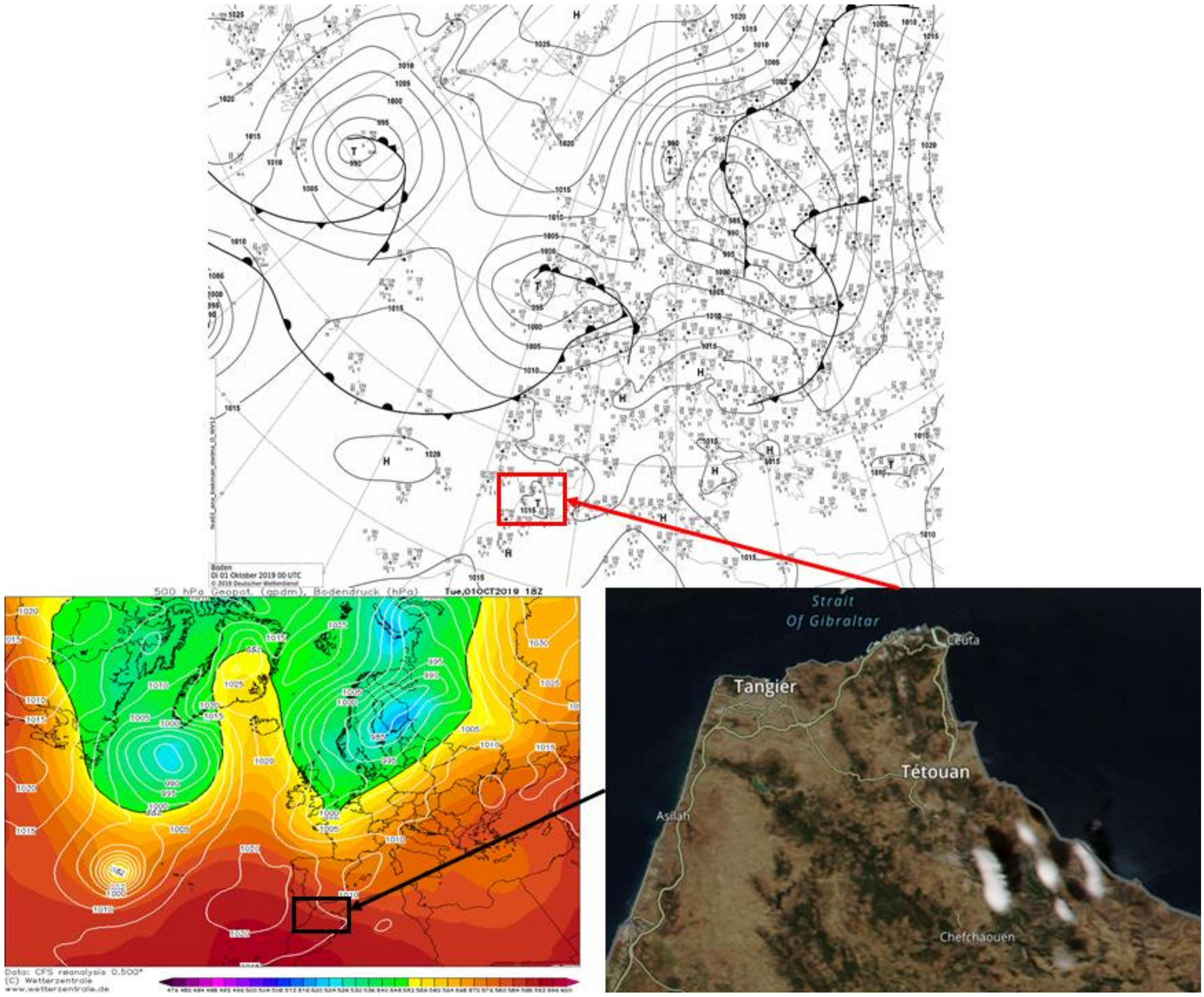
Appendix I. Cloudy Weather with Fairly Stable Atmospheric Conditions on October 1, 2019 (Sky Coverage 1/8)

This figure illustrates the weather condition of "Cloudy weather with fairly stable atmospheric conditions" observed on October 1, 2019, with approximately 1/8 cloud cover, measured in oktas. This sparse cloud coverage, shown in the satellite image, highlights limited cloud formation over northern Morocco, particularly in the areas surrounding Chefchaouen.

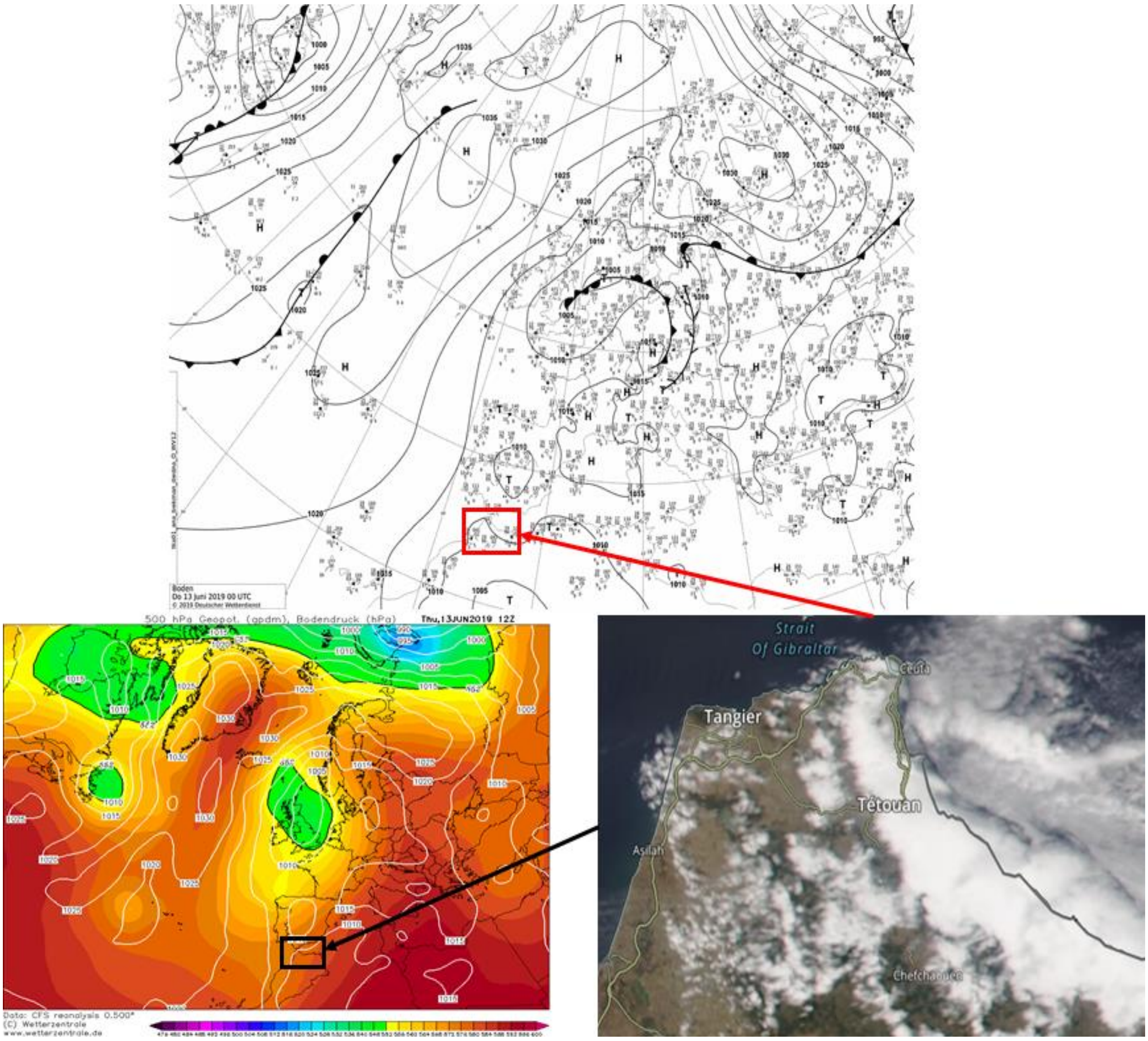
The synoptic chart reveals relatively stable atmospheric pressure with weak pressure gradients, conducive to minimal cloud development. The accompanying geopotential height map at 500 hPa further supports these observations, indicating a stable upper atmosphere with limited dynamic weather systems, which is consistent with the partly cloudy sky observed in the satellite image.



Appendix II. Cloudy Weather with Quite Unstable Atmospheric Conditions on June 13, 2019

This figure illustrates "Cloudy weather with quite unstable atmospheric conditions" observed on June 13, 2019, with approximately 4 oktas of sky coverage. The satellite image shows moderate cloud formation, particularly over northern Morocco, including Chefchaouen, suggesting a completely unstable atmosphere conducive to more dynamic weather changes.

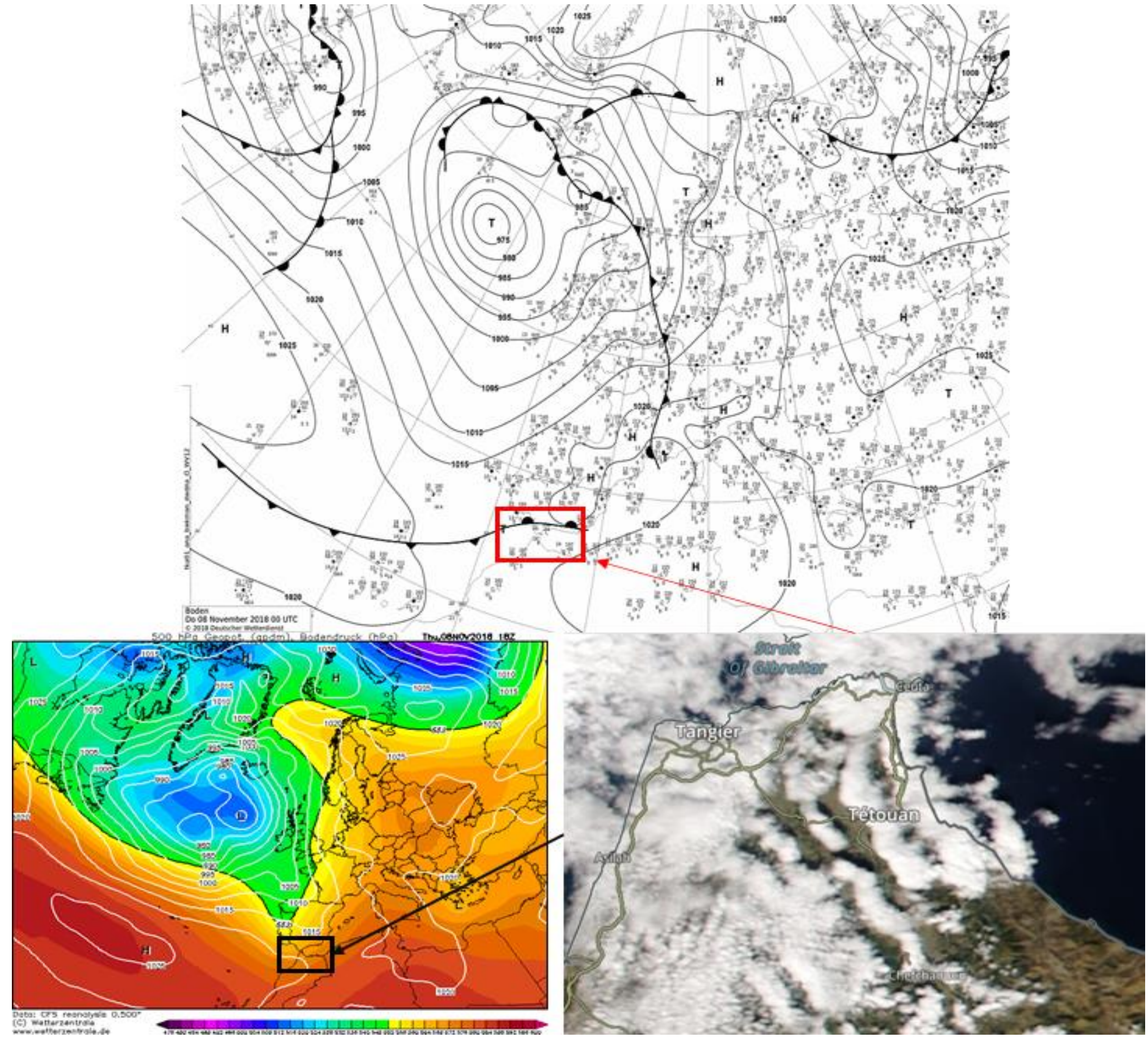
The synoptic chart reveals tightly packed isobars, indicating stronger pressure gradients, which contribute to the marked instability in the atmosphere. The 500 hPa geopotential height map further highlights the presence of upper-level troughs and dynamic weather systems, reinforcing the unstable conditions that led to moderate cloud cover and rapid fluctuations in weather patterns, as depicted in the satellite image.



Appendix III. Cloudy Weather at the Margins of a Frontal System on November 8, 2018

The figure illustrates "Cloudy weather occurring at the margins of the frontal systems", observed on November 8, 2018. The satellite image reveals significant cloud cover over northern Morocco, particularly around Tangier, Tetouan, and Chefchaouen. These clouds, although widespread, are not associated with heavy precipitation, as they are located at the periphery of a nearby frontal system.

The synoptic chart highlights low-pressure systems near the region, as seen on November 8, 2018, which facilitates the formation of these clouds at the edges of the front. This type of weather is typical when the region experiences cloud covers due to adjacent pressure systems, resulting in overcast skies without intense weather phenomena.



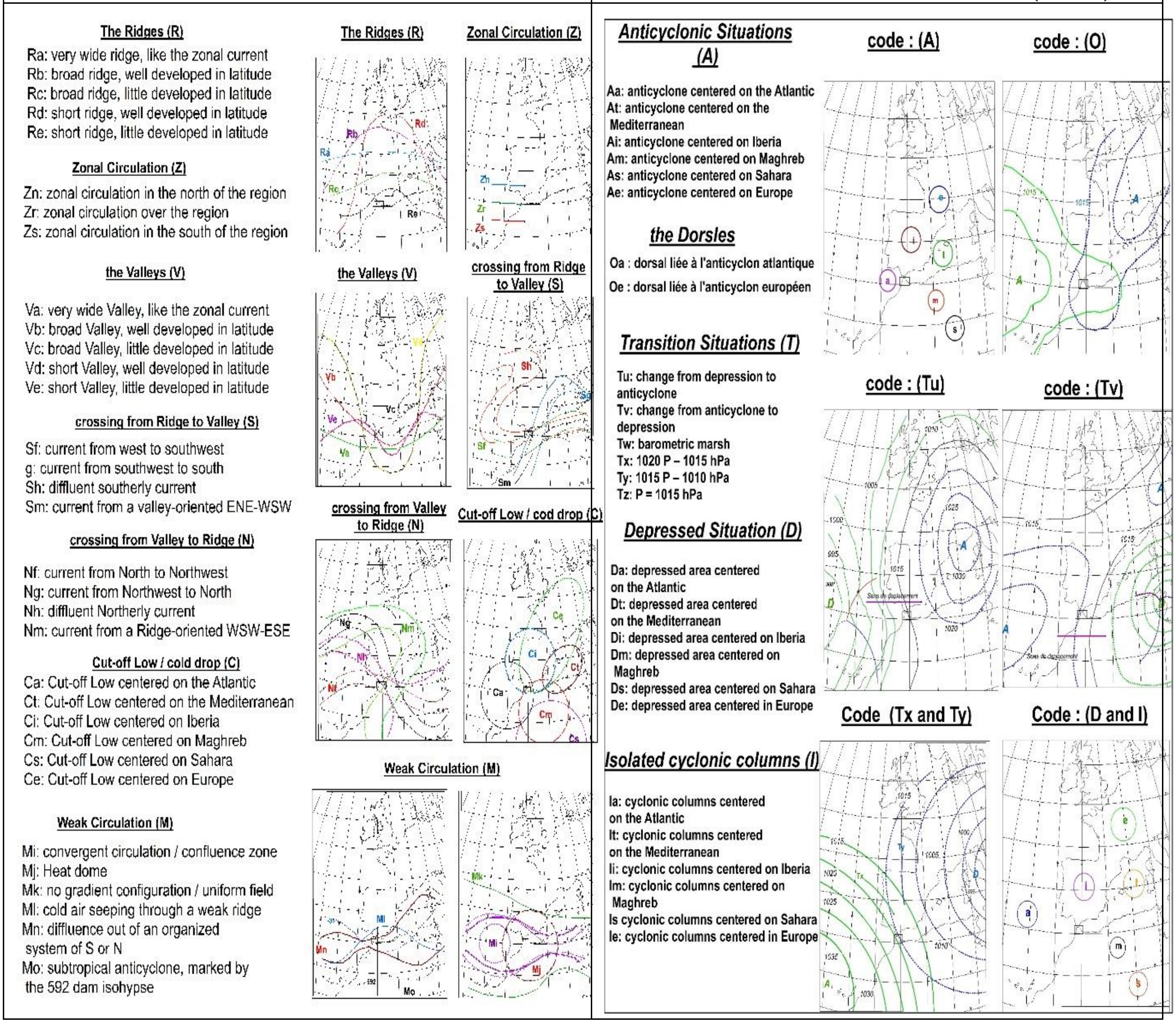
Appendix IV. Classification and Illustration of Atmospheric Circulation Patterns at GPH 500 hPa and Mean Sea Level Pressure (MSLP)

These figures provide a detailed representation of the significant atmospheric conditions observed over the past six years, derived from systematic daily analyses of synoptic weather patterns. The first figure illustrates the dominant circulation structures at the 500 hPa pressure level, highlighting the large-scale atmospheric dynamics that influence temperature variability in the Western Rif region. The colored lines correspond to distinct air mass movements and atmospheric configurations, each assigned a specific code to facilitate interpretation. These configurations reflect variations in pressure gradients, ridge-trough interactions, and the overall atmospheric stability that governs cloud cover formation and thermal fluctuations.

The second figure focuses on sea-level pressure (MSLP) variations, capturing key meteorological situations recorded between 2015 and 2020. This representation is crucial for understanding how surface-level high and low-pressure systems contribute to local climate dynamics. The patterns depicted in this figure emphasize the influence of synoptic-scale pressure anomalies, including the positioning of anticyclones, cyclonic depressions, and transition zones. These elements play a fundamental role in modulating temperature distributions, affecting the extent and persistence of non-precipitating cloud cover in the study area.

By integrating these atmospheric insights, these figures serve as essential references for interpreting the interaction between upper-atmosphere circulation (500 hPa) and surface pressure systems (MSLP), thereby enhancing our understanding of regional weather variability in Chefchaouen and the broader Western Rif region.

Classification and Illustration of Atmospheric Circulation Patterns at GPH 500 hPa	Classification and Illustration of Atmospheric Situations at Mean Sea Level Pressure (MSLP)



Source: Adapted and modified from Vigneau (1985), with updates by El Baye (1990) and further modifications by the author.

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The water accessibility of rural communities in the context of actual climate change: a focus on Sanyati District, Zimbabwe

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ABSTRACT: This study aims to examine the effects of climate change on access to and availability of water resources in rural communities, with a particular emphasis on Zimbabwe's Sanyati District. Using a quantitative research design, 230 questionnaires were applied to gather data between August and October of 2024 from residents. Simple random sampling technique was used to choose participants of the study. To evaluate past and current trends in climate, the research used scientific evidence documented in existing literature. Furthermore, the study used a descriptive survey methodology to assess climate change trends and their effects on rural communities' access to adequate water resources, based on the population's perception. Spearman's rank correlation coefficient was applied to determine the strength of the relationships between demographic characteristics of the population, their perceptions of climate change, and its impacts on water resource accessibility. Respondents noted observable changes in climate characterized by declining rainfall, rising temperatures and increasing incidence of droughts. Notably, the impacts of climate change on water accessibility were gendered, with women and those living with disabilities disproportionately affected. The research's findings underscore the urgent need for adaptive water management plans and regulations that tackle climate change's effects, while enhancing local resilience initiatives to ensure sustainable water access for communities in Sanyati. The study therefore recommends that there is need to promote community engagement and participation in decision making processes as this helps to build resilience and ensure the long-term sustainability of water resources in rural communities.

KEYWORDS: climate change, water stress, adaptation, vulnerability, drought, resilience, Zimbabwe

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1. INTRODUCTION

Witnessed changes in climate across the globe are a transformative trend within which, environmental experts are advocating for immediate action to address a myriad of interrelated problems (WHO, 2023; Hurtado et al., 2024). Sixty-one percent of Zimbabwe's populace resides in rural areas often relying on rainfed agriculture (ZimStat, 2022). Water accessibility in Zimbabwe's rural areas plays a significant role in sustaining livelihoods of rural residents. Water as a resource, is the source by which Africa's development can be driven (African Union, 2016). This underscores the importance of water

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accessibility in mainstreaming local efforts in realising several Sustainable Development Goals (SDGs) namely: eradicating poverty (SDG 1); ending hunger (SDG 2); promoting good health and wellbeing (SDG 3); providing quality education (SDG 4); addressing gender inequality (SDG 5); clean water and sanitation (SDG 6), and responsible consumption and production (SDG 12). Zimbabwe has not been an exception to the ravaging impacts of climate change, which has been attributed to both anthropological and natural causes (Goz, 2018; IPCC, 2023; Mata et al., 2024). Deforestation, overreliance on fossil fuels for energy production, unsustainable farming practices like monoculture and excesive use of fertizers, are amongst key anthropological factors that have made Zimbabwe susceptible to temperature fluctuations and erratic rainfall patterns (Chanza and Gundu-Jakarasi, 2020). These anthropological factors have been complemented by changes in weather patterns and geographical location, often categorised as natural causes of climate change. These changes in climate have negatively affected the accessibility of potable and non-potable water threatening food security, with the potential to create and sustain water related conflicts in Zimbabwe.

Zimbabwe upon gaining independence in 1980 adopted the 1976 Water Act which was grossly biased in providing the service in urban areas, disadvantaging rural residents. The formulation and adoption of the 1998 Water Act Chapter [20:24] sought to address mainly this inequality, by ensuring water accessibility was improved in underdeveloped rural areas (Malinga et al., 2017). The Water Act was complemented by the Zimbabwe National Water Authority Act Chapter [20:25], which saw the Zimbabwe National Water Authority (ZINWA) being the lead water authority exclusively responsible for water provision, supply and distribution. Regardless of the policy framework which has been put in place to ensure water accessibility in rural communities, surface water sources have proved to be seasonal. ZINWA has implored the need to invest more in ground water sources so as to improve on water accessibility.

The year 2018 saw the President of Zimbabwe His Excellency, Cde Emmerson Mnangangwa adopting Vision 2030 that seeks to attain an upper-middle income economy by 2030 (GoZ, 2018). At the core of this development thrust, lies water accessibility, a vital input in supporting various aspects of rural life, such as agriculture, health and economic development. In pursuing vision 2030, the Ministry of Lands, Agriculture, Fisheries, Water and Rural Development crafted rural development 8.0, a model that seeks to eradicate poverty through rural industrialization and agricultural development nexus. The model anchors on eight pillars and or interventions namely: 1) presidential rural development programme, 2) presidential climate proofed input scheme, 3) presidential cotton scheme, 4) presidential blitz-tick grease scheme, 5) presidential community fisheries scheme, 6) presidential poultry scheme, 7) presidential goat scheme and 8) local interventions and innovations (Chimenya, 2022). The government noted that as a result of climate change, annual number of days with rainfall decreased, negatively impacting on annual received rainfall (Ndlovu et al., 2014; GoZ & UNDP, 2017). These noted changes if not addressed will jeopardise governmment efforts in realising the thrust of rural development 8.0. Similar changes in climate affecting water accessibility in Zimbabwe have also been witnessed in South Africa (Republic of South Africa, 2024). Most rural livelihoods have been threatened as a result of worsened water accessibility by climate change, with government exploring on resilient coping mechanisms aspiring to improve water reliability (ZimStat & UNICEF, 2019). Local adaptive capacities and coping mechanisms have been generally determined by geospatial and temporal variability (Brazier, 2015).

However, there is a dearth of literature focusing on the interplay between climate change and water accessibility in rural Zimbabwe, particularly focusing on Sanyati as a district. Much concerted research efforts heve been placed on coping mechanisms against changes being brought through climate change. This research seeks to address three primary objectives namely: 1) understanding the people's perceptions on water accessibility in the light of climate change, 2) identifying the impacts of climate change on water accessibility in Sanyati District and 3) recognising adaptation mechanisms employed by rural residents residing under Sanyati District. The study not only deepens our understanding on climate change—water accessibility nexus in rural communities in semi-arid regions, but also proffers practical coping mechanisms challenging conventional gender stereotypes and fostering inclusive policies and interventions in Sanyati and beyond. Succeeding the introduction is the literature review section which contextualises this study within the broader academic discourse and a section on study materials and methods follows. Subsequently, results are presented focusing on residents' perceptions on climate change, climate change impact on water accessibility and the strategies for enhancing resilience to water scarcity. The paper ends with discussions and conclusion.

2. LITERATURE REVIEW

There is unequivocal evidence pointing to the fact that Zimbabwe`s geographical location presents major climatic challenges. Climate models run on Zimbabwe`s climate data reveal trends where most of the weather parameters have shifted from the longtime mean. Available evidence suggests that the country has experienced a wide array of changes in rainfall and temperature while extreme weather events such as floods, droughts, heatwaves and hailstorms are on an increasing trend. Rainfall patterns in the country have shown a downward trend, as exibited by various climate models used to analyze historical rainfall data. These models indicate a reduction in both the frequency and intensity of rainfall over time, highlighting the growing impact of climate change on the country's water resources.

According to the GoZ & UNDP (2017), the country has experienced nearly 5 percent decline in rainfall during the last century. Figure 1 depicts rainfall trends from 1980 to 2016. The report also argued that droughts have increased in frequency and severity, and this is heavily impacting on food security, livelihoods and other aspects of human and sustainable development. Mazvimavi (2010) argued that a decline of 10% or 100 mm in rainfall has been observed in the country. Brazier (2015) opined that rainfall pattern in Zimbabwe is now characterised by spatio-temporal variability, increasing uncertainty in timing and amount of rainfall received, while the frequency and length of dry spells during the rainy season have increased. Makaudze & Miranda (2010) and Ndlovu et al. (2014), argued that frequency of rain days has declined, resulting in droughts becoming a common phenomenon.

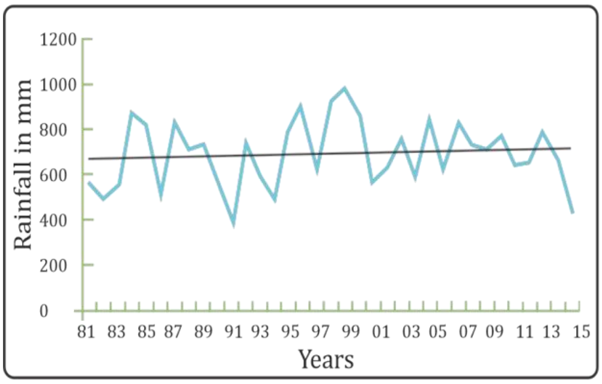

Figure 1. Zimbabwe average seasonal rainfall (mm) (1981- 2015).
Source: GoZ & UNDP (2017).

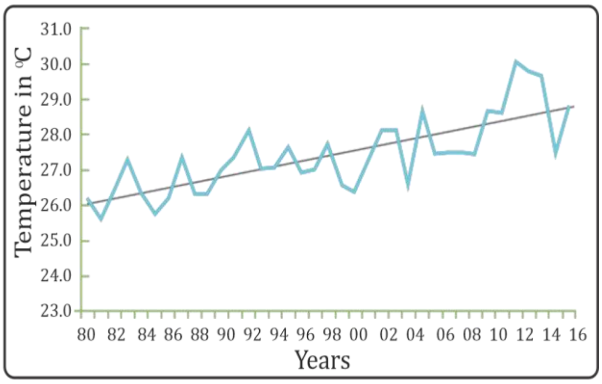

Figure 2. Zimbabwe’s mean annual maximum temperature ºC (1980 to 2016).
Source: GoZ & UNDP (2017).

The country has witnessed a significant increase in hot days and a decline in cold days due to the impacts of climate change and climate variability (Brazier, 2015). According to the GoZ & UNDP (2017), historical temperature records show that the period from 1980 to 2015 has been the warmest since Zimbabwe started recording its temperature (Figure 2). Over the past few decades, rising global temperatures and shifting weather patterns have contributed to these changes, affecting ecosystems, agriculture, and water resources. This warming trend aligns with global patterns of climate change, largely driven by greenhouse gas emissions, deforestation, and other anthropogenic activities. The increase in extreme heat events poses challenges for food security, public health, and water availability, making climate adaptation strategies crucial for Zimbabwe's sustainable development.

Furthermore, the increased frequency of weather hazards associated with the changing climate is a growing concern in Zimbabwe. Mazvimavi (2010) acknowledged that frequency of droughts increasing due to growing variability in climate, is presenting formidable challenges amongst rural communities. According to GoZ & UNDP (2017) droughts are adversely impacting on water availability for domestic and industrial use and power generation affecting cities and non-agriculture sectors. Furthermore, the report opined that records have shown that Zimbabwe's rainfall is on decrease and the country is now characterized with frequent droughts. According to Mazvimavi (2010), the country's rainfall patterns are influenced by El Nino Southern Oscillation events, which have a 30% chance of causing drought. He reiterated that most parts of Zimbabwe are increasingly becoming drier due to changes in climate. Mwadzingeni et al. (2022) noted that cyclones and floods have become a common phenomenon in many parts of Zimbabwe as a result of climate change. They reiterated that cyclone Eline of 2000, Cyclone Dineo of 2017 and Cyclone Idai of 2019 were the most disastrous and fatal cyclones over the past two decades.

A growing body of literature supports the idea that impact of climate change on water accessibility effect women disproportionately. Research suggests that women are more likely to spend more time on water-collection tasks than men, indicating a gendered dimension to this issue (Geere & Cortobius, 2017; UNESCO, 2020; Fruttero et al., 2023). Several districts in Zimbabwe have been affected by variations in climate, although felt impacts seem to vary in relation to spatial location (Nyahunda & Tirivangasi, 2019; Frischen et al., 2020; Makuvaro et al., 2023; Mavesere & Dzawanda, 2023). Zimbabwe as of late has become more and more arid, characterised with less precipitation and severe warming (Mwadzingeni et al., 2022). This has established a positive corelation between climate change and water accessibility challenges, especially in regions IV, Va and Vb as depicted in Figure 3 (World Bank, 2020; Mwadzingeni et al., 2022). These noted changes concur with the observation made by UNEP (2024), where it argued that most African countries that had a water surplus are now experiencing water stress. Rural communities have been dealt with a severe brunt as noted by Amraoui et al. (2019), as most communities are best described with basic, limited, unimproved and surface water categories, as depicted in Table 1.

Table 1. Drinking Water Ladder.

Drinking water ladder	Definition
Safely managed	Drinking water from an improved water source, which is located on the premises, is available for use when needed and devoid of disease-causing contaminants like fecal and priority contamination
Basic	Drinking water from an improved source provided collection time is less than 30 minutes for a roundtrip, including queuing.
Limited	Drinking water from an improved source where collection time exceeds 30 minutes for a roundtrip, including queuing.
Unimproved	Drinking water from an unprotected dug well or unprotected spring.
Surface water	Drinking water is directly collected from a river, dam, lake, pond, stream, canal, or irrigation channel.

Source: WHO & UNICEF (2017).

Zimbabwe is spatially made up of five agro-ecological regions which were defined in 1960 (Chikodzi et al., 2013). Variations in climate saw the reclassification of these agro-ecological regions in 1984 and 2020, as depicted in Figure 3. The main reason proffered for the reclassification of these agro-ecological regions was noted changes in temperature and rainfall patterns in conventional agro-ecological regions. These changes have led to water stress evident in lakes, rivers and wetlands adversely affecting anticipated agricultural yield (Manatsa et al., 2020; Chimbiro & Soniye, 2023). There are quite a number of effects felt across rural Zimbabwe, as a result of climate variability, and these are not only limited to incidence of floods, uncontrolled veld fires, and droughts. These highlighted hazards have negatively affected water accessibility and reliability mostly in rural communities (Word Bank, 2020). Drying up of open water sources has affected even the distance local residents and domestic animals travel in rural communities in search for clean portable water (Assan, 2022).

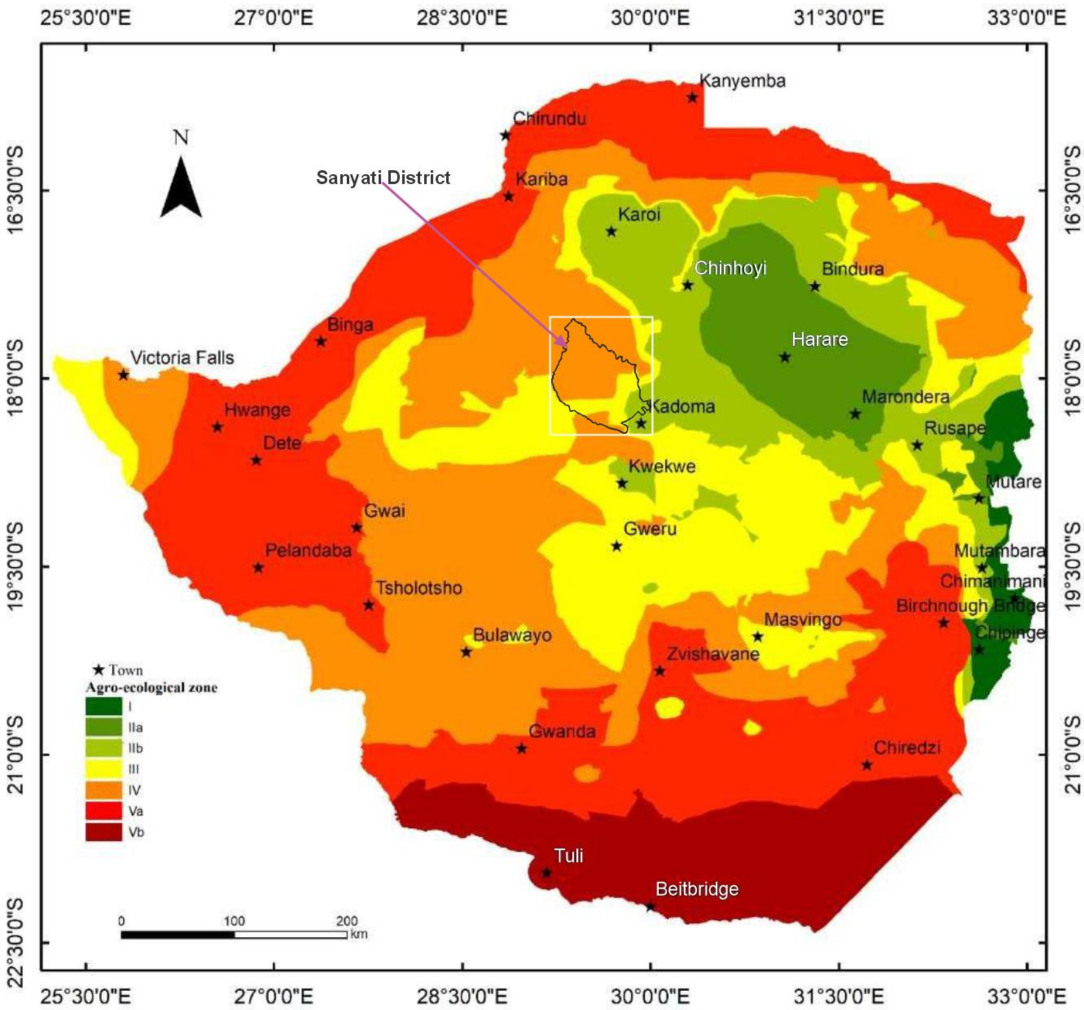

Figure 3. Revised Agro - ecological Regions of Zimbabwe.
Source: Manatsa et al. (2020).

The drinking water service ladder can best be used to describe different levels of access to drinking water, enabling data comparability on water accessibility and availability across diverse contexts. Climate change has worsened the water accessibility situation in rural contexts where a staggering 58% of local rural residents in Zimbabwe spend between 31 minutes to over 3 hours a day in one round trip, to and from a nearby water source (ZimStat & UNICEF, 2019). This observation is consistent with UNDRR (2021), which highlighted that in semi-arid Africa, 70% of the population rely on ground water source for domestic, economic and agricultural purposes. The ground water sources are greatly being affected by temperature and rainfall fluctuations, compromising on water accessibility in most rural communities (Fonjong & Zama, 2023). Distances being travelled by most rural residents in search for clean water in Africa has seen roughly 40 billion hours annually being lost to such an unproductive chore (UNICEF, 1999). These affected rural communities are collaborating with various stakeholders exploring on adaptation strategies (CARE International, 2022).

3. MATERIALS AND METHODS

3.1. The study area

The research was conducted in Sanyati District, situated at coordinates 17°57′00″S, 27°18′27″E within the Mashonaland West Province. The district spans over 4,832.98 square kilometers, comprising of 18 administrative wards and sustains a population of 139235 with a population density of 28.81

individuals per square kilometer (CSO, 2022). The location of the Sanyati District within Zimbabwe is showed in Figure 4. The district lies within the semi-arid areas of Zimbabwe, characterised by erratic rainfall patterns, leading to frequent food shortages (ZimVAC, 2009). Sanyati District falls within natural region III of Zimbabwe's agro ecological zone (refer to Figure 3). It receives a moderate mean annual rainfall ranging between 600-700mm, primarily during the rainy season from November to March. According to Mashizha et al. (2017), Zimbabwe's rainfall depicts significant year to year variability, with a standard deviation of 179 mm, exhibiting substantial fluctuations in annual rainfall levels. This high variability poses challenges for water resource management, agriculture, and climate adaptation strategies. The temperatures fluctuate between 28 and 32°C, occasionally experiencing severe dry spells and a relatively brief growing season.

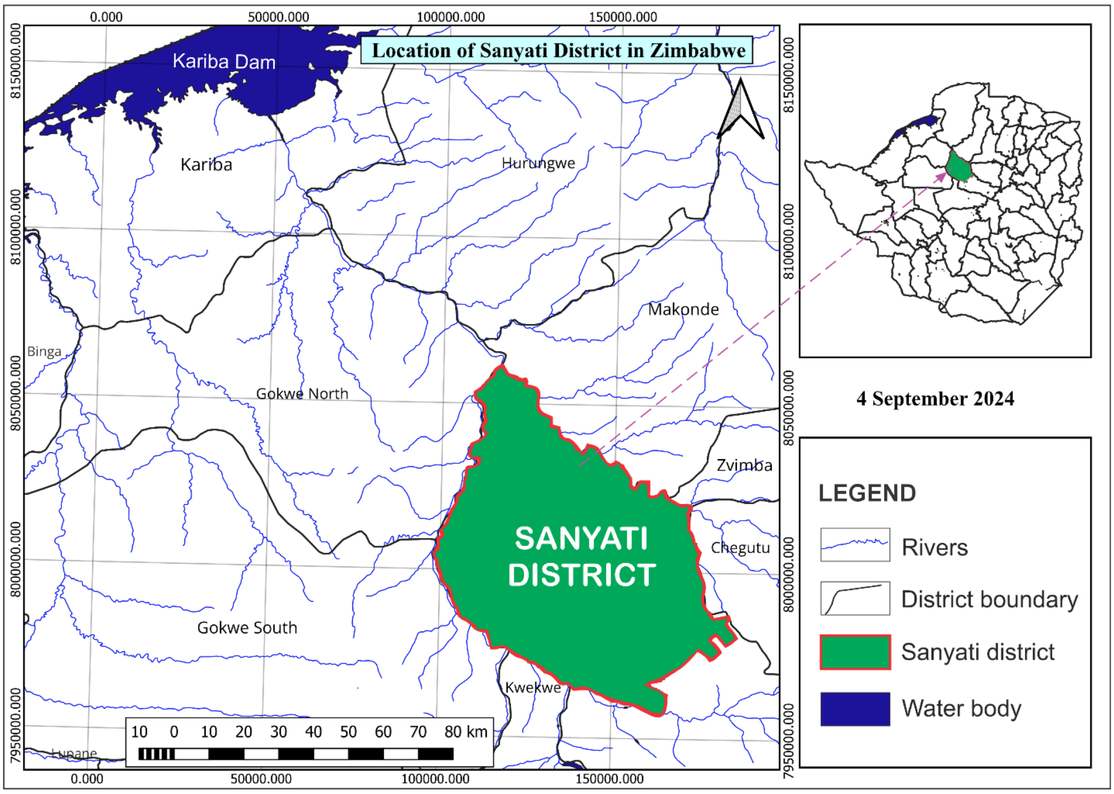

Figure 4. Location of the study area.

Sanyati District lies in the highveld, central plateau region of Zimbabwe. The general relief in the area is 1.250 m above sea level and interspersed with several hills which rise to about 1.300 m. The geology is mostly covered by the Mafic formation of the Bulawayo Group rocks (Boese-O'Reilly et al., 2004). The soils in the district vary from red loams to fertile lighter soils derived from schist and limestone, to granite and sandveld, with rich black soils in the vlei areas (Boese-O'Reilly et al., 2004).

The predominant vegetation in the area is mopani woodland, supporting the cultivation of crops like cotton, maize, soya beans, groundnuts, and sunflower. While cotton production dominates, the government is promoting the cultivation of small grains such as sorghum, millet, and rapoko. Notably, Sanyati District boasts rich gold deposits, fostering a landscape characterized by small-scale/artisanal gold mining activities.

3.2. Survey method

The study employed a descriptive survey methodology to assess the effects of climate change on rural communities' access to adequate water resources within Sanyati District. A total of 230 questionnaires were administered randomly amongst household heads to gather appropriate data regarding individuals' experiences and knowledge of climate change and water-related challenges in the region. The administered questionnaire had both open and closed ended questions focusing on demographic information, respondents` perceptions and awareness about climate change, proxy indicators of climate change, water resource availability and access issues, and adaptation mechanisms utilized by the residents to mitigate against the effects of water scarcity. Climate parameters that were considered in this research included rainfall, temperature, length of rainfall seasons and weather hazards such as floods, droughts and hailstorms. The interviews were conducted in person, necessitating the researcher to manually record responses provided by the respondents onto the questionnaires. Before commencing the interviews, participants were briefed on the logical objectives of the questionnaire and assured of the confidentiality of their identities. All participants engaged in the study voluntarily.

An in-depth statistical analysis was performed to discover the vital connections between the social and demographic characteristics of the population and their perceptions of climate change, as well as its impacts on water resource accessibility. Correlation analysis, specifically Spearman's rank correlation coefficient, was used to identify the intensity of the relationships between the considered variables. Spearman’s rank correlation coefficient is a measure of the strength of the relationship between two variables that cannot be measured quantitatively (Spearman, 1904). Spearman’s rank correlation coefficient is a nonparametric (distribution-free) rank statistic proposed as a measure of the strength of the association between two variables. The first step in establishing the value of r_s for a set of n bivariate data pairs was to rank the values of each variable. In this case, both were ranked from least to greatest.

The second step was to calculate the difference between ranks of corresponding observations calculated as $d_i = R_X - R_Y$, where the ranks of the values of x_i are represented by R_X, and the ranks of the values of y_i are represented by R_Y. In the third stage, squared rank differences were calculated - d_i^2. Once the values of d_i^2 were calculated, were then used along with the value of n, or the number of data pairs, in a general formula for Spearman`s rank correlation coefficient given as the following formula:

$$\mathrm{r_s} = 1 - \frac{6\sum d_i}{n(n^2 - 1)}, \quad (1)$$

where, r_s represents the coefficient, and the number of points in the data set is represented by n. The square of the difference in the ranks of the two coordinates for each point (x,y) is represented by d^2, and the expression $\sum d^2$ indicates that we should find the sum of each of these squares.

The Spearman correlation coefficient takes values from +1 to -1. Where r_s value of +1 denotes a perfect association between variables, while r_s of zero depicts no association between variables and r_s of -1 indicates a perfect negative correlation between variables. Additionally, the closer r_s is to zero, the weaker the association between the variables.

The results presented in the findings section exclusively consider coefficients that exhibit statistical significance above the 95% confidence level ($p < 0.05$). This stringent criterion ensures that the reported relationships are statistically robust and reliable, offering valuable insights into the interplay between climate change, water resources, and the rural community in Sanyati District. Furthermore, document analysis was utilised in this research to establish the historical context of Zimbabwe`s climate issues. Incidentally, document analysis was used to establish the climate change content by reviewing printed and electronic (computer-based and Internet-transmitted) material. Like other analytical methods in qualitative research, document analysis requires that data be examined and interpreted in order to elicit meaning, gain understanding, and develop empirical knowledge (Corbin & Strauss, 2008). Document analysis helped to compare people`s perceptions on climate change against scientific knowledge available on the subject to produce hybride research results.

4. RESULTS

This section presents findings obtained from 230 household respondents drawn from Sanyati District, Zimbabwe. It provides an overview of the demographic features of the respondents, the community's perceptions on climate change, proxy indicators for climate change, the effects on water resources and the adaptation mechanisms pursued by households in the area of study. By exploring these facets, the section provides light on the complex interlinkages between climate deviations and local livelihoods, providing valued insights into the adverse implications and responses within the study area.

4.1. Demographic characteristics

The demographic variables gathered in this study included information such as age, gender distribution of the respondents, types of family head, educational background, duration of stay in the area and family size. Table 2 provides an outline of the demographic profile of the whole sample, contributing valued insights into the diverse characteristics of the participants involved in the research.

Table 2. Demographic information on the sampled population.

Demographic	Frequency	Percent
Gender		
Male	90	39.0
Female	140	61.0
Age class		
Below 30 years	23	10.2
31 – 40 years	39	16.9
41 – 50 years	31	13.6
51 – 60 years	55	23.7
60 years & above	82	35.6
Type of family head		
Male headed	117	50.8
Female headed	74	32.2
Widowed male	4	1.7
Widowed female	35	15.3
Household size		
1 – 4 people	113	49.0
5 – 8 people	102	44.2
9 & above	16	6.8
Level of education		
No formal education	16	6.8
Primary education	51	22
Secondary education	129	55.9
Tertiary education	35	15.3
Years of residence		
Below 10 years	19	8.47
10 – 19 years	35	15.25
20 – 29 years	47	20.34
30 – 39 years	47	20.34
40 & above years	82	35.59

Source: Authors (2024).

Table 2 illustrates a predominant gender distribution pattern generally in rural locations, where women characteristically form a greater segment of the population. In this study area, women make up a significant majority at 61%, while men represent 39% of the surveyed population. This gender distribution trend can be attributable to traditional beliefs and roles in rural communities, where women are often seen as the primary custodians and caretakers of rural households, while men are regularly engaged in employment opportunities in urban areas. This demographic insight underlines the distinct gender dynamics and societal roles that shape community structures in rural communities. Regarding the age distribution depicted in table 2, descriptive statistics reveals a higher number of respondents across older age clusters. Notably, there is a difference between the proportion of youthful individuals and the aging population. For instance, the study indicates that 10.2% fall below the age of 30, while 16.9% are aged between 31 and 40. In contrast, a significant rate of the population 23.7% and 35.6%, comprises individuals aged 50 - 59 years, and above 60 years respectively. This demographic trend can be credited to several factors, including the predominant phenomenon of rural-urban migration among the economically active age group seeking better opportunities in urban centers. Simultaneously, older individuals tend to retire to rural areas, leading to a higher proportion of elderly people in these areas. This demographic analysis underscores the complex interplay between age demographics, economic dynamics and migration patterns that shape the population distribution within the study area.

The average size of household in the studied area stands at 4.2 individuals. These survey findings concur with the 2022 Census conducted in Zimbabwe, which reported average household sizes of 4 (CSO, 2022), indicating consistency in household compositions across different research endeavors. Referring to Table 2, the data reveals that the majority of households (49%) fall within the cluster of 1-4 members, followed by 44.2% in the 5–8-member range whilst households comprising 9 members and above making up a small proportion at 6.8%. Household size serves as a vital indicator of the pressure exerted on available resources within a household. Larger household sizes characteristically imply increased susceptibility due to higher resource demands. Conversely, a larger household can also indicate a greater labor force available to enhance and manage water resources effectively, highlighting the dual role of household size in both resource utilization and resilience within the community.

In terms of education, a substantial proportion of the respondents had received some level of formal education, including primary (22%), secondary (55.9%), or tertiary education (15.3%), while only 6.8% reported no formal education. It is notable that the study area revealed a paltry percentage of individuals with tertiary education, chiefly due to the tendency of educated individuals migrating to urban areas in search of employment opportunities in industries. Moreover, the prevalence of individuals without tertiary education can be attributed to the limited presence or absence of tertiary institutions in rural settings. Education plays a key role in shaping respondents' perceptions of climate change, adaptation strategies – its diffusion and sustainability. An educated household head, for instance, can read and understand educational materials such as brochures distributed by extension officers and NGOs, which aim to educate residents on climate change realities, innovative ideas, and technological advancements. This educational exposure can enhance the adaptability and creativity of households, ultimately reducing their vulnerability to water scarcity. Scholars like Weir (1999) have highlighted the direct impact of education on farm productivity by enhancing labor quality. Similarly, Shultz (1975) underscores the significance of education in farm production, particularly in dynamic technological and economic landscapes, emphasizing its role in fostering agricultural innovation and productivity.

Regarding the number of years of residence in the study area, the research reveals that the majority (35.59%) of the households have been staying in Sanyati for more than 40 years. On the contrary, only a small proportion of respondents (8.47%) reported living in the study area for less than 10 years. The number of years staying in the area is likely to influence adaptation of a household. An individual with more years of residence has more knowledge of the environmental changes and has had more time to devise strategies to cope with the adverse implications of such changes. Additionally, such households are more likely to adapt better to the changing environment compared to community members with less years of experience. An increase in the number of years lived in an area is associated with lower levels of vulnerability and conversely, a decrease in the number of years lived in the study area is related to higher levels of vulnerability.

4.3. Residents` perceptions of climate change

According to Adger et al. (2008), people's perceptions are closely related to the perceived risks and opportunities arising from climate change, ultimately influencing their livelihood strategies and adaptive actions. A significant majority (80%) of the respondents recognized a departure from common weather conditions in Sanyati, while a minority (20%) observed no noticeable shifts in the climatic conditions (Table 3). These findings mirror those of the Republic of South Africa`s report (2024) which reported that 83% of residents in South Africa recognized changes in the local climate. The acknowledgment of changes in climate emphasizes the importance of community awareness and reaction to environmental shifts. Such perceptions serve as critical drivers for the formulation and implementation of adaptation measures tailored to mitigate the impacts of climate change on livelihoods and local ecosystems. By recognizing and responding to these evolving climatic patterns, communities can better prepare and safeguard their well-being against the challenges posed by environmental changes.

Table 3. Residents' perceptions on climate change.

Response	Percent
No	20.3
Yes	79.7
Total	**100.0**

The survey respondents highlighted various proxy indicators of climate change, notably citing shifts in weather patterns such as rising temperatures, dwindling rainfall, and increasing frequency in weather-related hazards like droughts. The direction and magnitude of these changes were quantified and analyzed for all participants, with the findings detailed in Tables 4 and 5. Regarding the air temperature shifts, a significant rate of respondents (80%) indicated a noticeable increase in temperatures, 10% reported a decrease and 5% noticed no significant changes in temperature trends (Table 4). These findings underscore the widespread recognition among respondents of the changing climate dynamics and emphasize the urgency for proactive measures to address and mitigate the impacts of these changes.

Results presented in Table 5 reveals that an overwhelming 92% of respondents observed a decrease in rainfall, while a mere 3.4% reported a perceived increase in precipitation amounts. In contrast, a small proportion of the respondents (2%), reported no noticeable changes in rainfall patterns, while another 2% were not sure about the trends on this parameter. These findings are consistent with those of Fonjong & Zama (2023) who found that 76% of the respondents acknowledged experiencing rising temperatures, characterized with longer dry than rainy seasons and early sunshine than expected. It is worthwhile to note that people's perceptions in the study area are in sync with the scientific evidence on the climatic patterns that were observed in Zimbvabwe.

Table 4. Changes experienced in air temperatures.

	Percent
Increase	79.7
Decrease	10.2
No change	5.1
Not sure	3.4
No response	1.7
Total	100.0

Table 5. Changes experienced in rainfall.

	Percent
Increased	3.4
Decreased	91.5
No change	1.7
Not sure	1.7
No response	1.7
Total	100.0

A Pearson correlation matrix was calculated to examine the relationships between social characteristics of the population and their perceptions of climate change variables (e.g. access to weather information, knowledge of climate change, level of education and years of residence). The matrix is presented in Table 6. We found a moderate positive correlation between access to weather information and knowledge of climate change, with $r = 0.419$, $p < 0.001$. Consequently, access to weather information increases the knowledge of climate change, that is, residents with access to a television set, radio or newspaper have higher chances of acquiring knowledge on climate change. We also found a moderate, positive correlation between level of education and knowledge of climate change, r = 0.447, p < 0.001. Accordingly, the more the higher the level of education, the higher the knowledge on climate change. Level of education and access to weather information had a moderate, positive correlation with r = 0.394, < 0.001. No other significant correlations were found.

Access to weather information has become indispensable in light of ever-increasing concerns surrounding climate change and variability. This information not only enables rural communities to anticipate and adapt to the adverse implications of climate change but also plays a crucial role in enhancing overall preparedness.

Table 6. Correlations Matrix showing the relationship between demographic characteristics and their perceptions of climate change.

	Access to weather information	Knowledge of climate change	Highest education attained	Years of residence
Access to weather information	1			
Knowledge of climate change	0.419**	1		
Highest education attained	0.394**	0.447	1	
Years of residence	-0.150	-0.106	0.155	1

Note **. Correlation is significant at the 0.01 level (2-tailed).

In the context of this study site, a reasonable proportion (58%) of respondents have access to weather information, underscoring a moderate level of awareness regarding climate change (Figure 5). Moreover, a significant majority (66%) of respondents acknowledged the usefulness of the weather information they received (Figure 6).

However, there remains a resolute need for government intervention to improve the accessibility of weather information to a larger proportion of the population. It is imperative that this information is disseminated in a manner that is easily understood by individuals across all classes of the society. Implementing mechanisms to enhance the dissemination of weather information in a more user-friendly format can significantly boost community resilience and preparedness in the face of changing climatic conditions.

Regarding the sources of information owned by residents, it is evident that the most commonly cited mediums are "cell phones," indicated by 61% of respondents and "radio," constituting 58% of the surveyed population. Additionally, a sizable portion of respondents also rely on extension officers (37%) and information shared by their "families and friends" (25%). However, only an insignificant minority of individuals obtain information from "televisions" (15%) and "newspapers" (7%). This distribution of information sources reflects a prevailing trend in rural areas where the vast majority of the population live in abject poverty rendering the acquisition of televisions and newspapers financially unworthy for many. The widespread ownership of cell phones and radios can be attributed to their affordability and accessibility, making them indispensable tools for staying informed.

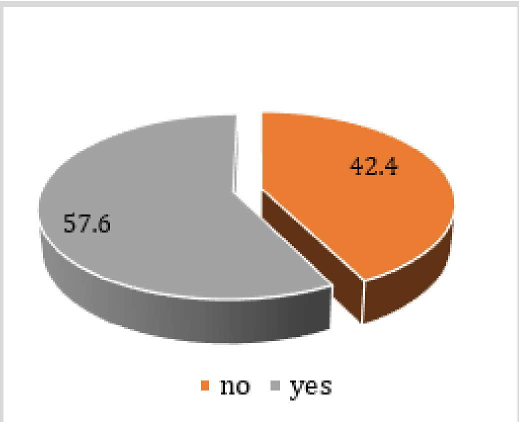

Figure 5. Pie chart showing people`s perceptions on access to weather information.

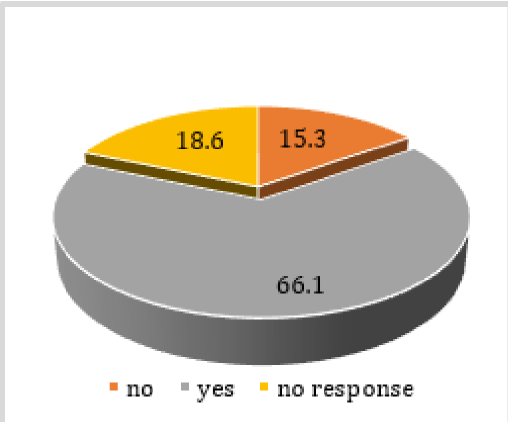

Figure 6. Pie chart showing people`s perceptions on the usefulness of weather information.

4.4. Climate change proxies in Sanyati

According to the feedback from respondents, the impacts of climate change in the study area are becoming increasingly apparent, characterized by rising temperatures, declining rainfall patterns, and an increased frequency of weather-related hazards. Notable climate change indicators identified by the study include a decrease in rainfall (92%), a rise in temperatures (80%), a reduction in the duration of rain seasons (92%), and a rise in occurrences of droughts (88%) (Figure 7). Responses regarding floods and hailstorms showed smaller decreases of these indicators (41% and 24% respectively).

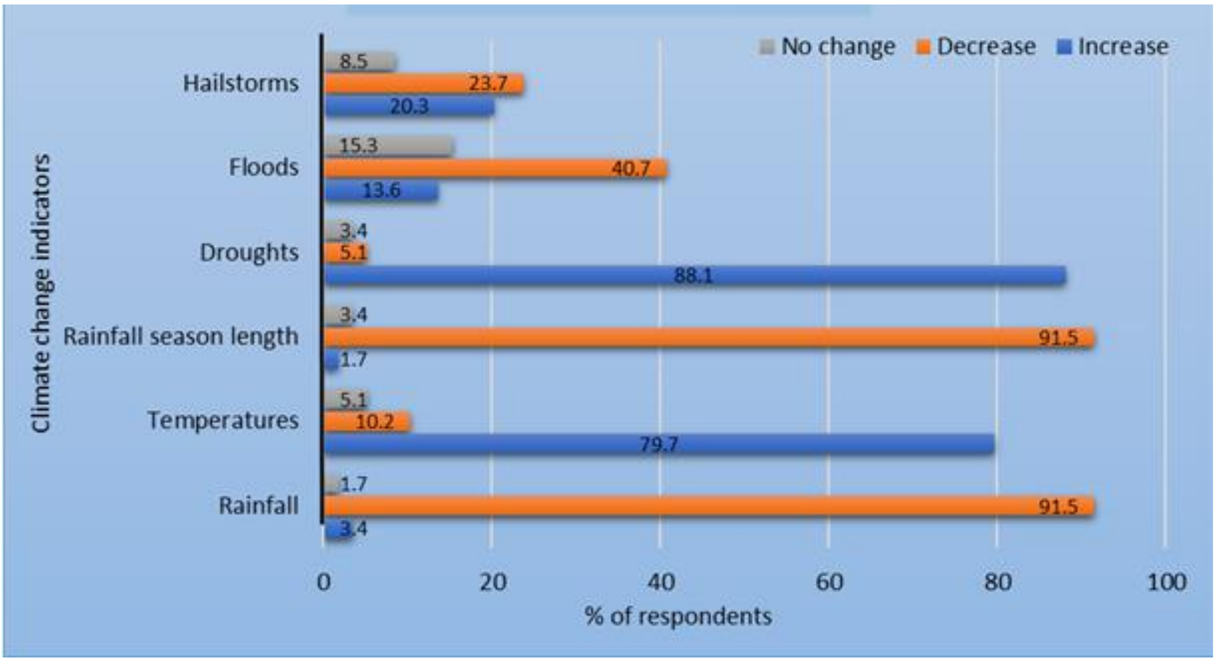

Figure 7. Proxy indicators of climate change as observed by the respondents.

These findings underscore the tangible effects of climate change on the local environment and people`s livelihoods. The overwhelming consensus on phenomena like reduced rainfall and increased temperatures highlights the urgent need for proactive measures to mitigate the adverse consequences of these changes. Understanding these key indicators can inform targeted interventions and adaptation strategies to strengthen resilience within the community. It is imperative to address these pressing climate challenges through informed policies and practices that safeguard both the environment and the well-being of residents in the study area.

4.5. Impacts of climate change on water access

The challenges caused by climate change on water resources manifest through water quantity and quality changes that are caused by climate factors mainly rainfall and temperature changes. According to Amraoui et al (2019), rural households in Southern Africa are the most vulnerable to climate change-induced drought and variability due to their high reliance on groundwater and groundwater-fed systems for potable water use. In Zimbabwe, ground water is a source of water for above 70% of the population (UNDRR, 2021). UNEP (2024) noted that many countries in Africa shifted from water surplus to water scarcity as a result of population changes coupled with the effects of climate-induced water stress. Water scarcity stands out in many research as a prominent challenge exacerbated by the impacts of climate change. Findings from this research, as highlighted in Figure 8, reveal a significant trend where the majority (72%) of respondents which reported difficulties in accessing adequate water resources for their day-to-day needs. This situation is primarily attributed to diminished precipitation patterns and the effects of global warming, resulting in an adverse water balance, particularly noticeable in agro-ecological regions 3 to 5. Moreover, a sizable proportion (59.3%) of the respondents indicated a worsening situation regarding access to water. Consequently, residents have observed an incremental decrease in adequate water accessibility over time. The repercussions of water scarcity have compelled a considerable rate of the population to endure longer distance in search of water sources.

The prevalence of water access issues underscores the perilous nature of the water scarcity problem in the study area. As climate change deepens, the strain on water resources is expected to exacerbate, posing serious implications for various sectors including agriculture and infrastructure. Addressing this challenge demands a multifaceted approach that integrates sustainable water management practices, community engagement and building climate-resilient livelihoods. By recognizing the specific regional vulnerabilities and implementing targeted interventions, stakeholders can work towards enhancing water security and building resilience in the face of evolving climatic conditions.

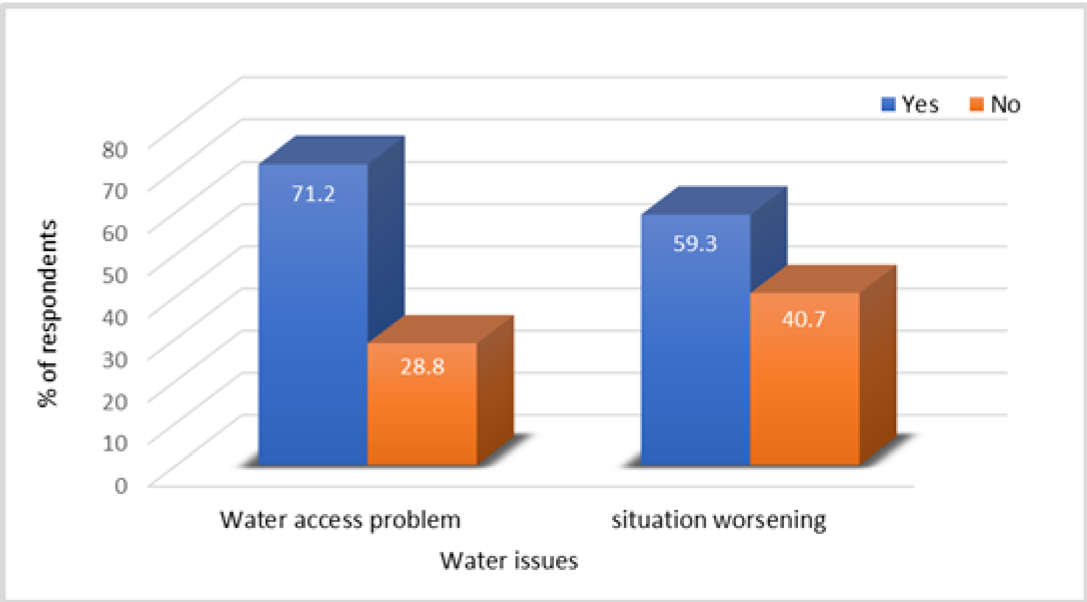

Figure 8. Residents` perceptions on water access.

Table 7. Correlation matrix showing the relationship between knowledge of climate change and water access challenges.

	Knowledge of climate change	Changes in water quantities per household	Changes in water quality noticed by household	Distance to a water source	Number of dried perennial sources
Knowledge of climate change	1				
Changes in water quantities per household	-0.488	1			
Changes in water quality noticed by household	-0.137	0.339**	1		
Distance to a water source	0.561	0.295*	0.121**	1	
Number of dried perennial sources	0.458	0.122	0.018	0.341**	1

*Note**.* Correlation is significant at the 0.01 level (2-tailed).

Upon conducting Pearson correlation analyses between variables representing challenges induced by climate change, significant findings emerged. As depicted in Table 7, a strong positive correlation was established, $r = 0.561$, $p < 0.001$, connecting climate change to the distance individuals need to travel to access water sources. This implies that residents of Sanyati witnessed an increase in distance to a water source as a result of ever-increasing changes in climate. Furthermore, the study discovered a moderate positive relationship between the increase in the distance to water sources and the number of dried perennial water sources within the research area, $r = 0.341$, $p < 0.002$. Additionally, a Pearson correlation matrix was also computed to explore the relationships between climate change and the number of dried perennial water sources, as well as climate change and changes in water quantities per household. Subsequently, a moderate positive correlation was observed between the knowledge of climate change and the number of dried perennial water sources, $r = 0.458$, $p < 0.003$, together with a moderate negative correlation between climate change and changes in household water supplies, $r = -0.488$, $p < 0.004$.

Conclusively, the study findings indicate that shifts in climate patterns have catalyzed an increase in the number of dried water sources and a reduction in the available water quantities for households within the study area. These outcomes underscore the pressing need for proactive measures to address the escalating water challenges aggravated by climate change in the region.

Additionally, the study reveals a prevalent trend among respondents, showcasing that a substantial portion of individuals walking longer distances to access the nearest water sources. Specifically, the research indicates that a majority of residents travel distances exceeding 1.6 kilometers to reach the closest borehole/well or river/dam (Table 8). Drawing from UNICEF's guidelines from 1999, it is recommended that each household should have access to a minimum of 40 liters of water within a distance of less than 1.6 kilometers, reachable within a maximum 30-minute walk time carrying three buckets one way. However, in the study area, approximately 45% of the population must travel more than 1.6 kilometers to reach a nearby safe water source, and a significant 73% walk a similar distance to reach a dam or river. These research findings concur with those from ZimStat & UNICEF (2019) report which acknowledged that climate change is worsening the water accessibility situation. It noted that 58% of local rural residents spend between 31 minutes to over 3 hours a day in one round trip, to and from a nearby water source.

The study also reveals that as the distance decreases, there is a diminishing proportion of respondents complying with the UNICEF-recommended distance criterion, signifying that only a small fraction of the population can access water within the stipulated 1.6-kilometer range. The long distances traveled by people not only indicate heightened energy and time spent carrying out this task but also hint at potential implications for reduced productivity among the local population. Addressing these challenges calls for strategic interventions to improve water accessibility and mitigate the adverse impacts of prolonged water fetching activities on community well-being and productivity.

Table 8. Percentages of people walking various distances to a water source.

Distance to water source	Borehole/Protected well (%)	River/Dam (%)
<500m	15.3	5.1
500m-1km	22.0	5.1
1km-1.5km	18.6	16.9
>1.6km	45.0	72.9

4.6. Strategies for enhancing resilience to water scarcity

Climate change and its impacts on water resource access are complex phenomena that require realistic and effective adaptation and mitigation measures tailored to the specific biophysical and socioeconomic conditions of the communities concerned. To enhance resilience against the impacts of climate change on water resources, the communities within the study area have implemented a wide array of adaptation and coping strategies. Figure 9 illustrates the diversity of mechanisms adopted by the community to mitigate the adverse effects of climate change on water resources.

The study findings indicate that a significant majority (44%) of the population relies on storage tanks as a primary method of combating water scarcity, while a negligible portion (5%) have resorted to using river water for abating the effects of water scarcity. Additionally, 20.5% of individuals have opted for increased boreholes, 16% have embraced water rationing practices, and 9% have turned to water harvesting as their preferred approach to address water challenges caused by climate change.

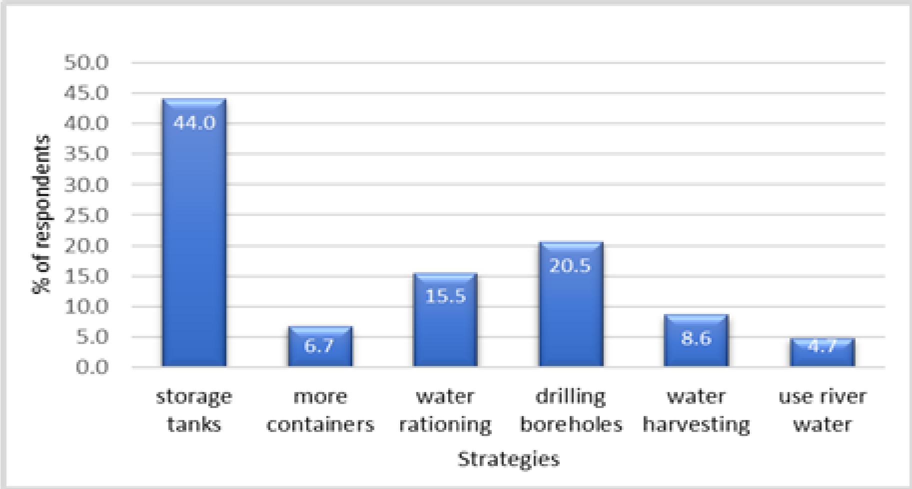

Figure 9. Strategies for building resilience used by the population in the study site.

These varied approaches highlight the community's proactive efforts to adapt to and cope with water scarcity induced by climate change. By diversifying their strategies and utilizing a combination of methods such as storage tanks, boreholes, water rationing, and water harvesting, residents are working towards building resilience and ensuring sustainable water access in the face of evolving environmental challenges.

5. DISCUSSION

The study explores various aspects, including demographic characteristics and inhabitants' perceptions of climate change. The demographic analysis shows a predominant gender distribution skewed towards women, highlighting traditional roles and dynamics within rural communities. The impacts of climate change on water accessibility appear to be gendered (Mudombi & Muchie, 2013; Tanyanyiwa & Mufunda, 2019; Fruttero et al., 2023). A 'gendered lens' on water accessibility resonates with socially constructed roles assigned with one's sex. The gender-based division of work has seen females in rural Zimbabwe spending most of their time, as compared to their male counterparts fetching water, an unpaid menial task (Geere & Cortobius, 2017). As climate change is affecting most rural livelihoods, men are migrating to urban areas seeking better employment opportunities, leaving women with the brunt of fetching water. Variations in climate has seen water accessibility for persons living with disability worse, when comparing experiences of people living with disabilities in urban and rural areas (UNESCO, 2020). Taking those who use wheelchairs for instance, they fail to easily access water from a borehole since boreholes are not wheelchair compatible. This gendered approach clearly depicts how climate change further compounds people`s ability to access water in rural Zimbabwe.

The study noted significant impacts of climate change on water accessibility in Sanyati. It highlighted those changes in climate has seen an increase in competing water needs amongst residents in rural communities. This is consistent with Chimbiro & Soniye (2023), who noted that water related ecosystems inclusive of rivers, wetlands and lakes have negatively been affected, resulting in local residents seeking alternative means of assessing water in response to water stress. Despite the looming challenges of water accessibility, rural communities in Sanyati have come up with adaptation strategies through collaborations. CARE International (2022) noted that rural communities in partnership with several stakeholders, have embraced on adaption strategies in combating water accessibility challenges. For instance, Mwenezi District, which is amongst the severely hot regions, has seen water harvesting initiatives being funded for, by collaborative stakeholders such as the Ministry of Lands, Agriculture, Fisheries, Water and Rural Resettlement in partnership with the Swedish Embassy, European Union, UNDP, and the Foreign Common Wealth Development Office. This project in Mwenezi District has led to the construction of 120 underground cement tanks and a dam with the capacity to hold 45 000 m^3 of water (CARE International, 2022). This collaboration has enhanced transformational resilience, capacity building and the general improvement to water access. In addition, collaborations in Shurugwi (Vimbai Village) and Mudzi (Fombe Project) have enhanced community water access by drilling 3063 boreholes which benefited these districts.

6. CONCLUSIONS

This study emphasises how climate change has a major effect on rural people's access to water, particularly in Zimbabwe's Sanyati District. The primary research topic evaluates the impact of climate change on rural communities' access to and availability of water resources. The results of this study show that rural communities' access to and availability of water resources has been influenced by climate change. This was demonstrated by the fact that 71.2% of respondents stated that they had trouble getting enough water resources, mainly because of decreased precipitation and global warming, and that 59.3% of participants stated that their access to water had gotten worse over time, pointing to a concerning trend in water availability. The results show a strong correlation between the reduced availability of water resources for nearby communities and shifting climatic patterns marked by less rainfall, warmer temperatures, and more frequent droughts. The community's perspectives show a keen awareness of these changes, underscoring the pressing need for flexible approaches to efficiently manage water supplies. A significant majority (79.7%) of the respondents acknowledged noticeable changes in weather patterns in Sanyati, indicating a strong awareness of climate change impacts. This reasonates with the study’s quantitative approach supported by the use of Spearman’s rank correlation coefficient which illustrates to what extent demographic factors influence perceptions of climate change and its impacts on water access.

The study also reveals a predominat gender distribution in Sanyati District, with women constituting 61% of the surveyed population compared to 39% for men. This finding reflects traditional societal roles where women are often the primary caretakers of households. This therefore underscores the intertwined relationship between gender dynamics and water accessibility in the context of climate change highlighting the need for targeted interventions or tailored strategies that support the resilience of rural communities in Zimbabwe, particularly emphasising women’s roles in water resource management. The study reveals that Sanyati District communities have taken a proactive approach to reducing the effects of climate change by implementing a range of measures to increase their resilience to water scarcity. From the study, 44% of the respondents use storage tanks as their primary strategy to deal with water scarcity, while 20.5% chose to drill more boreholes and 15.5% have used water rationing procedures.

The limitations noted in this study, such as its dependence on local specificity, point to the necessity of more research to deepen understanding and guide focused solutions in various circumstances in Zimbabwe and other areas. While the study utilised a cross-sectional approach, future research would benefit more from a longitudinal research design, enabling changes being witnessed as a result of climate change and its impact on water accessibility to be tracked over time.

These research findings highlight the urgent necessity for climate-responsive water management policies in rural communities. Considering that women constitute the greater proportion of the surveyed population and are directly involved in water resources supply and management issues at household level, women should be empowered to participate in water governance and decision-making at both community and country level. Furthermore, there is need to push for the incorporation of decentralization of water governance in existing policies in order to promote local participation in water conservation and sustainable use. This is based on a widely accepted notion that community-driven initiatives are more likely to succeed because they foster a sense of ownership and responsibility among members of the

community. In a bid to mitigate against water scarcity in the Sanyati District, this study recommends the following:
-Promote collaborative rural governance where local communities partner with the public, private sector and NGOs in borehole drilling programs in order to promote widespread utilization of groundwater resources.
- Expand access to affordable water storage tanks and this can be achieved through offering subsidized water tanks to low-income households.
- Providing training programs for women on sustainable water use and climate change adaptation strategies.
- Introduce affordable water purification technologies for rural communities in order to enhance access to safe water.
- Furthermore, it is imperative that policymakers create policies that support sustainable practices in the management of water resources while simultaneously lessening the effects of climate change.

For further research, the following research gaps should be considered:
- more research should focus on how climate change disproportionately affects women and how gender-specific adaptation strategies can be implemented effectively;
- there is a need for studies that analyze how government policies, economic conditions, and social structures influence climate adaptation and water security;
- future research should explore the use of GIS, remote sensing, and AI-based predictive models for real-time water resource monitoring and climate risk assessments.

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Use of AI tools declaration
The authors declare that they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflicts of interest
The authors declare that they have no conflicts of interest to.

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Cooperation and adaptation to climate change: the case of sea turtles from a transcale perspective

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ABSTRACT: The rate of biodiversity loss (terrestrial and marine) is among the nine critical environmental thresholds associated with subsystems or biophysical systems of the planet, beyond which the Earth system would undergo unsustainable, abrupt and irreversible environmental changes. This factor is profoundly influenced by climate change and anthropic practices, elements that are leading to the reduction and fragmentation of habitats and the development of a series of important physiological repercussions within the species most affected by these phenomena. Among these, the so-called keystone species and umbrella species are certainly of great interest, i.e. those species that are fundamental for the balance and survival of the ecosystems that host them, and can therefore, by their presence or absence, act as indicators of the wellbeing of these biomes. In this context, the policies implemented on a national and international scale by political actors and the presence of centres specialised in the protection and care of these wild species are fundamental. Therefore, taking these considerations as a starting point, this research, through the observation and mapping of the phenomena that are affecting sea turtles, aims to emphasise how top-down policies mixed with bottom-up actions - with a view to safeguarding them by mitigating the impacts of anthropogenic practices and thus compensating for the impacts of modernity - can be considered not only as actions to mitigate the impacts of the anthropocene, but also as a first step towards a return to cooperation between humans and other animals as a method of adaptation, resilience and resistance of the Earth's inhabitants to climate change.

KEYWORDS: cooperation, animal geography, political ecology, climate change, biodiversity

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1. INTRODUCTION

The continuous degradation and constant reduction of natural habitats, coupled with the selective disappearance of certain predator species, have led, on one hand, to the numerical increase of species generally preyed upon and, often today, considered invasive, and on the other hand, have driven many wild species, in search of food, to leave the residual ecological niches ideally destined for them and to reach urban areas, which are effectively domains and territories exclusively human. These factors are thus linked to the disruption of ecosystem balances caused by human action, which, when faced with a perceived emergency, generally intervenes through new acts of violence and domination, rather than through the rebalancing and restoration of disturbed ecological systems, within a perspective that, therefore, exacerbates and formalizes spatial conflicts triggered precisely by the humans who feel harassed and/or harmed by these species. This line of thinking, connected to the concept of human exceptionalism (Srinivasan & Kasturirangan, 2016), stands in stark contrast to the healing of the "metabolic rift" of Marxian memory (Marx, 1980) and, therefore, to the characteristic of the Earth as oikos,

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the home of all living beings present upon it (hence the term 'ecology': study of the home). As suggested by Redpath et al., (2014), the human group likely misidentifies certain animal species as antagonistic. It is precisely by considering them as such that it transforms issues of cohabitation/coexistence and their perception into conflict, which is currently becoming “one of the most challenging issues in wildlife conservation” (Sabuhoro et al., 2023, p. 1). This perception, therefore, which "masks the underlying human dimension” (Redpath et al., 2014, p. 222) both in terms of anthropogenic impacts on habitats and in terms of human-human conflicts (animal rights/environmentalists vs. other interest groups), not only fails to consider the complex webs underlying the process of spatial production - which, as Tsing (2015) emphasizes, is inherently multispecies - but currently seems to limit the likelihood of finding effective solutions and moving toward a new alliance based on cooperation.

However, the dimension just described does not appear to be the only one in play since not all wild species are regarded as antagonistic by the human group. Although the anthropocentric perspective still prevails, some species, considered keystone or umbrella species and thus essential for the balance and survival of the ecosystems they inhabit, capable, through their presence or absence, of serving as indicators of the well-being of such biomes, are protected at various levels by specific regulatory instruments.

Starting from the two concurrent trajectories present within today's society - one of a productive nature, which sees nature and its inhabitants (both human and non-human) as resources to be exploited indefinitely, and the other, in contrast, aimed at restoring balance and reconciling these three elements - the present contribution, through the protection systems implemented at both global and local levels for marine turtles, a species on which the relevant geographical literature has focused little so far (Tisdell & Wilson, 2001; Campbell, 2007; Anderson et al., 2013; Ramírez-Cover, 2013; Havice et al., 2018; Nurhayati et al., 2022; Darmawan & Takewaka, 2024; Nur et al., 2024), aims to emphasize how top-down policies combined with bottom-up actions - in a conservation perspective linked to the mitigation of the impacts of human practices and thus compensating for the effects of modernity - can be considered not only as actions mitigating the impacts of the Anthropocene but also as a first step toward the return to cooperation between humans and other animals. It is a method of adaptation, resilience, and resistance of Earth’s inhabitants to climate change, aimed at the possible realization of constructive relations of cooperation and coexistence, deep and beneficial for all living beings, as, within a damaged planet, an alliance with other species is essential " to rebuild places of refuge; only in this way will it be possible to achieve a partial and solid recovery and reconsolidation of the Earth in biological, cultural, political, and technological terms” (Haraway, 2019, p. 146).

2. METHODS AND DATA

This research was conducted through an exploratory study, both desk and field-based. More specifically, the desk research involved a thorough collection and analysis of secondary data gathered from databases, academic journals, websites, and social media platforms (Facebook, Instagram, etc.). This initial level of analysis was complemented by direct investigation. In particular, the latter included interviews with key informants and participation, during the years 2018-2019, in the monitoring activities of nesting sites organized by the Sea Turtle Recovery Centre (STRC) of the Museum of Natural History of Salento (MSNS). The results of this investigation also enabled the creation of specific cartographic material produced using QGIS software (Figure 1 and Figure 2).

This study is situated within the field of animal geography and thus contributes to the body of research that considers animals as spatial actors and agents within territorial dynamics. The adopted approach is grounded in critical posthumanism and political ecology - frameworks that move beyond the nature/culture dichotomy to analyze multispecies relations and power dynamics that traverse ecological and social systems in an integrated manner.

3. MARINE TURTLE RECOVERY CENTRES (STRCs): A GLOBAL SCALE ANALYSIS

The link between human activities and the rise in global temperatures, which has been considered an "unequivocal" fact since the late 19th century (Hartmann et al., 2013, p. 198), is now well established (IPCC, 2023, p. 42). The IPCC (Intergovernmental Panel on Climate Change) has set a limit of maximum global temperature increase of 1.5°C relative to pre-industrial levels, beyond which conditions on the planet would no longer be "liveable". However, as of today (2011-2020), an increase of 1.1°C has already been reached compared to that period (IPCC, 2023) [see Note 1], while six out of the nine planetary boundaries identified as critical to maintaining a "safe operating space for humanity" have already been surpassed (Rockström et al., 2009a, 2009b; Steffen et al., 2015) [Note 2]. Among these critical environmental thresholds, associated with subsystems or biophysical systems of the planet, beyond which the Earth system would experience unsustainable, rapid, and irreversible environmental changes, is the rate of biodiversity loss (both terrestrial and marine) [Note 3], which is currently 100 times higher than its natural rate (Barbiero, 2011), leading toward what has been identified as the sixth mass extinction (Ceballos et al., 2015; Braje & Erlandsonb, 2013; Lewis & Maslin, 2019). Specifically, it is estimated that between 11,000 and 58,000 animal species go extinct each year (Dirzo et al., 2014), while climate change has been identified as the cause of the extinction of entire populations of more than 1,000 plant and animal species (WWF, 2022).

Among the impacts identified by the IPCC, should the temperature limit be reached or exceeded, are the increase in the frequency of marine heatwaves, with a subsequent heightened risk of oceanic biodiversity loss (also due to mass mortality events); short-term risks of biodiversity loss (ranging from moderate to high for forest ecosystems and kelp and seagrass ecosystems, and from high to very high for Arctic sea ice, terrestrial ecosystems, and warm-water coral reefs); degradation of permafrost; continuous sea level rise and the increased frequency and intensity of extreme events involving seawater inundating coastal human settlements, damaging infrastructure in these areas, with submergence and loss of low coastal ecosystems, expansion of soil salinization, and cascading risks for livelihoods, health, well-being, cultural values, food and water security (IPCC, 2023, pp. 98-99).

Among the species at risk in this context are also those of the *Cheloniidae* and *Dermochelyidae* families, which include the seven existing species of sea turtles [Note 4], all listed in the International Union for Conservation of Nature (IUCN) Red List. Due to their ecosystem functions, they are considered "umbrella species" for coastal and marine habitats and, due to their charisma, "flagship species", meaning they can attract public interest, thereby facilitating the implementation of conservation and habitat protection practices, thus serving as a driving force for conservation and simultaneously symbolizing ecosystem well-being (Frazier, 2005).

Currently, sea turtles are included in the following regulatory references (ISPRA, 2013):

- Washington Convention (1973; Appendix I: "Species that are severely threatened with extinction and for which trade is strictly prohibited");
- Bern Convention (1979; Appendix I: "Migratory species that are in danger");
- Bonn Convention (1979; Appendix II: "Migratory species that have an unfavorable conservation status and require international agreements for their conservation and management");
- Habitat Directive 92/43/EEC on the conservation of natural and semi-natural habitats and of wild fauna and flora (1992; Annex II: "Animal and plant species of community interest whose conservation requires the designation of special areas of conservation"; Annex IV: "Animal and plant species of community interest that require strict protection");
- SPA/BIO Protocol (1995; Annex 2: "Endangered or threatened species");
- Regulation (EC) No. 1967/2006 on management measures for the sustainable exploitation of fishing resources in the Mediterranean Sea, amending Regulation (EEC) No. 2847/93 and repealing Regulation (EC) No. 1626/94 (2006; Article 3).

This regulatory framework has enabled the creation of specific Recovery and First Aid Centers (STRCs; Figure 1), often real monitoring and research hubs at the local scale, with the aim of both rehabilitating and releasing into the wild sea turtles found at sea or stranded on the shore, as well as monitoring their nesting sites, when present, which during the summer characterize certain coastal stretches: securing the area, potential relocation to a more suitable location (this happens when the nest is too close to the shore), biometric analysis, guiding the hatchlings to the sea after birth (in case of severe light pollution), and nest inspection.

In this regard, it should be noted that due to the rising seawater temperatures, specifically referring to the Mediterranean Sea, the nesting range is shifting increasingly northwest, extending its limits to new regions of southern and central Italy (Bentivenga et al., 2010; Marzano, Nannarelli & Scarafino, 2010; Garofalo et al., 2016; Carlino et al., 2020; Hochscheid et al., 2022; Mancino, Canestrelli & Maiorano, 2022). Furthermore, the increase in temperatures, combined with sand color, influences the sex of the hatchlings, leading to a higher number of female births (Laloë et al., 2014; Tanner et al., 2019).

An example of this is certainly the nesting boom that characterized the Salento region of Lecce during the summer of 2024, with a total of 81 nests recorded out of 104 for the entire region (48 of which were in Ugento, making it the leading municipality in Italy for the number of deposits; see the following paragraph). This phenomenon of nesting has significant economic, social, and cultural implications, as it represents both a major attraction for the beaches involved and an opportunity for raising awareness and developing specific knowledge within the local community.

The discovery of a nest and the subsequent actions of securing and monitoring it allow for direct contact with another species, enabling the local community to learn about its specific characteristics through information provided by the operators. An alien species thus becomes, for the local community, something to care for and protect, producing an additional impact: the beach, understood both as a public space and as a liminal space (Preston-Whyte, 2004), gains another factor of characterization in the development of a sense of place by the users.

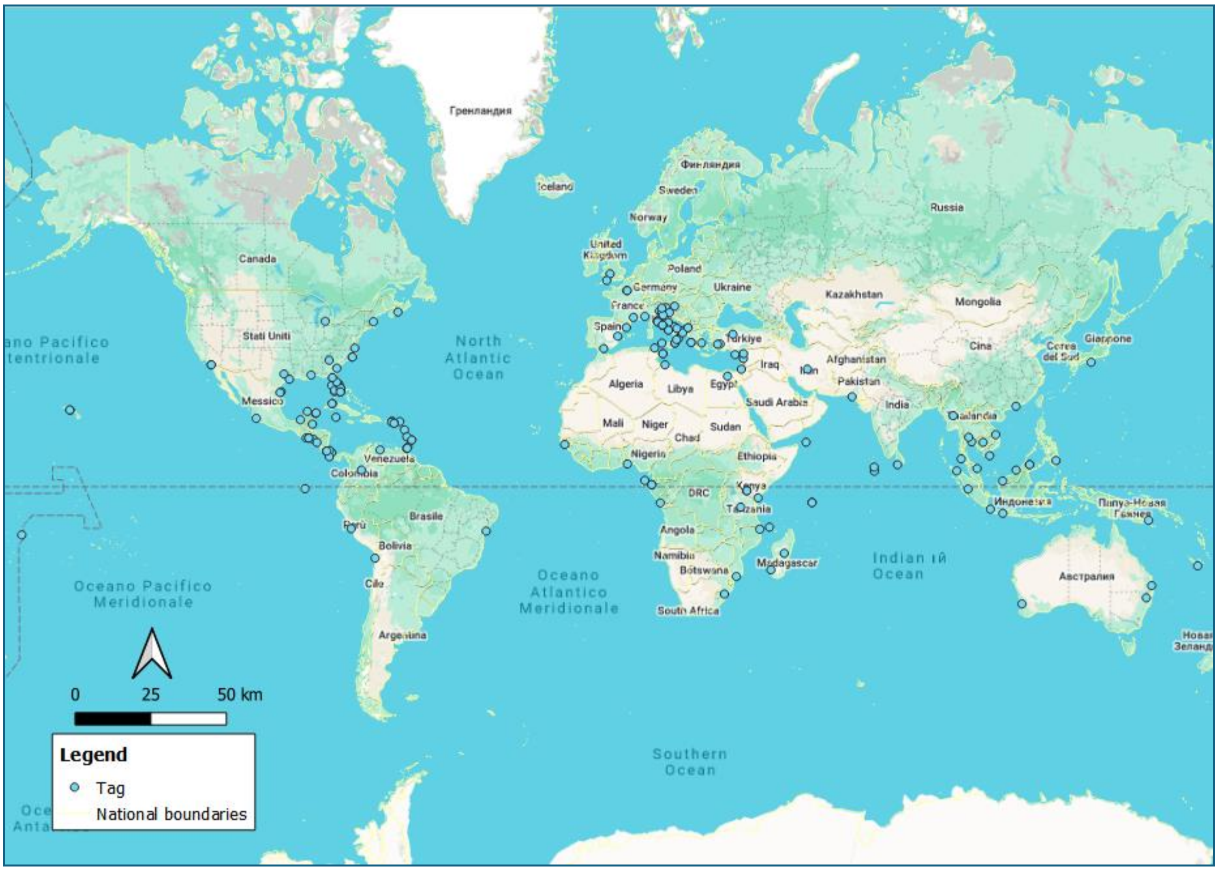

Figure 1. Mapping of Tag series present on a global scale.
Source: Own processing through QGIS software.

Regarding the global distribution of such centers, it is important to highlight that the data in the inventory of tags, which are plastic or metal labels that STRCs must attach to each rehabilitated and released turtle, and which are updated by the Archie Carr Center for Sea Turtle Research (ACCSTR), has allowed for a mapping, albeit partial, of STRCs and research projects (also promoted by various institutes) worldwide [Note 5]. This has resulted in 1,371 tag series held and associated with 174 institutions, 24 of which are located in Italy (currently, there are 23 STRCs in Italy, not all of which are listed in the aforementioned inventory; Figure 1 and Figure 2).

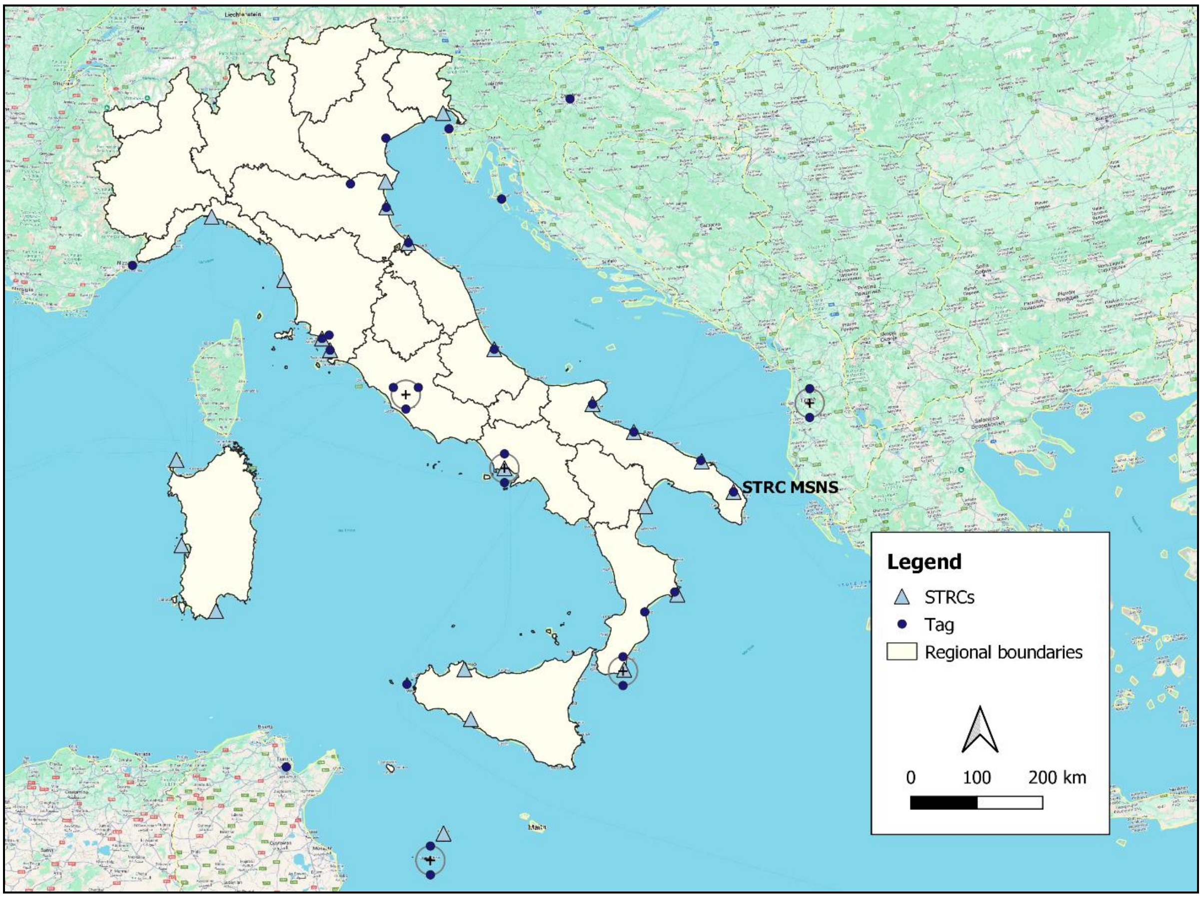

Figure 2. Mapping of CRTMs present in Italy and tag series.
Source: Own processing through QGIS software.

4. THE SEA TURTLE RECOVERY CENTRE (STRC) OF THE NATURAL HISTORY MUSEUM OF SALENTO: A LOCAL CASE STUDY

The Sea Turtle Recovery Centre (STRC) of the Museum of Natural History of Salento (MSNS; Calimera, Italy; Figure 2) was established in 2017 (becoming fully operational in 2018), to rehabilitate and release into the wild sea turtles found at sea or stranded on the shores of the Salento region, as well as monitoring their nesting sites discovered during beach monitoring activities and/or reported by citizens during the summer period (Figures 3 and Figure 4).

Figure 3. Ward of STRC and two sea turtles in the recovery centre.
Source: Author's photograph.

Figure 4. *Caretta caretta* nesting site.
Source: Author’s photograph.

The role of this facility, both within the local area and at a broader regional scale, is undoubtedly fundamental to the conservation of this species. This observation is attributable to the various intervention strategies implemented, which characterize the STRC of the MSNS as a cross-cutting actor within the Local Territorial System: a) rehabilitation function and reintroduction to the wild; b) monitoring and management of nesting sites; c) scientific research; d) networking operations; e) design and promotion of targeted communication campaigns and specific events.

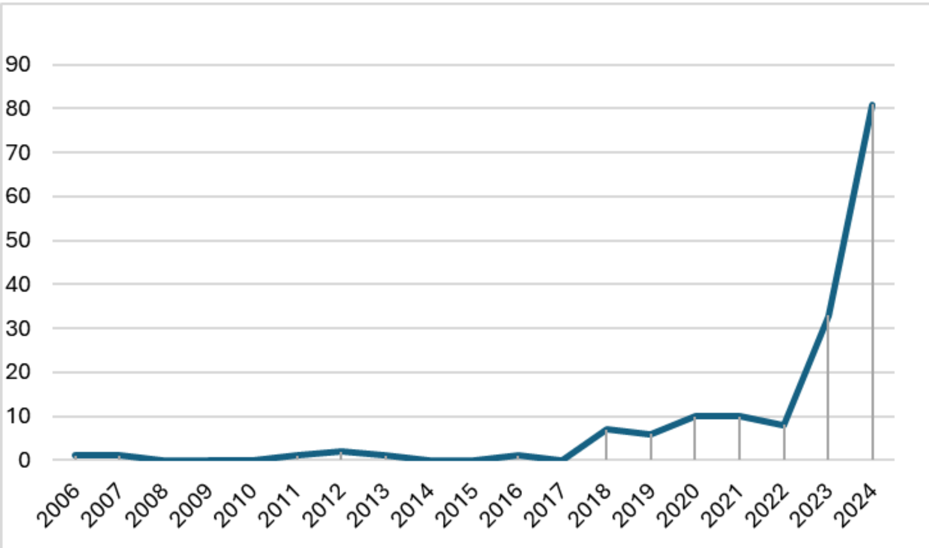

Figure 5. Recorded nesting events in Salento (2006-2024).
Source: Author's elaboration.

For the period 2018-2022, the data on the admissions to the STRC registered a steady increase, reaching a peak of +102% in 2022. This increase is likely attributable to two factors: on one hand, the establishment of an organizational network between the STRC, coastal municipalities, the Coast Guard, and environmental associations operating in the province of Lecce (which has allowed for the improvement and strengthening of monitoring activities); on the other hand, the design and development of awareness campaigns aimed at enhancing basic knowledge, engaging local communities, and facilitating communication between citizens and relevant authorities (Carlino et al., 2020). Another significant initiative in this regard was the recruitment of “Seaturtle Watchers” starting in June 2020, a network of volunteers who, under the coordination and training of the Centre, provide support to the STRC’s activities. This support became crucial during the nesting and hatching period, particularly due to the exponential increase in the number of nests recorded since 2018 and the extension of the nesting season, both of which are correlated with rising temperatures (Figure 5).

More specifically, the specimens cared for by the center during the aforementioned period numbered 220, of which 29% were admitted for anthropogenic causes (ingestion of hooks and lines: 17%; entanglement in nets and/or plastic debris: 6%; collisions with boats: 5%; intentional killing: 1%), and 71% for natural causes (cold stunning: 46% and/or debilitation: 25%). These percentages, however, are heavily influenced by the phenomenon of cold stunning, hypothermic stunning that primarily affects juvenile specimens (hatchlings), causing weakness and inactivity (Christiansen et al., 2016). Without this factor, admissions due to anthropogenic causes would account for 53%, while those due to natural causes would account for 47%. This exclusion from the total count is possible because the marine turtle species treated at the center (*Caretta caretta* and *Chelonia mydas*) reach sexual maturity between the ages of 16 and 28 (Casale et al., 2009; Van Hautan et al., 2018), which, from an ecological standpoint, makes younger specimens unsuitable for the species' perpetuation and thus for its survival, unlike adults, on which data shows a high impact from anthropogenic practices.

In addition to being an operational center, the structure also serves as a research center. The data collected through recovery, rehabilitation, and monitoring activities are analyzed and shared with other institutions, and over time have led to several publications. The networking activities developed by the center have been particularly fruitful. Currently, the STRC of the MSNS has established various agreements and collaborations with research institutions, organizations, and associations, both at the local, national, and international levels, through which numerous research, cooperation, and awareness projects have been carried out over time. Among these, the NEMO – Mediterranean Coastal Communities project and Blue Tyre are particularly noteworthy. The former, launched in 2014, funded by the Italian Cooperation and implemented by CIHEAM Bari, in collaboration with the Lebanese Ministry of Agriculture and key stakeholders in the Tyre coastal community (Tyre Nature Coast Reserve, Tyre Municipality, Tyre Municipalities Union, GAL TYROS, Mosan Center, Fishermen's Union and Cooperative), aimed to "create sustainable development for Mediterranean coastal communities in the fishing, agriculture, and tourism sectors" [Note 8], with active participation from STRC in the creation of the Sea Turtle Exhibition, a permanent exhibition area dedicated to marine turtles managed by the Tyre Nature Coast Reserve, aimed at raising awareness among both insiders and outsiders about the importance of turtle conservation, with particular emphasis on threats from human activities. The latter, led by the Municipality of Tricase with the participation of the *Cooperazione nei Territori del Mondo* association, the Department of Biological and Environmental Sciences and Technologies at the University of Salento, the *Magna Grecia Mare* Association, and the *Naturalia* Cooperative (currently managing the MSNS), funded by the Italian Agency for Development Cooperation, aims to promote sustainable and resilient coastal development in the coastal and marine area of Tyre, Lebanon. This 36-month project, launched in 2021, targets local institutions and communities to "implement measures for adaptation and prevention of climate change risks and provide marine-coastal waste management and environmental monitoring services" [Note 9]. Among the planned actions was the creation of an environmental observatory and a marine turtle recovery center within the Tyre Coast Nature Reserve. In this context, the researchers and operators from the STRC of MSNS have structured several moments of discussion and training with the local community, both in Tyre and in Salento, to share experiences and best practices.

The structure is also part of the AdrioNet network – the Adriatic-Ionian Network for coordination among Sea Turtle Rescue Centers – created to coordinate and standardize intervention methods and protocols, share management experiences, establish common data collection rules to conduct broader and more significant scientific studies, enhance its influence with decision-makers, and, similarly, implement information campaigns targeting citizens to promote programs and initiatives aimed at safeguarding turtles and, more generally, biodiversity and the good conditions of the Adriatic and Ionian Seas in all their components [Note 10]. To date, the network includes six centers: Torre Guaceto Marine Protected Area, Cetacean Study Center Onlus, "Luigi Cagnolaro" Pescara STRC, MSNS STRC, WWF Molfetta STRC, Cetacea Foundation Onlus, Rimini/Riccione Center, and WWF Bosco Pantano Oasis.

Another significant aspect of this specific case study concerns the development of events and projects aimed at raising awareness both among the visitors to the MSNS, where the STRC is located, and more broadly among the general public. Among these, we can certainly highlight the initiatives of reintroducing rehabilitated specimens into nature, the creation of a life cycle exhibition dedicated to marine turtles within the museum's exhibit paths (Figure 6), and an open rehabilitation room, both inaugurated in 2021, as well as educational workshops for schools and families.

Figure 6. Exhibition hall dedicated to sea turtles at the MSNS.
Source: Author's photograph.

5. CONCLUSIONS

Due to their intrinsic characteristics, which are related to both their evolutionary history, their distribution range, and their life cycle, sea turtles currently serve as an important bioindicator of the effects of climate change on coastal and marine ecosystems (Hawkes, 2009; Patrício, 2021).

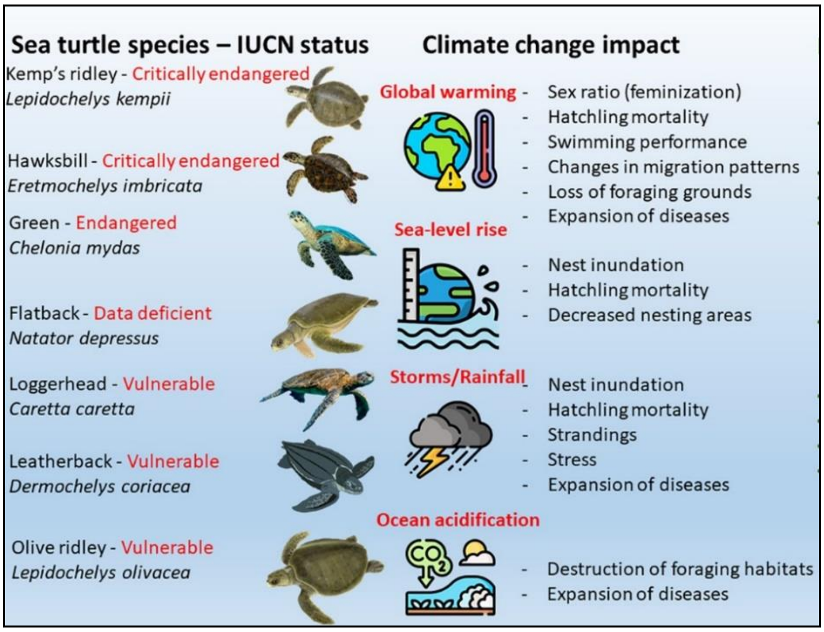

Figure 7. The major effects of climate change on sea turtles.
Source: Simantiris, 2024.

More specifically, climate change, particularly concerning phenomena such as sea level rise, extreme weather events, temperature increases, and ocean acidification (Simantiris, 2024; Figure 7), is recognized as one of the five threats identified for all seven species by the Marine Turtle Specialist Group (MTSG) of the Species Survival Commission (SSC) of the IUCN [Note 11].

As highlighted in the previous sections, the establishment of STRC both globally and locally represents a blend of top-down policies and bottom-up actions, thus forming a new bridge between humans and other animals. In this context, the concept of care, in its many forms, becomes predominant and serves as a potential tool for implementing adaptation and mitigation actions in response to climate change.

However, this state of affairs is undermined by the broader context, as these centers partially see their efforts thwarted when the rehabilitated animals are released into an environment that remains degraded, within an overexploited territorial context, and a culture driven by anthropocentrism and an extractivist economy.

This contradiction, however, highlights how STRCs still hold significant potential for change—not only as spaces for interaction between different species (humans and sea turtles) but also as producers of new symbolic and material places of interaction and awareness, where trans-species alliances are experimented with. These alliances, as suggested by Lorimer (2007), represent novel relational configurations in which animals are not mere recipients of care and protection, but active subjects in the co-construction of shared landscapes, the co-production of space, and the transformation of environmental governance practices. In this sense, the notion of trans-species alliance should not be understood as merely rhetorical, but rather as a genuinely geographical category—one that can activate both theoretical and practical reflections on the role of nonhuman life forms in territorial processes. By intersecting concepts such as place, scale, network, and landscape, it contributes to problematizing the exclusively human status of spatial and environmental actions and, more broadly, to rethinking geography as a multispecies field of study. From this perspective, it emerges as a socio-ecological and territorial practice that enables us to imagine new forms of coexistence in times of ecological crisis. Building alliances thus means envisioning new modes of ecological territoriality in which the human is no longer at the center, but part of a broader constellation of agents, memories, relationships, and interdependencies. It calls for a reconfiguration of geography not as a discipline centered solely on the human, but as a multispecies field capable of interpreting and accompanying territorial transformations driven by complex interspecific relations. It is in these hybrid spaces—such as STRCs —that new territorial narratives emerge, capable of re-signifying human action through the lens of care, responsibility, and coexistence.

As evidenced by the local case study, the establishment of such centers can lead to the development of specific projects, including thematic pathways and other scientific and outreach initiatives. These initiatives, also through the use of mass media and particularly social media platforms [Note 12], allow for the raising of awareness among visitors and the general public regarding the importance of biodiversity, the impacts of climate change on it, and its protection and conservation.

In this regard, it is worth noting that, from the very first findings, the nests discovered along the Salento coast have never been subject to acts of vandalism. On the contrary, they have become an attraction for the local community and, consequently, an appealing element for the beaches on or near the nesting areas. The analysed case study highlights how these structures potentially possess a dual dimension of awareness and intervention, both local and transnational, through the concept of transcalarities, which, even through the use of citizen science, helps engage citizens and expand their territorial presence.

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Use of AI tools declaration
The author declares they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflicts of interest

The author declares no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

NOTE

1. In particular, 2024 was the first year with an average temperature 1.5° higher than the pre-industrial period (source: https://climate.copernicus.eu/global-climate-highlights-2024).
2. The planetary limits identified by Rockström et al. [19, 20] are: climate change, rate of biodiversity loss (terrestrial and marine), interference with the nitrogen and phosphorus cycles, global freshwater use, land-use change, chemical pollution, ocean acidification, stratospheric ozone depletion and atmospheric aerosol load, of which the first six are exceeded to date.
3. According to Article 2 of the 1992 Convention on Biological Diversity (CBD), "biological diversity" is defined as: "all forms of variability among living organisms, including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems" (ONU, 1992).
4. *Dermochelys coriacea* (leatherback turtle), the only species belonging to the family *Dermochelidae*; *caretta caretta*, *chelonia mydas* (green turtle), *natator depressus* (or flat-backed turtle), *lepidochelys kempii* (kemp's turtle), *lepidochelys olivacea* (olive turtle) and *Eretmochelys imbricata* (hawksbill turtle), the latter species belonging to the *chelonidae* family (Figure 7).
5. It should be emphasised that the inventory (https://accstr.ufl.edu/resources/tag-inventory/), which includes the tag series, the tag manufacturer and style, the ocean basin where the tags were used and the reference organisation, may not be exhaustive as it is limited to external tags and does not include PIT tags. Specifically, it includes all tag series issued by ACCSTR since the 1950s, when Archie Carr began distributing tags, and all tag series issued by the Cooperative Marine Turtle Tagging Program (CMTTP) originally issued by NMFS and now by ACCSTR. The inventory also includes tag sets that researchers have submitted for inclusion in the database. In addition, other tag sets that the Centre knows have been used but for which it does not have complete data are also listed (accstr.ufl.edu/resources/tag-inventory).
6. "Seaturtle watcher. Un anno di attività da guardiani delle tartarughe marine", a documentary that won the Earth Day 2022 Award at the Cefalù Film Festival, "for having documented with a film the securing of some sea turtle nests on the beaches of Torre San Giovanni in the province of Lecce. For the beautiful images with which it shows the general public the care that was given to 450 small sea turtles for four months" (festivalcinemacefalu.it; Retrived from: https://festivalcinemacefalu.it/index.php/2022/04/22/il-premio-speciale-earth-day-a-seaturtle-watcher-di-andrea-fiorito/).
7. Retrieved from: https://www.seaturtlewatcher.com/
8. diari.aicstirana.org; see https://diari.aicstirana.org/2017/05/10/porto-palermo-e-il-progetto-nemo/
9. www.ctm-lecce.it; see https://www.ctm-lecce.it/it/causes/blu-tyre-partenariato-locale-per-lo-sviluppo-marino-e-costiero-sostenibile/
10. Retrieved from: https://www.tartalife.eu/it/nasce-adrionet-una-svolta-epocale-la-tutela-delle-tartarughe-e-del-mare
11. These threats are both anthropogenic and natural and concern: bycatch from fishing activities, coastal development, pollution (plastic waste, fishing-related waste, chemical pollutants, etc.) and pathogens, direct capture and illegal trade (food, oil, leather, jewellery) and climate change.
12. The CRTM of the MSNS is present both on Facebook ("Centro Recupero Tartarughe Marine - Museo di Calimera": 8299 likes and 9782 followers, creation date: 13.05.2020) and on Instagram ("crtm_calimera": 1,584 followers and 165 posts, the first dated 02.06.2021). Data updated as of: 03.02.2025.

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- Does this part include research limitations?
- Does this part include suggestions for future research? (Cambria, 10pt, Normal).

ACKNOWLEDGMENTS: (Cambria, 10pt, Bold. Spacing: Before 12pt; After 6pt. Line spacing: At least; At 13pt). Apart from the usual acknowledgements, use this section to mention sponsoring and funding information (Cambria, 10pt, Normal).

USE OF AI TOOLS DECLARATION: (Cambria, 10pt, Bold. Spacing: Before 12pt; After 6pt. Line spacing: At least; At 13pt). The authors declare they have not used Artificial Intelligence (AI) tools in the creation of the articles (Cambria, 10pt, Normal).

AUTHOR CONTRIBUTIONS: (Cambria, 10pt, Bold. Spacing: Before 12pt; After 6pt. Line spacing: At least; At 13pt) Each author is expected to have made substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data; or the creation of new software used in the work; or have drafted the work or substantively revised it; and has approved the submitted version (and version substantially edited by journal staff that involves the author's contribution to the study) (Cambria, 10pt, Normal).

CONFLICTS OF INTEREST: (Cambria, 10pt, Bold. Spacing: Before 12pt; After 6pt. Line spacing: At least; At 13pt). Authors must identify and declare any personal circumstances or interest that may be perceived as influencing the representation or interpretation of reported research results. If there is no conflict of interest, please state *"The authors declare no conflict of interest."* (Cambria, 10pt, Normal).

REFERENCES (Cambria, 10pt, Bold. Spacing: Before 12pt; After 6pt. Line spacing: At least; At 13pt) The list of references should be complete and accurate. For each work shown in the list of references, there must be a reference in the text.

Beginning with Volume 5, Issue 1 / 2023, the citation of authors in the text will follow the 7th edition of the APA style (American Psychological Association), instead of the previously used Vancouver style.

Citations in the text and the list of references should follow the referencing style used by the American Psychological Association, the latest version of the APA Publication Manual (i.e., APA 7), which released in October 2019. Details concerning this referencing style can be found at **http://www.library.cornell.edu/resrch/citmanage/apa**. Authors can also use citation machine at **http://citationmachine.net/**

References should be arranged first alphabetically and then further sorted chronologically if necessary. More than one reference from the same author(s) in the same year must be identified by the letters "a", "b", "c", etc., placed after the year of publication.

In every article there should be at least 20 references and majority of references have to be from SCOPUS/Web of Science. The authors should concentrate on the references to publications for recent years.

Authors are required to complete the reference in a list of literature used with DOI (Digital Object Identifier) if it has been assigned to the publication. To search for the DOI, please visit: **http://www.crossref.org/guestquery/**

- ***In-text citations:*** The citation of authors in the text will follow the 7th edition of the APA style.

Every use of information from other sources must be cited in the text so that it is clear that external material has been used. For every in-text citation, there should be a full citation in the reference list and vice versa. In APA style, in-text citations are placed within sentences and paragraphs so that it is clear what and whose data or information is being quoted or paraphrased.

If the author is already mentioned in the main text then the year should follow the name within parentheses.

- Research by Posea (2005) and Ielenicz (2003) supports…

If the author's name is not mentioned in the main text then the surname and year should be inserted, in parentheses, after the relevant text. Multiple citations should be separated by semicolon and follow alphabetical order.

- The petrographic composition of the massif explains this type of relief (Ielenicz 2003; Posea 2005).

If three or fewer authors are cited from the same citation then all should be listed. If four or more authors are part of the citation then 'et al.' should follow the first author's name.

- (Ielenicz, Comanescu & Nedelea 2010)
- (Ielenicz et al.2008)

If multipe sources are used from the same author and the same year, then a lowercase letter, starting from 'a', should be placed after the year.

- (Ielenicz 2003a; Ielenicz 2003b)

If you are directly quoting from a work, you will need to include the author, year of publication, and page number for the reference (preceded by "p." for a single page and "pp." for a span of multiple pages, with the page numbers separated by an en dash).

You can introduce the quotation with a signal phrase that includes the author's last name followed by the date of publication in parentheses.

- According to Ielenicz (2003), "quoted text" (p. 199).
- Ielenicz (2003) found "quoted text" (pp. 199-202).

If you do not include the author's name in the text of the sentence, place the author's last name, the year of publication, and the page number in parentheses after the quotation.

- The author stated, "quoted text" (Ielenicz, 2003, p. 199), but he did not offer an explanation as to why.

Authors with the Same Last Name: To prevent confusion, use first initials with the last names.

- (D. Privitera, 2004; A.C. Privitera, 2019)

The names of groups that serve as authors (corporate authors) are usually written out each time they appear in a text reference.

- (European Environment Agency [EEA], 2018)

When appropriate, the names of some corporate authors are spelled out in the first reference and abbreviated in all subsequent citations. The general rule for abbreviating in this manner is to supply enough information in the text citation for a reader to locate its source in the Reference List without difficulty.

- (EEA, 2018)

If the name of the group first appears in the narrative, put the abbreviation, a comma, and the year for the citation in parentheses after it.

- The European Environment Agency (EEA, 2023) state that extreme weather threat makes climate change adaptation a top priority.

When a paper has no author, use the first two or three words of the paper's title (using the first few words of the reference list entry, usually the title) as your text reference, capitalizing each word. Place the title in quotation marks if it refers to an article, chapter of a book, or Web page. Italicize the title if it refers to a book, periodical, brochure, or report.

- On climate change ("Climate and Weather", 2010) ...
- Guide to Hydrological Practices (2008)

Please do not include URLs in parenthetical citations.

(Cambria, 10pt, Normal).

- ***Reference list***: References follow the 7th edition of the APA style, which includes a dedicated section to the citation of electronic resources.

We strongly recommend the use of reference management software such as Mendeley or Zotero. The official APA style manual can be purchased through their website. (Cambria, 9pt, Normal, Idendation, Special: Hanging; By: 1cm; Line spacing: Single).

Triple-check your references details and their correspondence with the in-text citation. Be aware that despite doing our best to remediate possible issues, authors are responsible for the accuracy of references.

Some examples of references in APA style (7th edition) are included below.

Book with one author:

Fennell, D. (2008). *Ecotourism.* Third edition. Routledge.

Book with two authors:

Jones, R., & Shaw, B.J. (2007). *Geographies of Australian Heritages: Loving a Sunburnt Country?* Routledge. https://doi.org/10.4324/9781351157520

Book with more than two authors:

Carter, T., Harvey, D., Jones, R., & Robertson, I. (Eds.). (2019). *Creating Heritage: Unrecognised Pasts and Rejected Futures*. Routledge. https://doi.org/10.4324/9781351168526

Journal article with DOI:

Leimgruber, W. (2021). Tourism in Switzerland – How can the future be? *Research in Globalization, 3*, Article 100058. https://doi.org/10.1016/j.resglo.2021.100058

Journal article without DOI (when DOI is not available):

Ianos, I., Sirodoev, I., & Pascariu, G. (2012). Land-use conflicts and environmental policies in two post-socialist urban agglomerations: Bucharest and Chișinău. *Carpathian Journal of Earth and Environmental Sciences, 7*(4), 125–136. https://www.cjees.ro/viewTopic.php?topicId=276

Journal article with an article number or eLocator:

Ivona, A., Rinella, A., Rinella, F., Epifani, F., & Nocco, S. (2021). Resilient Rural Areas and Tourism Development Paths: A Comparison of Case Studies. *Sustainability, 13*(6), Article 3022. https://doi.org/10.3390/su13063022

Article in a magazine or newspaper:

Benabent Fernández de Córdoba, M., & Mata Olmo, R. (2007, July 13). El futuro de la geografía. *El País.* https://elpais.com/diario/2007/07/13/opinion/1184277607_850215.html

Edited book:

Yang, P. (Ed.) 2018. *Cases on Green Energy and Sustainable Development.* IGI Global.

Chapter in an edited book:

Privitera, D., Štetić, S., Baran, T., & Nedelcu, A. (2019). Food, Rural Heritage, and Tourism in the Local Economy: Case Studies in Serbia, Romania, Italy, and Turkey. In J. V. Andrei, J. Subic, A. Grubor & D. Privitera (Eds.), *Handbook of Research on Agricultural Policy, Rural Development, and Entrepreneurship in Contemporary Economies* (pp.189-219). IGI Global. DOI: 10.4018/978-1-5225-9837-4.ch010

Conference proceedings (published):

García Palomares, J. C., Gutiérrez Puebla, J., Romanillos Arroyo, G., & Salas-Olmedo, H. (2016). Patrones espaciales de concentración de turistas en Madrid a partir de datos geolocalizados de redes sociales: Panoramio y Twitter. In *Aplicaciones de las Tecnologías de la Información Geográfica (TIG) para el desarrollo económico sostenible* (pp. 131-139). Actas del XVII Congreso Nacional de Tecnologías de Información Geográfica. Málaga, June 29-30 and July 1. http://congresotig2016.uma.es/downloads/separadas/lt1/García%20Palomares.pdf

Working paper (more than twenty authors):

De Stefano, L., Urquijo Reguera, J., Acácio, V., Andreu, J., Assimacopolus, D., Bifulco, C., De Carli, A., De Paoli, L., Dias, S., Gad, F., Haro Monteagudo, D., Kampragou, E., Keller, C., Lekkas, D., Manoli, E., Massarutto, A., Miguel Ayala, L., Musolino, D., Paredes Arquiola, J., … Wolters, W. (2012). *Policy and drought responses–Case Study scale* (Technical report no. 4). DROUGHT-R&SPI project. http://www.isa.ulisboa.pt/ceabn/uploads/docs/projectos/drought/DROUGHT_TR_4.pdf

Webpage or piece of online content:

Vasile Loghin – Geographical Works. *Volcano Island. Geological, geomorphological and volcanological features*.

https://vasileloghin.files.wordpress.com/2015/02/insula-vulcano-cu-foto-final.pdf

Facebook page:

American Association of Geographers - Home [Facebook page]. Facebook. Retrieved September 19, 2022 from https://www.facebook.com/geographers

Non-English references should contain, at the end, additional explanation in which language it was written. If the article contains English summary it should be mentioned. For example:

Grahovac, M., Pivac, T. & Nedelcu, A. (2018). Značaj internet prezentacije za razvoj vinskog turizma Banata(Srpski i Rumunski Banat), *SINTEZA 2017, International Scientific Conference on Information Technology and Data Related Research.* (in Serbian with English abstract & summary)

Dinu, M. (2002). *Geografia turismului [Tourism Geography]*. Editura Didactică și Pedagogică. (in Romanian)

Language and Text

Foreign concepts, proper nouns, names of institutions etc.

If the article discusses foreign institutions or businesses, the original name should be provided in parentheses. Foreign terms and phrases should be set in italics and followed by an English translation enclosed in parentheses; for example, *griko* (the good food).

Spelling

Submissions must be made in English. Authors are welcome to use American or British spellings as long as they are used consistently throughout the whole of the submission.

- colour (UK) *vs.* color (US)

When referring to proper nouns and normal institutional titles, the official, original spelling must be used.

- World Health Organization, *NOT* World Health Organisation

Grammar

American or English grammar rules may be used as long as they are used consistently and match the spelling format (see above). For instance, you may use a serial comma or not.

- red, white, and blue *OR* red, white and blue

Authors not proficient in English should have their manuscripts checked before submission by a competent or native English speaker. Presenting your work in a well-structured manuscript and in well-written English gives it its best chance for editors and reviewers to understand it and evaluate it fairly.

Font

The font used should be commonly available and in an easily readable size. This may be changed during the typesetting process.

Underlined text should be avoided whenever possible.

The use of bold or italicised text to emphasise a point is permitted, although it should be restricted to minimal occurrences to maximise its impact.

Lists

Use bullet points to denote a list without a hierarchy or order of value. If the list indicates a specific sequence then a numbered list must be used.

Lists should be used sparingly to maximise their impact.

Acronyms and Abbreviations

Except for units' measurement, abbreviations are strongly discouraged. With abbreviations, the crucial goal is to ensure that the reader – particularly one who may not be fully familiar with the topic or context being addressed – is able to follow along. Spell out almost all acronyms on first use, indicating the acronym in parentheses immediately thereafter. Use the acronym for all subsequent references.

- Research completed by the International Geographical Union (IGU) shows …

A number of abbreviations are so common that they do not require the full text on the first instance of use. Examples of these can be found **here**.

Abbreviations should usually be in capital letters without full stops.

- USA, *NOT* U.S.A.

Common examples from Latin do not follow this rule, should be lower case and can include full stops.

- e.g., i.e., etc.

Use of footnotes/endnotes

Use endnotes rather than footnotes (we refer to these as 'Notes' in the online publication). These will appear at the end of the main text, before 'References'.

Notes should be used only where crucial, clarifying information needs to be conveyed.

Avoid using notes for the purposes of referencing; use in-text citations instead.

Symbols

Symbols are permitted within the main text and datasets as long as they are commonly in use or an explanatory definition is included on their first usage.

Hyphenation, em and en dashes

For guidelines on hyphenation, please refer to an authoritative style guide, such as The Chicago Manual of Style (16th ed.) (US English) or Oxford's New Hart's Rules (UK English). Be consistent in your style of hyphenation.

Em dashes should be used sparingly. If they are present they should denote emphasis, change of thought or interruption to the main sentence; em dashes can replace commas, parentheses, colons or semicolons.

En dashes can be used to replace 'to' when indicating a range. No space should surround the dash.

- 10–25 years *OR* pp. 10–65

Numbers

For numbers zero to nine please spell the whole words. Use figures for numbers 10 or higher. We are happy for authors to use either words or numbers to represent large whole numbers (i.e. one million or 1,000,000) as long as the usage is consistent throughout the text.

If the sentence includes a series of numbers then figures must be used in each instance.

- Thermal springs were found in the north of Bucharest at depths of 100, 175, and 230 m.

If the number appears as part of a dataset, in conjunction with a symbol or as part of a table then a figure must be used.

- This study confirmed that 7% of…

If a sentence starts with a number it must be spelt, or the sentence should be re-written so that it no longer starts with the number.

- Fifteen examples were found to exist… *RE-WRITTEN*: The result showed that 15 examples existed…

Do not use a comma for a decimal place.

- 2.56 *NOT* 2,56

For numbers that are less than one a '0' must precede the decimal point.

- 0.29 *NOT* .29

Units of measurement

Symbols following a figure to denote a unit of measurement must be taken from the latest **SI brochure**.

Formulae

Formulae must be proofed carefully by the author. Editors will not edit formulae. If special software has been used to create formulae, the way it is laid out is the way it will appear in the publication.

Tables

Tables must be created using a word processor's table function, not tabbed text.

Tables should be included in the manuscript. The final layout will place the tables as close to their first citation as possible.

All tables must be cited within the main text and numbered with Arabic numerals in consecutive order (e.g. Table 1, Table 2, etc.).

Each table must have an accompanying descriptive title. This should clearly and concisely summarise the content and/or use of the table. A short additional table legend is optional to offer a further description of the table.

The title should be above the table (font 10pt) and the source of the data below (font 10pt).

Example:

Table 1. This is a table. Tables should be placed in the main text near to the first time they are cited

Year	Number of foreign tourists (millions)	Foreign currency cashing (USD billions)	Cashing increase compared to 1950
1950	25,3	2,1	-
1990	410,4	300,4	143,0
2010	940,0	919,0	437,6
2013	1, 087,0	1, 159,0	551,9

Source: UNWTO, 2015

Tables should not include:

- Rotated text
- Images
- Vertical and Diagonal lines
- Multiple parts (e.g. 'Table 1a' and 'Table 1b'). These should either be merged into one table, or separated into 'Table 1' and 'Table 2'.

NOTE: *If there are more columns than can be fitted on a single page, then the table will be placed horizontally on the page. If it still cannot be fitted horizontally on a page, the table will be broken into two.*

Figures

All photographs, maps and graphs have to be named as Figure. The figures have to be enclosed in the text, in their order of appearance and should be numbered consecutively using Arabic numbers. The title (font10pt) has to be below the figure. All figures (photographs and maps) have to be submitted as a separate file. All graphs have to be submitted as a separate file in MS Excel format with all the data needed for making the graph. The file should be named as the number of the figure in the main text. Example: Figure 1, Figure 2, etc. If a figure has been previously published, acknowledge the original source. Example:

(a) **(b)**

Figure 1. This is a figure. Schemes follow the same formatting. If there are multiple panels, they should be listed as: (**a**) Description of what is contained in the first panel; (**b**) Description of what is contained in the second panel. Figures should be placed in the main text near to the first time they are cited. A caption on a single line should be centered.
Source: Adrian Nedelcu, 2014.

Figure 1. Sardinia. La Pelosa beach with marine abrasion forms.
Source: Adrian Nedelcu (2019).

NOTE: *All figures must be uploaded separately as supplementary files during the submission process, if possible in colour and at a resolution of at least 300dpi. Each file should not be more than 20MB. Standard formats accepted are: JPG, TIFF, GIF and PNG. For line drawings, please provide the original vector file (e.g. .ai or .eps).*

Reviewer Suggestions

During the submission process, please suggest three potential reviewers with the appropriate expertise to review the manuscript. The editors will not necessarily approach these referees. Please provide detailed contact information (address, phone, e-mail address). The proposed referees should neither be current collaborators of the co-authors nor have published with any of the co-authors of the manuscript within the last five years. Proposed reviewers should be from different institutions to the authors. You may suggest reviewers from among the authors that you frequently cite in your paper.

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