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Multi-scale analysis of intense cold waves and atmospheric circulation mechanisms in northern Morocco

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ABSTRACT

Due to its geographical location, the Mediterranean region is subject to increasingly frequent and intense climatic events. Within this region, northern Morocco is one of the areas most exposed to extreme temperature phenomena, which manifest themselves either as very large positive temperature anomalies, reflecting intense heat, or as negative anomalies, synonymous with cold spells. This study aims primarily to fill the gaps in the analysis of the frequency and evolution of cold spells in the north of the country, based on the design of an innovative statistical model that allows the use of absolute temperature thresholds. Secondly, it was essential to assess the applicability of this approach to regionally heterogeneous climatic conditions. To achieve these objectives, several climate indices were used. The calculations were developed on RClimdex using maximum daytime temperatures and minimum nighttime temperatures. The results reveal that an extremely severe cold wave was recorded at 70% of the coastal and continental stations studied between January 1 and 7, 2025, with a total weight varying between 11.3 °C and 37 °C and between 2.4 °C and 7.8 °C during the month of February. The calculation of thermal indices (TX10p, TN10p, FD, and CSDI) showed variable trends. The TX10p showed a drop of -0.13 days (10 yr)$^{-1}$ in Tangier and Casablanca. A slight increase was observed for the TN10p index +0.04 days (10 yr)$^{-1}$. Similar results were detected for the FD +0.024 days (10yr)$^{-1}$ and the CSDI +0.012 days (10 yr)$^{-1}$. The use of weather maps (at 500 and 1015 hPa) enabled a more in-depth analysis and confirmed the results obtained. the research demonstrates the scientific relevance of coupling innovative statistical model with regionally heterogeneous climatic conditions for cold waves risk assessment in North African countries, offering insights that can guide both policy design and climate risk management strategies.

Keywords: cold waves, intense, ETCCDI, LST, atmospheric, northern Morocco.

INTRODUCTION

Natural climate variability has always given rise to extreme events. However, the increased frequency of these events could be linked to climate change. Indeed, the scientific community agrees that the physical characteristics of meteorological and climatic events in recent decades are increasingly the result of climate change (Azzi et al., 2015). In addition, In the context of global warming experienced by the world in recent decades (2015 to 2025), several studies have been launched to investigate the associated climate changes and their impacts on human and natural systems (Ouattab., et al 2019; IPCC., 2013; 2007). The Mediterranean region, characterized by high climate variability due to its geoclimatic position (in the northern Africa), is highly vulnerable.

Regarding extreme climatic phenomena, particularly cold waves, (Aurélien et al., 2020) highlighted that A natural question concerning such a remarkable event, which has been discussed for many extreme weather events in recent decades, concerns the link between this event and climate change, he therefore raised two fundamental questions related to this topic First, a retrospective one: Has such a cold spell become more or less common as a result of global warming? Second, from a forward-looking perspective: Should we prepare for further events of this type, despite ongoing warming? (Aurélien et al., 2020). According to (Judah et al., 2014), the occurrence of this extreme event is attributed to These profound changes to the Arctic system have coincided with a period of ostensibly more frequent extreme weather events across the Northern Hemisphere mid-latitudes, including severe winters (Judah et al., 2014).

Analyzing the evolution and intensity of severe cold waves in relation to atmospheric circulation is a major challenge for northern Morocco. Although this phenomenon is traditionally observed in winter, it appears to be becoming more complex and unpredictable due to the climate change affecting the country. In particular, intense cold waves can cause sudden drops in temperature, affecting not only local weather conditions, but also public health, agriculture, and infrastructure (IPCC., 2007; 2019; Beniston et al., 1997; 2007).

According to scientific studies on the climate situation in northern Morocco, Sebbar et al., 2012 concluded that the general climate trend during the 20th century, at least in its second half, shows a warming trend. However, falling temperatures and more frequent periods of drought generally create new challenges that are difficult for a developing country to overcome.

According to more recent studies, northern Morocco, with its mountainous and coastal regions, is particularly vulnerable to variations in atmospheric circulation with the advent of cold spells of varying intensity. The study of these phenomena for the year 2025, marked by significant snowfall in several mountainous regions of Morocco, as well as an intense cold wave and stormy showers, provides a better understanding of the dynamics of cold waves. It also allows for analysis of their increasing frequency and the atmospheric circulation mechanisms that underlie them. Disturbances in the Azores High or polar air invasions, for example, may explain these episodes of extreme cold, which mainly affect urban and rural areas (Hui et al., 2023;_Khomsi., 2013; 2014; Hanchane et al, 2025). Cold waves are among the most worrying climatic extremes in terms of the vulnerability of our societies and the expected increase in their frequency and intensity in the 21st century. In this context, a cold wave corresponds to a marked drop in temperatures or the arrival of extremely cold air over a large region, which can last from a few days to several weeks (WMO, 2000). In addition to their impact on health, these climatic events affect various economic sectors, including transportation, energy, and agriculture (GIEC., 2007).

Taking into account atmospheric circulation and its influence on cold waves is therefore crucial for anticipating and minimizing the risks associated with this phenomenon in northern Morocco. This study aims to examine the frequency and evolution of cold waves, based on a grid of absolute thresholds, which is appropriate for the context of Mediterranean countries in 2025. It also seeks to identify trends in these waves in order to understand the reality of climate change in the region. The atmospheric circulation mechanisms that generate cold waves will also be examined, as well as trends in 500 hPa geopotential heights, which is the reference level for all climate studies in northwestern Africa, located in a meteorological shelter zone affected by Atlantic disturbances (Traboulsi et al., 2014; 2017). Therefor, this paper attempted to answer the following hypotheses:

- the orographic factor is responsible for the spatial and temporal variability of cold waves,
- the size of the study area implies a spatial and temporal evolution of cold waves,
- the region studied is one of those in the country that have experienced a significant decrease in cold waves since the 1980s.

DATA AND METHOD USED

Presentation of the study area

Conducting a climate study demands an extensive geographic coverage and the collection of comprehensive atmospheric data. Consequently, the study area spans roughly 335,000 square kilometers, located between 36° and 30° north latitude and 10° to 1° west longitude. This extensive region serves as a transitional zone bridging temperate and tropical climates, featuring two coastlines: one along the Atlantic Ocean and the other bordering the Mediterranean Sea (Sebbar et al., 2012; Badri et al., 1994). Inland, the landscape is dominated by the Rif, Middle Atlas, High Atlas (ranging from 3,000 to 4,000 meters in elevation), and Anti-Atlas Mountain ranges, which extend along a northeast-southwest axis (Badri et al., 1994). This mountain alignment effectively divides the area into two distinct parts: the western and northern section influenced by North Atlantic weather systems, and the eastern section, where southeastern climatic influences prevail. Average annual precipitation declines gradually from north to south and from west to east throughout the region, ranging from approximately 1300 mm per year in the northern highlands to less than 150 mm per year in the arid southern desert (Fig. 1). Average annual temperatures exceed 22 °C in the south and southeast of the study area (Northen Morocco), vary between 12 and 18 °C in the mountains and highlands, and vary between 18 and 20 °C elsewhere. In summer, the maximum daily temperature frequently exceeds 40 °C in the interior of the country. In winter, the daily minimum temperature drops below 0 °C in mountainous areas.

Dataset used

Firstly, in order to meet our objective, this research is based on the use of temperature data provided by the General Directorate of Meteorology (DGM) for the following stations: Tangier, Casablanca, Fez, Marrakesh, Ouarzazate, and Agadir. and the Provincial Directorate of Agriculture for the stations: Taza and Oujda.

The data used are the maximum daytime temperatures (Tx) and minimum nighttime temperatures (Tn) observed for the period from 2024 to 2025 (Table 1). For the study of atmospheric circulation, our study is based on an analysis of Moroccan and European weather maps. These maps are available on several websites, including: www.wetterzentarale.de & www.wetter3.de. It's also important to point out that the statistical data used in this study doesn't have any missing data because it only covers a limited time span, no more than two years.

For Landsat data, NASA Terra Modis satellite images were used to estimate emissivity. These images are available free of charge on the USGS website: https://earthexplorer.usgs.gov/, with a spatial resolution of 30 m in the visible spectrum and 120 m for thermal imaging. for the purpose of determining the spatial evolution of this cold wave in our study area (the characteristics of these images are illustrated in Table 2).

Methodology

Eight weather stations with varied exposures, well distributed throughout the study area (northern Morocco) and representative of the main

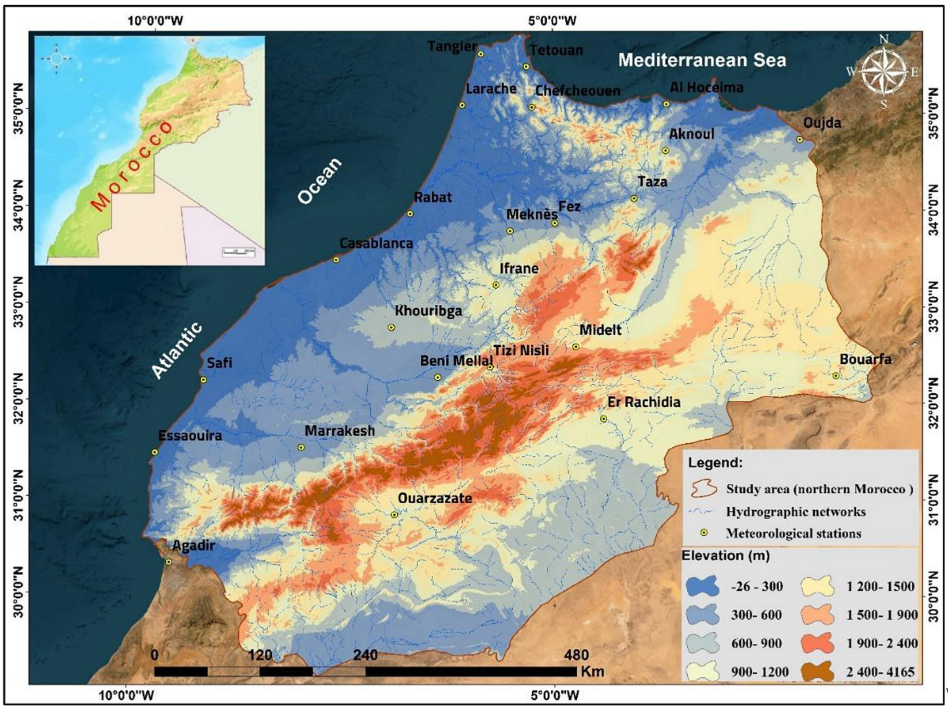

Figure 1. Study area location map and location of meteorological stations

Table 1. Geographic data for the selected stations

Stations	Range	Y (°W)	X (°N)	Z (m)	January (°C) 2025		February (°C) 2025		Regions
					TN	TX	TN	TX	
Tangier	1	-5.90	35.73	21	*11*	*18.5*	*10.9*	*18*	North Atlantic
Casablanca	2	-7.67	33.57	62	*14*	*20*	*12*	*19.6*	
Fez	3	-5.00	34.02	415	*4.8*	*17.2*	*5.6*	*17.9*	Mountainous
Taza	4	-4.02	34.21	521	*5.1*	*18*	*6.3*	*18.5*	
Marrakesh	5	-8.03	31. 61	474	*3.6*	*21*	*5.1*	*21*	Central
Agadir	6	-9.56	30.30	23	*11*	*22*	*10*	*23*	South Atlantic
Oujda	7	-1.93	34.78	470	*6.4*	*18.2*	*7.2*	*19*	Eastern
Ouarzazate	8	-6.90	30.93	1136	*2.9*	*18*	*4*	*20*	Sub-Saharan

Note: Data source – General Directorate of Meteorology.

Table 2. Description of layers for LST

SDS name	Description	Units	Data type	Fill value	No data value	Valid range	Scale factor	Additional offset
LST-Day-1km	Day time land surface temperature	°C (*)	16-bit Unsigned integer	0	N/A	7200 to 65283	0.02	N/A
LST-Night-1km	Night time land surface temperature	°C (*)	16-bit unsigned integer	0	N/A	7200 to 65283	0.02	N/A
Thermal strips			(10 and 11(**))					

Note: * Temperature values were converted from (°F) to (°C) using the Build Model in ArcGIS; **do not use band 11 because it contains errors due to stray light anomalies (Hassani et *al*., 2020; Renard et *al*., 2019).

topoclimates of the region, were selected (North Atlantic, Mountainous, Central, South Atlantic, Eastern and Sub-Saharan), The variety of data and sources used also ensures spatial representation, which is essential for a detailed analysis of the dynamics and spatiotemporal contrasts of extreme climate-related phenomena within the study area (Janati., 2014; Addou et al., 2024). The methodology used consists of classifying cold waves according to a number of parameters (Aurélien et al., 2020) (Table 3 & Fig. 2).

The indices considered are part of a standard list of extreme indices. The use of these indices for detecting climate change has several advantages. On the one hand, these indices can be applied to different parameters and allow for the comparison of trends between regions. On the other hand, they are understandable and easily usable in studying the impacts of these rains on the population and the territory (Khomsi., 2013; 2014; Ben Boubaker., 2010; Zhang et al., 2004; Coles., 2001; Mudelsee., 2010; Alaouane, 2002). These indices are presented in Table 4.

To meet our objective, we have attempted to define a cold spell that is specific to Morocco in geographical terms. Before beginning any analysis, it is therefore necessary to refer to the scientific definitions of these phenomena used in other geographical contexts. This will consolidate the conceptual framework of the study, ensure the comparability of results, and refine the perception of the spatial and climatic specificities of the extreme phenomena analyzed. In America (Gollin et al., 2021) knew a cold spell as a period during which the minimum daily temperature remains below (-2°C) for at least 7 consecutive days and during which the minimum for that period falls below the (-7°C) threshold at least twice. Then he added that short duration cold snaps can kill plants, freeze exposed pipes, freeze wind turbines, and contribute to dangerous roadway conditions (Gollin et al., 2021).

In France, the terms cold and very cold are commonly used without there being a precise climatic definition. The thresholds of (-5 °C) and (-10 °C) for minimum temperatures are used as a decision-making aid in the winter emergency plan of the Secretariat for the Fight against Precariousness and Exclusion, to implement measures to help homeless people (Laaidi et al., 2009;

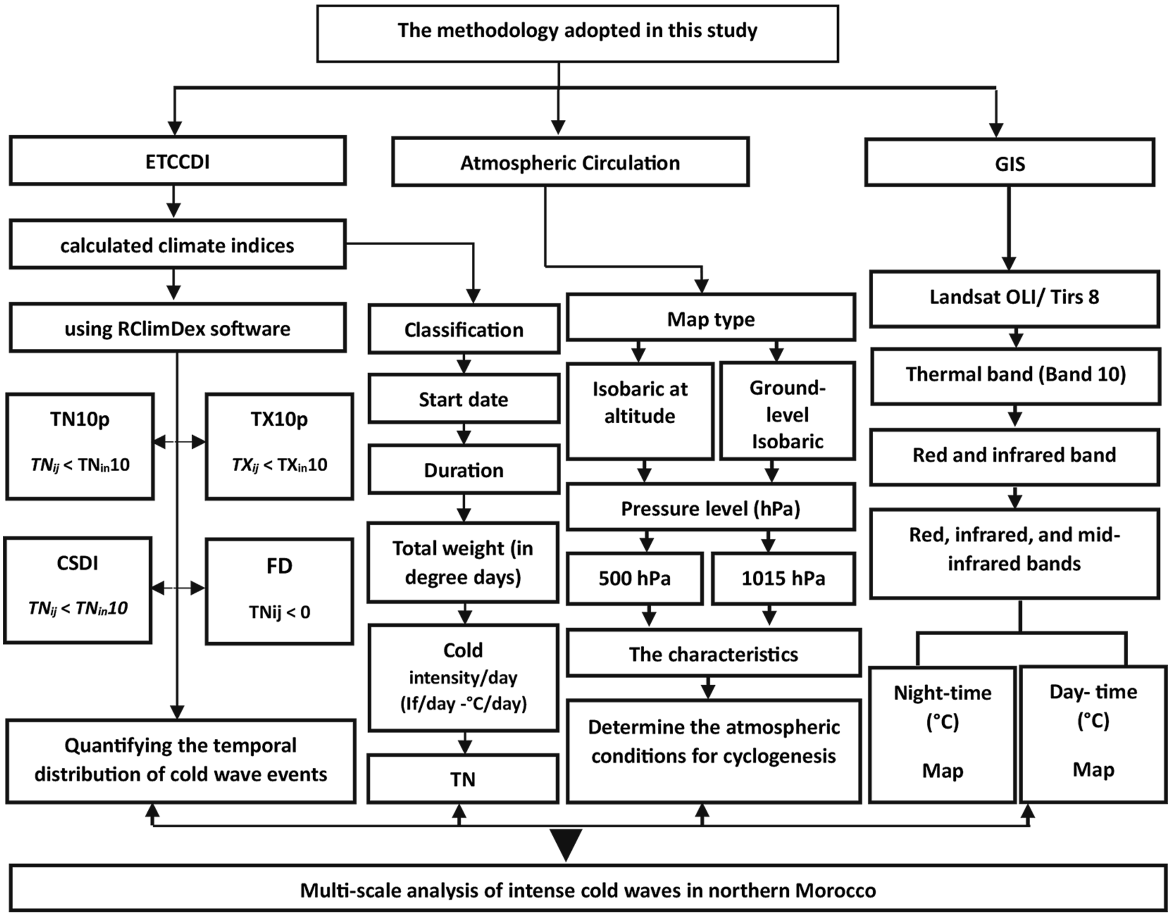

Figure 2. Methodology of the study

Table 3. Parameters taken into account for the classification of cold waves in northern Morocco

Start date	Start and end dates of the cold spell
Duration	Number of days in the cold spell
Total weight (in degree days)	The method consists first of calculating the daily degree days that's to say (TX – Y in °C) + (TN – Y in °C). Next, the sum of the degree days for each episode including at least one cold day is used to deduce its weight. In fact, the weight of a cold spell lasting N days is given by the following formula: $Weight = \sum_{i=1}^{N}([Tn])i - [\mathrm{NorDec}]i$ (1)
Cold intensity/day (If/day -°C/day)	This weight, divided by the number of days in the episode, gives the intensity of the cold on day.
Minimum temperature (MT) :	Absolute minimum temperature recorded during this cold spell

Note: Data source: https://www.drias-climat.fr/accompagnement/sections/181.

Bissonnet, 2006). These criteria cannot be applied to our study area for several reasons. First, temperatures that are too low, below -10 °C for example, have never been measured at the stations studied. We therefore define a cold spell as a period during which the minimum daily temperature remains below (−2 °C) for at least three consecutive days and during which the minimum temperature for that period falls below (−6 °C) at least twice (Ben Boubaker., Bari et al., 2006; 2010; Azzi et al. 2015; Rabinson., 2001).

RESULTS AND DISCUSSION

Trends in cold waves observed in northern Morocco

Among the main statistical approaches applied in recent years to the study of extreme events, particularly cold spells, are extreme value theory (Beniston et al., 2007; Coles, 2001) and another based on climate indices calculated according to the needs of the studies carried out (Sensoy, et al.,

Table 4. Indices used to characterize extreme cold events in northern Morocco

Index designation	Meaning of the index	Index source	Unit of measurement
Tx10p	Cold days: number of days when the maximum temperature is below the 10th percentile	(ETCCDI) Expert team on climate change detection	[Days]
TN10p	Cold nights: number of days when the daily minimum temperature <10th percentile		
FD (Number of frost days)	Annual count of days when *TN* (daily minimum temperature) < 0 °C.		
CSDI (cold spell duration index)	Cold period duration index: number of days in a period of at least six days where the minimum daily temperature is < 10th percentile		

2015; New et al., 2006). After adopting the second theoretical approach, we analyzed temperature-related climate indices eight stations, between 2000 and 2025, for the same period of the same climate in order to compare the results from these stations. Before calculating the indices, the quality of the data was checked and their homogeneity was tested. The indices were calculated using the RClimDex (1.0) software (Sensoy, et al., 2015; Zhang, X., et al., 2022; 2023; 2005).

For (TX10p), This indicator demonstrates resilience insofar as it applies to two territories of the same geoclimatic type on the Atlantic Ocean horizon, which exceeds the ordinary and plays a key role in climate regulation and the creation of conditions conducive to the sustainability of human settlement. Analysis of Figures (Fig. 3A & 3B) also indicates a downward trend in the number of days with a daily maximum temperature < 10th percentile (TX10p), at both stations (Tangier and Casablanca). The Tangier station recorded the lowest number of such days in 2007, while at the Casablanca station, the total number of days reached 289, recording a daily maximum temperature <10th percentile (Fig. 3A). We can therefore say that this downward trend will see a decrease of 2.3 days to 3.9 days per 25 years. This shows that the duration of cool nights is decreasing more rapidly in urban areas.

For the Taza station, there has been an increase of six days in 25 years (Fig. 3C). in the number of days where the minimum daily temperature <10th percentile (TN10p), and a decrease of seven days of cold nights for the Marrakech station (Fig. 3D). What distinguishes this index (FD) at the two stations, Oujda in the east and Ouarzazate in the

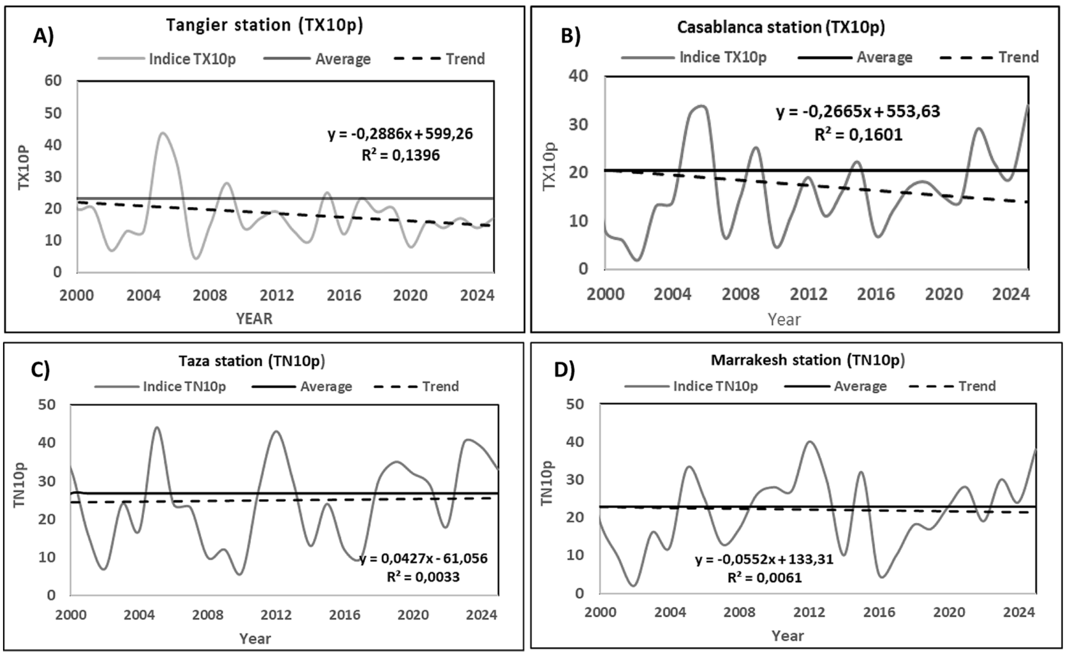

Figure 3. Cold night trend: number of days when the daily minimum temperature is below the 10th percentile (A: Tangier & B: Casablanca); cold days: number of days when the daily maximum temperature is below the 10th percentile (C: Taza & D: Marrakesh) from 2000 to 2025

southeast, is the fluctuation between years that recorded a number of frost days, with a daily minimum temperature below 0 °C. At the Ourzazate station, this index remained relatively stable during the period studied (2000 to 2025), with a slight increase since 2009 (Fig. 4B). However, analysis of data from the Oujda station, which recorded 16 days more than the average, shows that the number of years above the average remains at nine (Fig. 5A). The increases range from 0.09°C/day to 0.50°C/day per decade at both stations. On the other hand, the decreases are relatively small (not exceeding 0.03°C/day per decade) (Fig. 4A and B).

The cold index (CSDI) applied to two different areas based on climatic characteristics, Fez in northern Morocco, located between the Rif Mountains and the Middle Atlas, and Agadir in the southwest, indicates that there is a clear divergence in the results obtained. This difference mainly concerns the number of days in a period of at least six days where the minimum daily temperature is < 10th percentile. At the Agadir station, this index has shown a slight upward trend since 2015 and a significant decline in the number of days where minimum daily temperatures are < 10th percentile. However, this station again recorded the highest number of days with cold periods (19 days) in 2024–2025 (Fig. 4C). However, at the Fez station in northern Morocco, an upward trend has been recorded for this index (CSDI) since 2009 (15 days). However, during 2008, this station recorded the lowest average for the same index (Fig. 4D). But in general, we can see that the Agadir station has experienced a decline in this index of between 0.18 and 0.19, in contrast to a tangible change for the Agadir station, which rose from 0.21 to 0.39 and then to 0.60.

Cold wave classification and intensity assessment during 2025

Based on the scientific studies cited on cold spells, (Besancenot., 1986; Campetella et al., 1998) emphasizes here that these events are notable manifestations of climatic extremes and that cold weather coincides with the peak in overall mortality. Humans always seek to protect themselves from the cold through endogenous physiological thermoregulatory mechanisms. When the ambient temperature is low, heat loss increases for a high body surface area/mass ratio. Thus, extreme cold, like extreme heat, poses a health hazard.

With regard to the cold spell affecting northern Morocco in 2025, The data presented in Table 3 indicate that January 2025 saw the most persistent cold spell of the last decade in the city of Fez, with a cumulative heat index of (37 °C) during the period from January 1 to 7, 2025. In the city

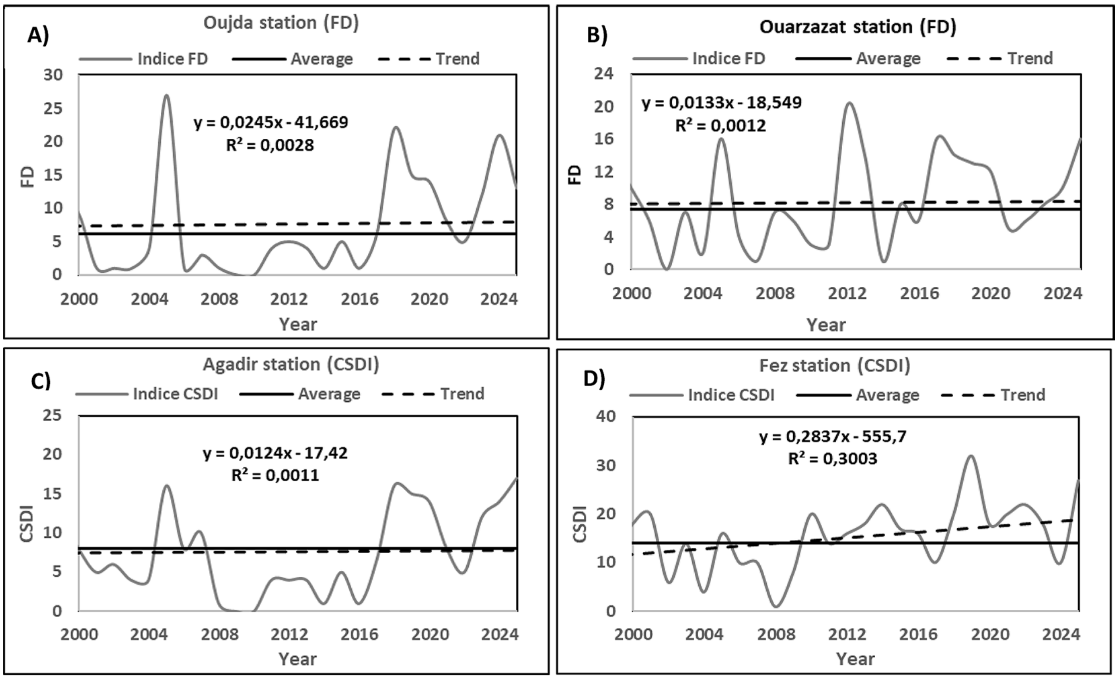

Figure 4. Cold night trend: number of frost days, daily minimum temperature <0 °C (A: Oujda & B: Ouarzazate); Index of cold period duration (C: Agadir & D: Fez) from 2000 to 2025

of Taza, a notable episode was also recorded, with a total heat weight of 32 °C between January 14 and 16, 2025. Minimum nighttime temperatures ranged from (-1.4 °C) to (4.6 °C), compared to 6.5 °C to 12.7 °C for maximum daytime temperatures at both stations (Table 5).

The city of Fez recorded the most intense cold spell in terms of daily values. The average (If) index reached 5.2 °C/day during the spell from January 1 to 7, 2025. As for the station in Tangier on Morocco's north Atlantic coast, it also recorded a more intense cold spell during February, with an average of (7.8 °C), but for the period from February 13 to 14, 2025 (Table 5). Morocco's climate is generally sheltered from extreme cold. Even very cold days, compared to the average climate, remain a rare phenomenon, particularly in the north of the country. Cold spells are therefore considered a minor climate risk, much less worrying than episodes of extreme heat.

Generally, to further analyze the intensity of cold spells in northern Morocco, we refer to the three-hourly temperature observation scale, with a view to monitoring the persistence of sub-zero temperatures in particular. It turns out that frost, however rare it may be (6 days over the entire observation period), never persists during the day. Even when frost does occur, it happens at the end of the night (around 6 a.m.) and is brief (Aurélien et al., 2020; Laaidi et al., 2009).

To assess the intensity of the cold, we worked on a long series of data (1976–2025) to detect the intensity and evolution of cold spells. It is therefore necessary to take into account two fundamental aspects related to ambient temperature. First, the temperature anomaly, deduced from the difference between the observed temperature and the average temperature for the corresponding month (Fig. 5 and 6). Analysis of the evolution of daily minimum temperatures over a 49-year period at two representative stations in northern Morocco, one in the east (Oujda) and the other in the sub-Saharan region (Ouarzazate), clearly shows four distinct episodes. The Oujda station recorded a total of 18 days on which the absolute minimum temperatures were below (−2 °C), with a minimum of (−8 °C) on January 19, 2015 (Fig. 5). In addition, the Ouarzazate station recorded a total of 20 days on which the absolute minimum temperatures were below (−2 °C), with a minimum of (−6 °C) on December 18, 2005.

Cold spells are becoming increasingly rare in northern Morocco. The most notable occurred from January 1 to 20, 2025, with exceptionally low temperatures in the north of the country. Ifrane recorded a minimum temperature of -5.6 °C, while the temperature in Fez and Taza dropped to 1.4 °C. Then, from February 1 to 15, 2025, with minimum temperatures of -5.9 °C in Ifrane, -2.6 °C in Oujda, -1.1 °C in Taza, and -1.7 °C in Ouarzazate (Fig. 6).

On a seasonal basis, we chose these stations based on the criteria of continentality and ocean (depending on proximity to the sea). The stations in Tangier, Casablanca, Fez, and Marrakesh record an average monthly frequency of cold days. The risk of cold spells is particularly high in the middle and late winter at most of the stations studied in northern Morocco. December, January, and February have the highest number of very cold days and cold days (Fig. 7). However, such episodes can also occur outside of winter, either early in November or late in March. In these cases, their unusual and unexpected nature makes them particularly feared because of their effects on the comfort and health of the population.

Table 5. Characteristics of the main cold spells at the stations studied for the year 2025 (total weight > 4 °C)

Station	Episode date				Total weight (in degree days)		Cold intensity/day (If/day, in °C/day)	
	January 2025	Duration (days)	February 2025	Duration (days)	January 2025	February 2025	January 2025	February 2025
Tangier	15 to 20	5	13 to 15	3	12.5 °C	24 °C	4.4 °C	7.8 °C
Casablanca	14 to 16	3	1 to 4/02/25	4	11.8 °C	23.4 °C	3.9 °C	5.8 °C
Fès	01 to 07	7	1 to 07/2/25	7	37 °C	24.4°C	5.2 °C	3.4°C
Marrakesh	14 to 20	4	1 to 6/02/25	6	16.2 °C	12 °C	4.0 °C	4 °C
Agadir	16 to 19	4	01 to 03/2/25	3	10.7 °C	20.4 °C	2.9 °C	4.8 °C
Taza	14 to 17	4	6 to 7/02/25	2	32 °C	21.4°C	4.2 °C	2.4°C
Oujda	13 to 17	7	05 to 07/2/25	2	11.3°C	10.8 °C	3.7°C	3.6 °C
Ouarzazate	15 to 18	4	01 to 03/2/25	3	13.6 °C	19.9 °C	3.4 °C	6.3 °C

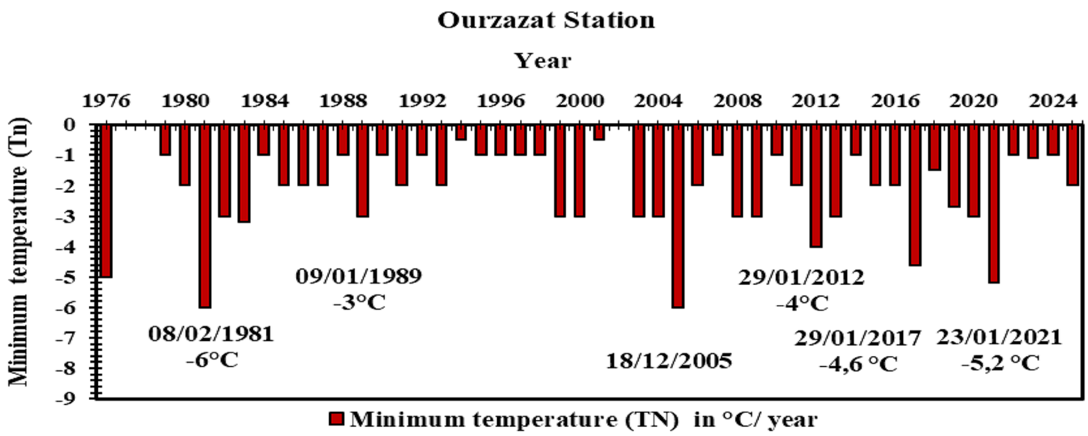

Figure 5. Daily minimum temperatures at the Ouarzazate station for the period 1976-2025

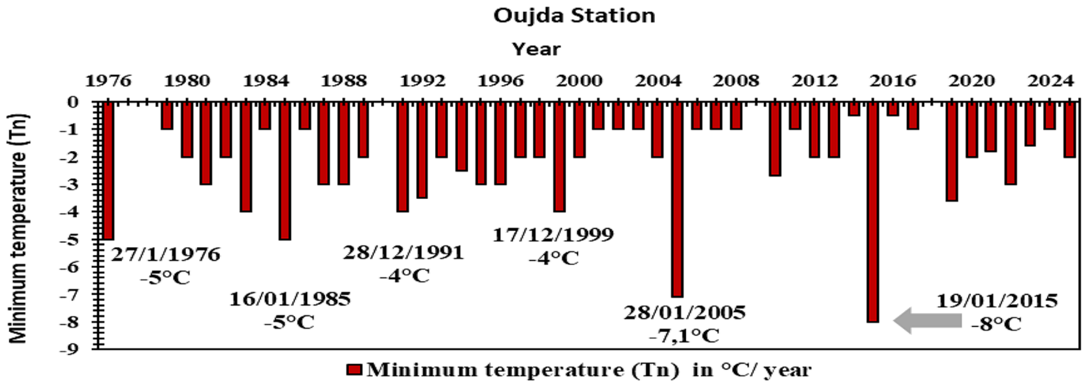

Figure 6. Daily minimum temperatures at the Oujda station for the period 197–-2025

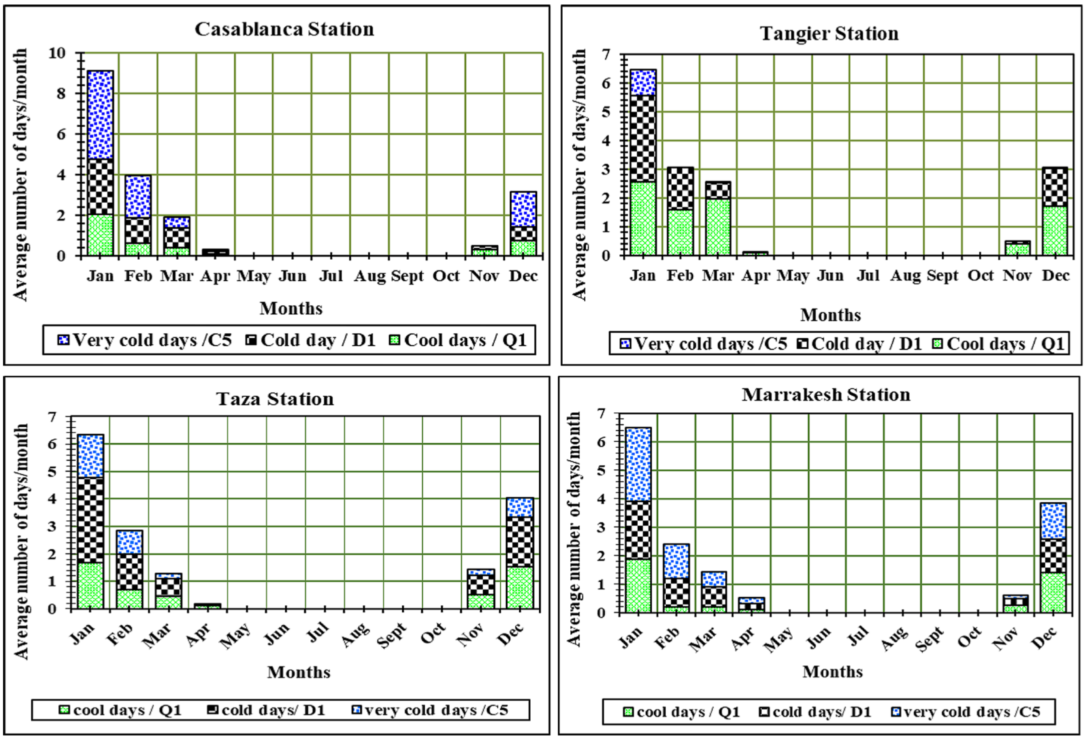

Figure 7. Average monthly frequency of cold days for the stations in northern Morocco (Tangier, Casablanca, Fez and Marrakesh) for the period 2000–2025

Furthermore, these cold spells are more frequent in winter than in spring and autumn, which are relatively colder seasons. This choice is mainly justified by the desire to assess the intensity of cold spells in northern Morocco but also to highlight a period of cold weather common to all stations, even though the intensities observed there are very contrasting.

The spatial distribution of cold waves in northern Morocco during the year 2025

Thanks to the high density of the observed temperature data network, it was possible to obtain a spatial view of cold waves on the surface of the study area using a number of geometric or geostatistical interpolation methods. With the revolution in geographic information systems (GIS) and their ever-increasing functionality, we were able to spatialize day and night temperatures for the year 2025, particularly for the month of January, for the entire observation network using GIS. Among the best-known methods are kriging and IDW, all of which are statistical models of nonparametric regression. They interpolate point values from a number of sampling points (Gilles, 2004). Based on our analysis of daytime and nighttime temperatures, we have found that temperatures in northern Morocco are characterized by significant spatial and temporal irregularity. This irregularity reflects the random nature of extreme weather events in our study area. We will highlight the characteristics of daytime and nighttime temperatures in January 2025 based on the following points:

- daytime temperature variation for the month of January 2025,
- nighttime temperature variation for the month of January 2025.

Daytime and nighttime temperatures vary geographically in northern Morocco in January 2025 from 3.5 °C to 14 °C, representing a range of variation for this short period of 10 to 11. As of January 2025, daytime temperatures have dropped significantly across the country, reaching very low values both in high altitude areas (above 2,500 m) and in coastal plains, where the cold spell has been more severe. The high-altitude stations (Midelt, Tizi N'Sli, Ifrane, Ouarzazate, and E-rrachidia) recorded maximum temperatures of around (5.6 °C to 6.7 °C), with a slight rise towards the foothills of the High and Middle Atlas (7.6–9.8 °C), while the maximum

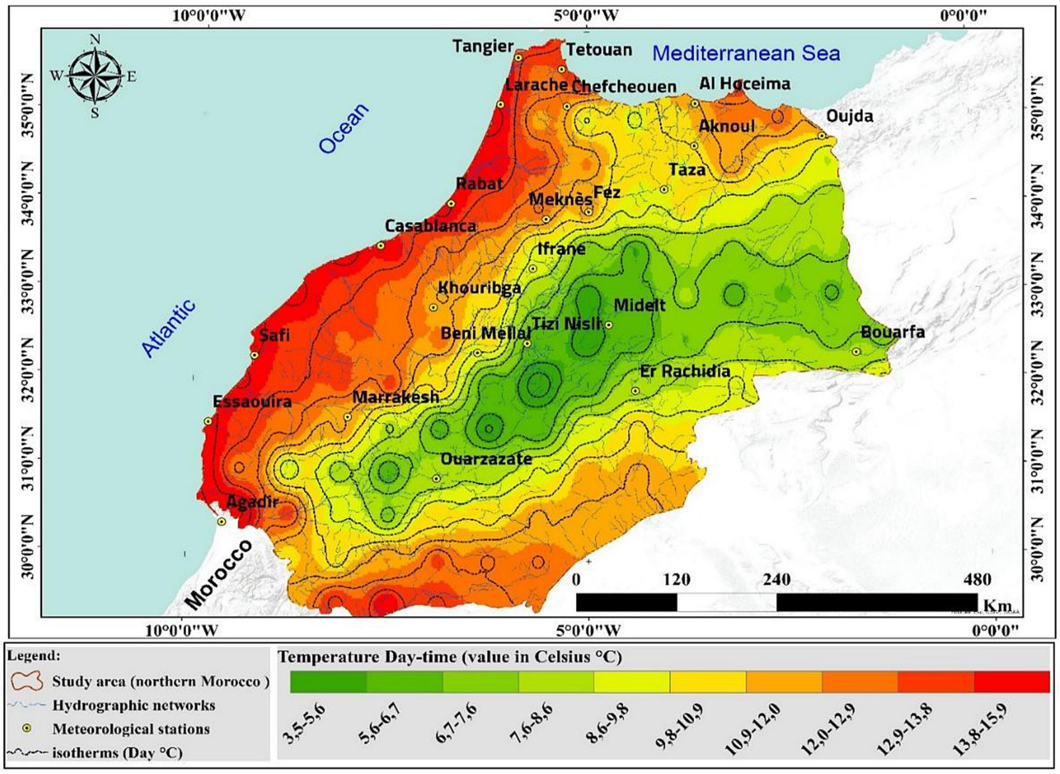

Figure 8. Spatial distribution of absolute minimum temperatures (daytime temperatures) for the month of January 2025

temperatures recorded in the coastal plains were at best 10.9–12 °C on the Mediterranean coast (Tetouan, Chefchaouen, and Al Hoceima) and around 13.8–15.9 °C on the Atlantic coast (Tangier, Casablanca, and Agadir) (Fig. 8).

As for the minimum temperature in January during the night, it ranges from 3 °C to 14 °C and decreases from the Atlantic and Mediterranean coasts towards the mountains. As a general rule, the highest minimum temperatures are found in desert areas. Nighttime temperatures are significantly more extreme than daytime temperatures. High-altitude areas (Atlas Mountains) and their eastern or western slopes, which are far from the maritime influence, are most affected by the intense cold, with temperatures sometimes ranging between 3.5 °C and 8.3 °C (Fig. 9). The cold spells even extend to certain coastal areas that are not normally moderated by the sea, where the sea is supposed to play a regulating role, such as the regions of Doukkala and Abda and a large part of the Rif, more precisely the northern part. However, this is not the case in the northwestern region (Tangier, Larache) or along the coastline from Safi to Essaouira, which have recorded relatively mild temperatures between 11.8 °C and 14.9 °C at night (Fig. 9). The northern origin of the disturbed flows caused temperatures to drop, resulting in heavy precipitation, particularly in the Rif and Atlas Mountain ranges. At the end of December 2024 and the beginning of January 2025, according to the national weather service, snow depths reached 30 cm at the summit and 20 cm on the slopes of Jbel Bouyblane in the Middle Atlas, while in the Rif Mountains the snowfall was lighter (only 10 cm at the summit in the province of Chefchaouen) (Fig. 10B). As a result, several roads were closed to traffic following the snowfall in the Middle Atlas Mountains in December 2024 and January 2025. Traffic jams were longer and dozens of vehicles were immobilized. Major roads were affected, including Ifrane-Azrou, Ifrane-Boulemane, and Azrou-Midelt (Fig. 10A).

Analysis of the synoptic and isobaric situation in January 2025 in northern Morocco

The cold snap in January 2025 was the direct result of the interaction of several pressure systems, notably the shift between the Azores high and the Icelandic low. On the other hand, several intense low-pressure systems developed over the Mediterranean and Atlantic Ocean, causing unusually cold and snowy weather across southeastern

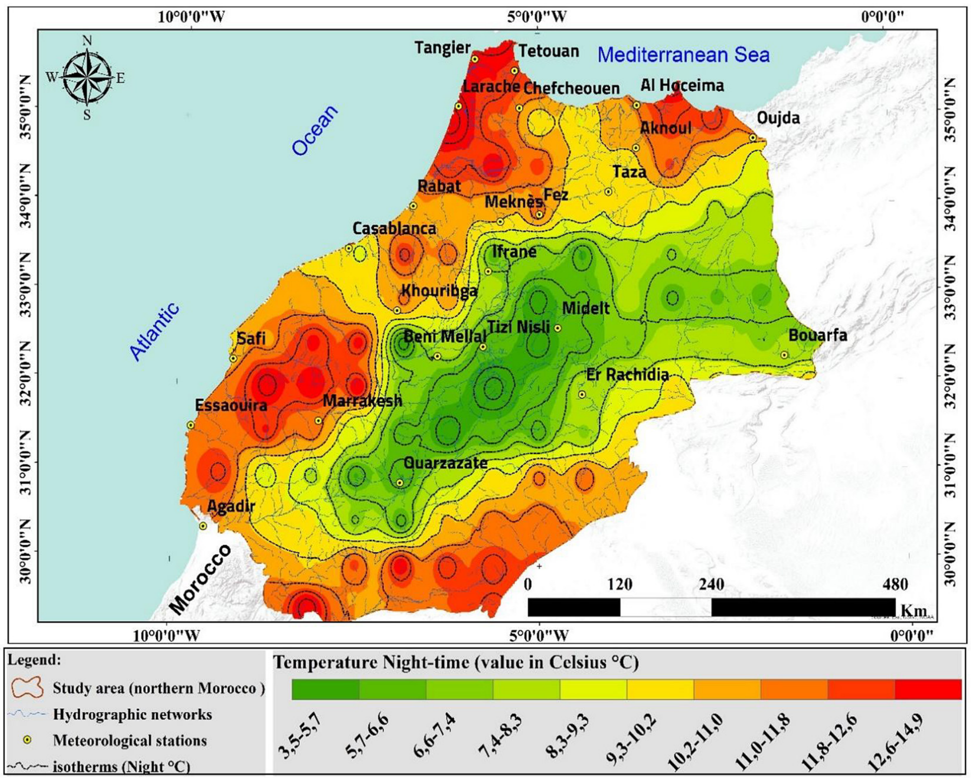

Figure 9. Spatial distribution of absolute minimum temperatures (night time temperatures) for the month of January 2025

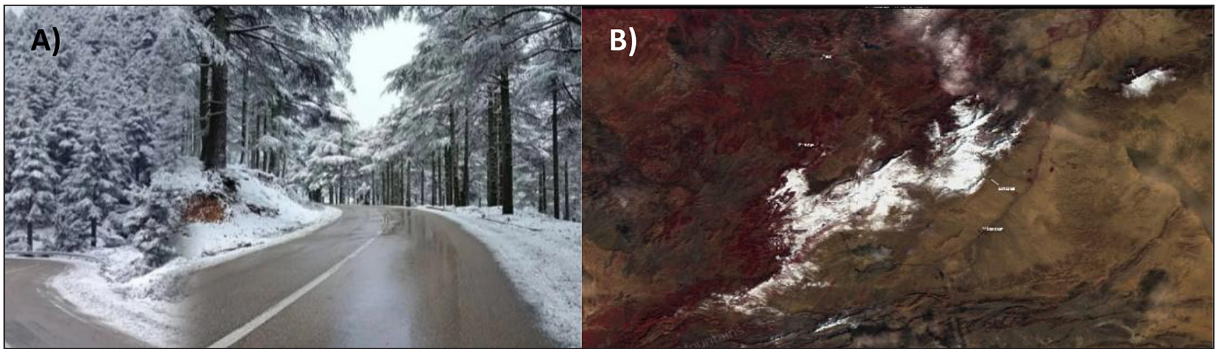

Figure 10. A: Snow removal on the Azrou-Midelt road, B: Between 17 and 18 January 2025, Morocco was affected by significant snowfall, particularly in mountainous regions above 2,400 meters

Europe (WMO., 2000) and Northern Africa. Analysis of the maps shown (Fig. 11A and 11B) reveals that Morocco is swept by the polar front margin topped by the upper-level jet stream, which takes a southerly position with strong undulations allowing energy exchanges between the deficit polar zone and the surplus tropical zone. This occurs in a context of hemispheric atmospheric circulation that is predominantly meridional. The westerly flows, forced to bypass the subtropical anticyclones largely pushed towards the poles, find themselves forced to bypass once again the deeply intrusive subpolar depressions to the very edges of the subtropical zones (Karrouk., 2017; 2015).

A significant polar discharge occurred towards eastern Morocco. This led to the formation of a strong barometric minimum centered on the Mediterranean Sea, supported at altitude by a cold drop (-15°C) within a meridional wave towards the south of the subtropical jet. This depression caused snowfall (between 15 and 30 cm) in the provinces of Al Hoceima, Guercif, Taourirt, Figuig, Jerada, Boulemane, Sefrou, Ifrane, Taza, and Midelt.

Winter thermograms (Fig. 12) indicate that during the cold spells of January 2025, maximum LSTs extend beyond strictly urban areas to agricultural areas, despite their geographical location (Gommes, 2012). Extreme temperatures were recorded in both city centers (dense built-up areas) and rural areas with no vegetation (bare ground), particularly in mountainous areas. However, for this period, high LSTs are concentrated in all dense urban areas and industrial zones (economic activity zones) in the municipalities of Casablanca, Kenitra, and Tangier, as well as in the Casablanca train turnaround area (Fig. 12). Thus, the spatial extent and intensity of cold spells during cold waves could be correlated with the intensity and duration of these periods due to the thermal inertia of ground surfaces. In this context, the results of LST index mapping in northern Morocco show temperatures falling in urban areas during the

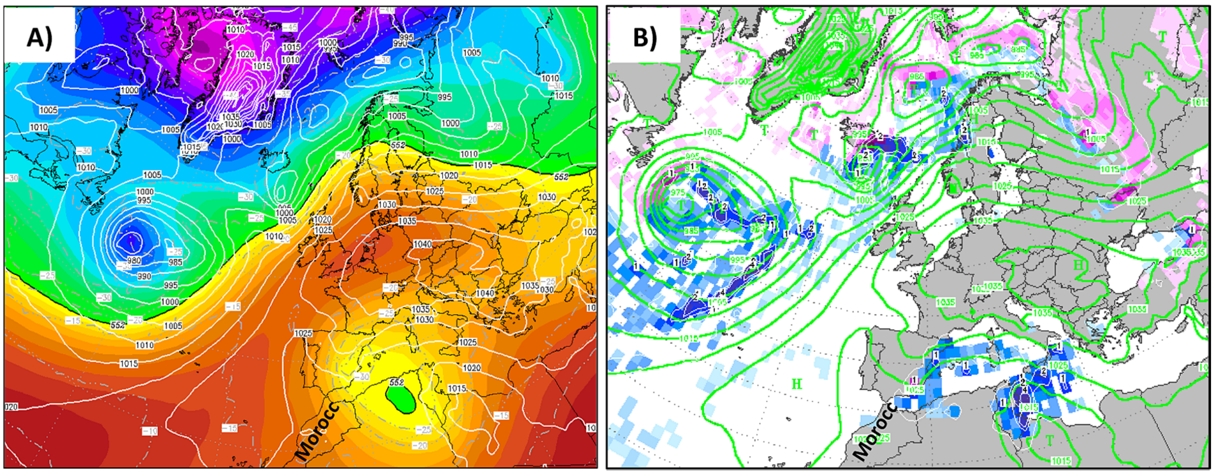

Figure 11. Synoptic situation at 500 hPa on January 17, 2025, at 00:00 UTC (A), Isobaric situation at ground level on January 17, 2025, at 00:00 UTC (B)

night and day. Furthermore, inland, particularly in mountainous areas, very low temperature spots have been observed (Ifrane, Azilal, Tizi N'sli). appear according to the classification used (Fig. 12).

DISCUSSION

Cold waves are a major cause of weather-related deaths. With the current concern for global warming it is reasonable to suppose that they may increase in frequency, severity, duration, or areal extent in the future. However, in the absence of an adequate definition of a heat wave and cold waves, it is impossible to assess either changes in the past or possible consequences for the future (Robinson., 2001).

We believe that these methods, the statistical method (calculated climate indices: TX10p, TN10p, FD, and CSDI) and the method of classifying cold waves based on intensity, have strengths and advantages that can complement each other. Each of these approaches can also meet specific needs. The application of relative cold thresholds (statistical approach) provides more relevant results when it comes to a detailed analysis of cold waves across several stations or a large region. This method is easy to apply not only by researchers, but also by managers, decision-makers, and other users, even if they are not specialists. However, when it comes to comparing a set of stations belonging to different regions and topoclimates, these methods pose a problem. Indeed, the use of statistical thresholds that vary from one region to another, even if it allows adaptation conditions to be taken into account, complicates the interpretation and implementation of adaptation strategies (Ben Boubaker., 2010; 2017; Traboulsi., 2017).

In this context, Sebbar (2022), and Kessabi et al., (2022) note that northern Morocco, due to its meteorological and geographical position, is located in a region that is vulnerable to climate change, both in terms of temperature and rainfall. Indeed, the changes observed show a lengthening of the maximum drought period, particularly in winter, an increase in the average maximum and minimum temperatures, as well as an increase in the amplitude of hot extremes (hot days, heat waves) and a decrease in cold days. According to the results of the four indices, there has been a 30% decline in the number of cold spells over the last two decades, accompanied by a significant increase in heat waves. This climate imbalance is certainly accompanied by negative impacts on natural resources and socio-economic activities (Achir et al., 2024; Khomsi et al., 2015).

With regard to the intensity study for the year 2025, this method allows cold spells to be classified according to their intensity, severity, or persistence. It can be deduced that cold spells occur mainly in December, January, and February. In terms of severity and persistence, the cold spell from January 1 to 7, 2025, at the Fez station was the most significant (with P = 37 °C). This method has therefore made it possible to identify the area's most vulnerable to the intensity of cold spells. To map cold days and nights in northern Morocco, we created two maps (days and nights) using GIS (kriging). Despite the climatic unity of the study area, which is entirely subject to a Mediterranean

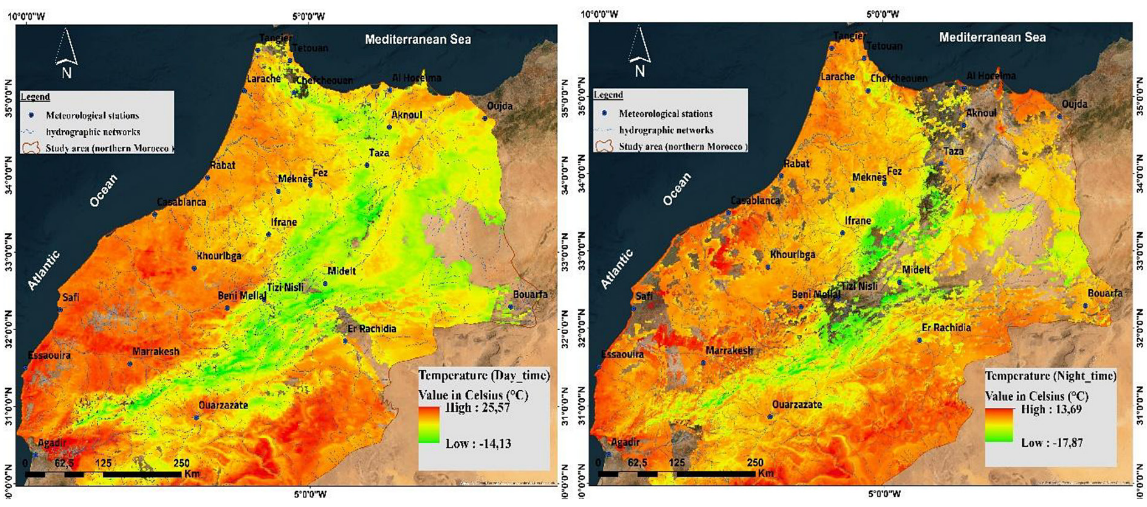

Figure 12. Mapping of LST during cold spells (cold days and nights) in northern Morocco (January 2025)

climate, the diversity of the terrain and continentality introduce significant regional variations in the distribution of cold days and nights. Thus, it appears that cold nights and days are significantly more intense in mountainous areas (3.5–7.4 °C), while they remain relatively milder in coastal areas (with temperatures of 11–14 °C).

North Africa, like the entire Mediterranean region, experiences a transitional climate between the Ferrel cell and the Hadley cell (Queney, 1974; Aguado et al., 1999). The mechanisms of general circulation are governed by the global energy balance, which changes throughout the year depending on the apparent movement of the sun (Traboulsi, 2014). In order to understand the characteristics and factors behind the cold spells of January and February 2025, a climate analysis and an analysis of synoptic conditions show that northern Morocco is under the influence of cold and disturbed troughs. This has led to the formation of a strong barometric minimum centered over the Mediterranean Sea, supported at altitude by a cold drop (-15 °C) within a meridional wave to the south of the subtropical jet stream.

Cold waves, although less frequent and less persistent than heat waves, represent a more morbid, even more deadly hazard. This aspect, which seems paradoxical, deserves further investigation. A vigilance scale and relevant adaptation strategies that take both types of extreme events into account are also imperative for northern Morocco. The method proposed in this study may be useful for this purpose. We believe that absolute thresholds are appropriate for a larger scale, in this case the entire territory of Morocco. They provide a better understanding of the risk thresholds associated with cold waves and allow for regional nuances to be taken into account. These absolute thresholds have stable references, facilitating in-depth analysis of thermal extremes in their spatial and temporal variation. It is also essential to develop a relevant approach for estimating wind chill temperatures, taking into account other environmental factors (wind and air humidity), and to deduce appropriate cold risk thresholds for northern Morocco. Referring to machine learning will make it possible to predict cold waves in the long term, prepare for them in advance, and thus avoid human and material losses as part of a coherent risk management approach. The implementation of warning models based in particular on spatial remote sensing will be an effective means of dealing with cold waves.

CONCLUSIONS

The study of the frequency and evolution of intense cold waves in northern Morocco has revealed significant climate trends. The results show that these phenomena are closely linked to atmospheric circulation patterns, particularly the intensity of polar depressions and interactions with subtropical high pressures. Analysis of meteorological data confirms that interannual variability plays a major role in the occurrence of these cold episodes. In addition, the influence of global climate phenomena such as the North Atlantic Oscillation (NAO) has been decisive in the atmospheric dynamics observed.

This study provides essential insights for anticipating future trends in cold waves. It also contributes to a better assessment of their impacts in a context of climate variability and change in Morocco. Further research, incorporating climate modeling and more detailed analyses of atmospheric forcings, would be necessary to refine these conclusions and better anticipate the associated risks. Cold spells pose a real risk to northern Morocco. Their downward trend is consistent with the shortening of the rainy season (Traboulsi, 2014) and raises the issue of water scarcity and high energy demand for a rapidly growing population. Any development plan should therefore take this reality into account.

In this study, we developed three models (calculated climate indices using RClimDex software, Atmospheric Circulation, Landsat OLI/ Tirs 8) to assess the cold waves risk in the northern Morocco using maximum daytime temperatures and minimum nighttime temperatures. It was noted that the three models, presented a good result in analysis of the frequency and evolution of cold spells with an overall accuracy of = 80.3%, 77.9%, and 83.5%, respectively.

The results obtained from the use of the three models show that 70% of the coastal and continental stations studied recorded a total weight varying between 2.4 °C and 37 °C during the months of January and February. The calculation of thermal indices (TX10p, TN10p, FD, and CSDI) showed variable trends, with an overall accuracy of 0.13, 0.04, 0.02, and 0.012 day (10 yr) $^{-1}$ respectively.

The findings generated from the study and mapping of cold waves within the northern Morocco constitute a significant scientific tool for many stakeholders such as land-use engineers, urban planners, and local and regional authorities to utilize when managing climate risk and reducing socio-economic impacts. The study demonstrates that by employing a hybrid method involving climate data, barometric models and Geographic Information System (GIS) techniques, it is possible to delineate areas that are most at risk for cold waves, particularly in mountainous and inland regions that are far removed from maritime influences. Additionally, the methods utilized for the study may be demonstrated by the ability to expand the study's methodology to develop cold waves risk maps for other regions of the mountain range of Morocco that possess similar physical, geographical and climatic characteristics to northern Morocco. Lastly, this model can be applied to cold and semi-arid regions in Northern Africa, the Middle East and Central Asia. This model allows decision-makers to prioritise actions that will either protect sensitive crops, direct guide reforestation projects and select for most frost-resistant species or to find accurate planning infrastructure improvements in areas prone to extreme drops in temperatures. This analytical framework is therefore a proactive tool for supporting strategies to adapt to extreme weather events and promoting sustainable regional development.

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