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Spatiotemporal Assessment of Wind Speed, Relative Humidity, and Dew Point Temperature over Iraq during 1980–2023 under Climate Change

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ABSTRACT: This study analyzed annual data for wind speed, direction, relative humidity, and dew point temperature in selected Iraqi governorates for the period 1980–2023, using an annual average set from the European Centre for Medium-Range Weather Forecasts (ECMWF). The data were processed using Grid Analysis and Display System (GrADS) simulation software, network rendering software, and Sigma Plot software. A wind speed and direction chart were created to represent the frequency and intensity of wind directions across different regions, allowing for an understanding of the changing behavior over the study period. The results showed that northwesterly winds are dominant across most of Iraq, although wind speed exhibits significant spatial variation between the northern, central, and southern regions. Furthermore, the analysis revealed a strong positive correlation between relative humidity and dew point temperature, both of which are influenced by atmospheric water vapor content. These findings highlight the importance of incorporating humidity and dew point variables into wind speed assessments, which could improve our understanding of regional atmospheric circulation and provide valuable insights for renewable energy planning and climate studies in Iraq..

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1.INTRODUCTION

The environmental changes that the Earth has undergone recently are due to several factors, some of which may be unnatural as a result of human activities and others natural as a result of terrestrial processes or which have changed the Earth's natural processes [1,2]. Climate change disrupts the atmosphere and affects Earth's processes and its inhabitants. One of the most important causes of global climate change is fossil fuels, as fossil fuel emissions account for more than 75% of global greenhouse gas emissions. Human activity has warmed the atmosphere, oceans, and land, causing widespread and rapid changes in the atmosphere, oceans, cryosphere, and biosphere [3].

One of the most important ways to mitigate climate change is to reduce the use of fossil fuels to halt and reduce the concentration of carbon dioxide and methane, which are greenhouse gases, in the atmosphere. The solution to all these problems is to use alternatives, such as renewable energy, such as solar, hydroelectric, and wind power [4]. Climate change and global warming are among the most important issues today. They concern not only scientists and politicians, but also the general public [5]. Numerous studies have concluded that global warming directly impacts the environment. Furthermore, we observe the effects of the Industrial Revolution, which contributed to massive emissions of harmful substances into the atmosphere, water, and soil [6].

There is concern about climate change, which is one of the reasons behind the rapid development of wind energy projects [7]. The Intergovernmental Panel on Climate Change (IPCC) observed evidence of widespread and long-term climate changes in 2003, such as increased westerly winds and polar shifts, and these observed changes are likely to continue. Research indicates that jet streams have increased the movement and strength of the polar vortices in both hemispheres [8]. Any disruption to these changes directly affects energy production in current and future wind energy projects [9]. There are many studies that look into the use of wind energy as an alternative to mitigate global warming and support the development of sustainable energy, considering the impact of climate change on wind energy related to wind turbines to ensure its long-time sustainability [10]. This study highpoints the ability of mixture systems to offer stable energy production from wind bases [11].

To study the fluctuations in wind directions caused by global climate change, it must be considered that the results vary according to climate projections, numerical modeling methods, and geographical contexts [12]. Although positive regions, such as North America, are expected to experience an increase in wind speed, a possible decrease in wind speed has been observed in the Mediterranean region [13, 14]. Relative humidity affects air density, which can indirectly affect wind speed. Air density decreases as the amount of water vapor in the air increases. This change in density, in turn, affects atmospheric pressure distribution, as less dense air tends to rise, potentially contributing to the formation of low-pressure areas. Since wind typically moves from high-pressure areas to low-pressure areas, pressure changes resulting from density differences can affect wind patterns and speeds [15]. Simple equations that illustrate the effect of wind on evaporation are presented as Equations 1 and 2 [16, 17]:

$$E = K(e_s - e\alpha)(1 + \alpha u) \qquad (1)$$

Where E: evaporation rate, es: saturated vapor pressure, eα: actual vapor pressure, u: wind speed, and k and α are empirical constants that depend on local conditions. Relative humidity (RH) is calculated from [18]:

$$R.H = \frac{e_\alpha}{e_s} * 100 \qquad (2) \qquad (2)$$

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Wind speed can change the values of e_α, shown in the equation above, thus affecting relative humidity [19]. The statistical significance of both the relative humidity trend and dew point temperature, as influential factors in global warming and climate change, was assessed. Therefore, these factors were analyzed at a site in northern Nigeria (Abuja) for a full year, as atmospheric water vapor, a greenhouse gas, is one of the most influential factors in weather and climate [20]. Water vapor in the atmosphere is one of the most important factors affecting weather and climate on Earth. Therefore, the results showed that there is a strong linear relationship between these two factors. It is also noted that the weather is affected by human activity, supported by the prevailing weather conditions in the study area [21].

Relative humidity (RH) and dew point temperature (td) are two common measures of the amount of moisture in the air. Accurately converting RH to Td is complex and difficult to do easily without a calculator or computer. However, there is a very simple rule of thumb that can be very useful for approximating the conversion of humid air (RH > 50%). This rule is not widely known in meteorological circles: td decreases by approximately 1 degree Celsius for every 5% decrease in relative humidity. Wind speed also plays a role in changing these ratios, as well as other relationships between dew point and relative humidity [22]. When relative humidity is high, the air is saturated with water vapor, reducing its density [22].

The dew point temperature is the temperature at which air must cool. When air cools to the dew point temperature, water vapor condenses. This sudden change in density affects air movement, leading to the release of latent heat in the atmosphere. This heat can potentially affect atmospheric stability [23]. There are also tools, such as vegetation, which is a fundamental component of the ecosystem and plays a vital role in regulating the climate. Since vegetation changes dynamically throughout the seasons in response to climate factors, such as temperature, rainfall, and solar radiation, monitoring these changes and understanding their patterns is essential for assessing the impact of climate on ecosystems [24].

Population growth, urban expansion, the unprecedented increase in the number of cars, transport vehicles, and factories, and the growing demand for energy production in all its forms have resulted in the release of millions of tons of pollutants and harmful gases into the air daily. In addition, the increased concentration of carbon dioxide in the atmosphere has contributed to rising global temperatures, leading to the expansion of drylands at the expense of wetlands [25]. Increases in human activity over the past three decades has led to a rise in atmospheric temperature, depletion of the ozone layer, and exacerbation of global warming. This rise in atmospheric temperature could lead to the submergence of many coastal cities as a result of melting glaciers, rising sea levels, and severe droughts affecting many regions of the world due to low annual rainfall rates and irregular distribution [26]. Relative humidity also affects the annual wind energy loss rate in the city of Samawah, southern Iraq, for five years (2012-2016) for the purpose of generating electricity. Data on relative humidity and wind speed were measured at an altitude of 11 meters at the Samawah meteorological station. A decrease in annual density rates was observed with increasing altitude [27].

The present research analyzed the temporal and spatial patterns and trends of wind speed, relative humidity, and dew point temperature in Iraq from 1980 to 2023. This is to understand climate variability, monitor long-term changes, and assess their potential impact on weather patterns. Furthermore, it is to study historical trends in wind speed, dew point, and relative humidity in various regions of Iraq, as well as to identify seasonal and internal variations in these variables.2.

2. MATERIALS AND METHODS

2.1 Study areas

The study areas were selected based on the prevailing northwesterly wind direction, which predominantly flows toward the southern and southeastern regions of Iraq. Accordingly, twelve provinces located along the dominant wind trajectory were identified for this study. The geographic coordinates of the selected study areas are provided in Table 1**.**

Table 1: Study stations and their coordinates

Station	Lo	La	Station	Lo	La
Baghdad	44.4	33.3	Nasiryah	46.2	31
kut	45.7	32.5	Rutba	40.2	33
Khanaqeen	45.3	34.4	Samawa	45.3	31.3
Hella	44.4	32.4	Muthna	45.6	31.1
Karbala	44	32.6	Amara	47.1	31.8
Basra	47.8	30.5	Najaf	44.3	31.9

Lo: Longitude; La: Latitude

2.2 Meteorological data collection and processing

Wind speed (m/s) at a height of 10 m, relative humidity (%), and dew point temperature (°C) were collected for the period 1980–2023 from the European Centre for Medium-Range Weather Forecasts (ECMWF) for the ERA5 weather station. Data quality was assessed, including verification of physical ranges, exclusion of anomalies ($\pm 3\sigma$), and gap correction with a 25% threshold for missing data, which was considered zero. Annual averages were calculated for each variable, as well as the long-term average for the period, using the formula presented as Equation 3.

$$\bar{x}_y = \frac{1}{12} \sum_{m=1}^{12} x_{y.m} \qquad (3)$$

Where x_y is the annual average, m is the number of months, and y is the value of the variable for the month.

2.3 Spatial mapping of climate variables

To prepare spatial maps of climate variables in Iraq, the GRADS (Grid Analysis and Display System) software was used to represent the geographic distribution of the data. The WGS84 geographic coordinate system was adopted, with the data converted to the UTM Zone 38N projection system to ensure the accuracy of spatial measurements and minimize distortions resulting from projection.

2.4 Spatial interpolation

Climate station data were entered as spatial points and then transformed into continuous surfaces using spatial interpolation techniques. Two main methods were employed: Inverse Distance Weighting (IDW) with a power of 2, requiring the use of at least eight adjacent points in the estimation process, and Kriging using a spherical model to represent the spatial structure of the data.

2.5 Map production and visualization

The interpolated climate surface maps were produced with a grid cell size ranging from 5 to 10 km, depending on the density and geographic distribution of the stations. A uniform color scheme and quantitative classification were used to facilitate comparison between different regions.

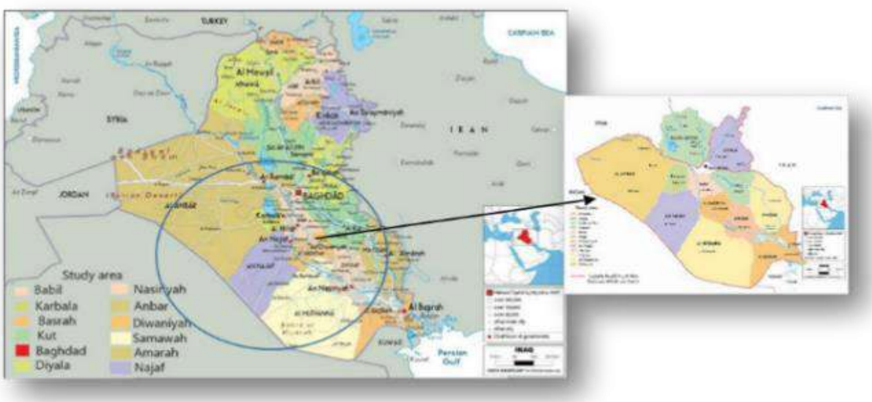

Figure 1: Study area in Iraq

2.6 Wind rose analysis

To analyze wind direction characteristics, wind rose diagrams were created based on wind speed and direction data. The directions were divided into 16 major and minor sectors (N, NNE, NE, ENE, E), while wind speeds were classified into five categories: 0–2, 2–4, 4–6, 6–8, and over 8 m/s. The frequency of each category and direction was then calculated as a percentage of the total number of observations during the study period, allowing for the identification of dominant trends and the most common speed ranges.

2.7 Statistical analysis

Statistical analysis was performed using Origin software. The annual time series for the period (1980–2023) was first organized and entered into the software, and then the data quality was checked to identify anomalies or missing values. The normality of the data distribution was then tested using the Shapiro-Wilk test. Pearson's correlation coefficient was used for normally distributed data, and Spearman's rank correlation coefficient for non-normally distributed data, with a significance level of $\alpha = 0.05$. To determine the nature of the relationship between the studied climatic variables, scatter plots were constructed for all possible binary relationships. Linear regression models were then applied according to Equation 4:

$$y = a + bx \qquad (4)$$

Where a represents the constant (intercept), and b represents the slope.

The coefficient of determination (R^2) was calculated to estimate the proportion of variance explained by the model, along with 95% confidence intervals to assess the reliability of the results. In cases where the data did not meet the linearity assumptions, alternative nonlinear models were tested, and the best model was selected based on the highest R^2 value and the best statistical fit indices.

3. RESULTS AND DISCUSSION

3.1 Spatial distribution of prevailing wind direction and speed

Figure 2 shows a series of monthly wind direction and speed charts for annual averages in several different regions of Iraq. The overall analysis of these charts indicates that the wind direction in most areas is from the northwest (northwest) and north (north). Wind directions may vary in some areas due to topographical influences or local factors. Wind speed varies from region to region, but generally ranges between 1.6 and 3 meters per second, as indicated by the color key. Blue represents the fastest winds (over 3 meters per second), while red and orange represent the slowest. Some areas have more regular and consistent winds, while in others the winds may be somewhat variable. In other areas, the winds may be scattered or distributed in more than one direction, indicating differences in climatic and geographical influences between different regions. These variations in wind patterns are attributed to factors such as local topography, including mountains, rivers, and deserts. Cities located near bodies of water may experience different wind flows compared to inland cities. These variations in wind patterns are evident when comparing the different stations shown in the figure. A common pattern is observed in most areas, with winds blowing primarily from the north and northwest. However, some areas, such as Rutba and Baghdad, may exhibit wind directions or distributions that deviate from the general pattern. In Rutba, winds blow mainly from the northwest with some northerly influences, while in other areas, winds blow predominantly from the northwest, a pattern that differs slightly from the others.

The weather stations in Samawah, Hilla, and Nasiriyah show a similar pattern, with northwesterly winds blowing at moderate to high speeds. In Karbala, winds blow mostly from the north to northwest at moderate speeds. In Samawah, Kut, and Amarah, northwesterly winds exhibit more consistent speeds compared to other areas. Based on the colors in the graphs, wind speeds in most areas range between two and three meters per second. Although not strong, these speeds are consistent and can be utilized

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in some areas, such as Najaf, Rutba, Samawah, and Kut. Wind speeds in these areas are consistently high, exceeding three meters per second (areas shaded in dark blue), making them suitable for wind farms. In contrast, some areas, such as Kut and Nasiriyah, experience lower wind speeds, which may make them less suitable for large-scale wind turbine projects. The same applies to Basra, where the fastest winds are recorded and indicated in blue, the most common color even at stations leading to the city.

3.2 Climatic and environmental impacts

Deserts and open terrains (such as rutba and karbala) contribute to higher wind speeds due to fewer natural obstacles, such as trees and buildings. Urban areas, such as Baghdad may exhibit more dispersed wind patterns due to tall buildings and air pollution that may affect airflow. Areas closer to rivers or water bodies (such as Kut and Amara) may result in more stable winds but at lower speeds due to the effects of water on air stability. Therefore, potential applications of this data can be used in renewable energy projects, where areas with strong and stable winds, such as Rutba, Karbala, and Najaf, can be selected for the construction of wind power plants. Even in air quality and pollution management, where knowledge of wind directions helps determine how air pollutants are transported, allowing for smarter industrial planning in large cities.

3.3 Relationship between wind speed and relative humidity

Wind is the movement of air driven by differences in atmospheric pressure, whereas humidity refers to the amount of water vapour present in the air. Although the relationship between wind and humidity is indirect, the two variables are closely interrelated. An increase in wind speed enhances atmospheric mixing and promotes the continuous renewal of air masses, thereby influencing the distribution and concentration of water vapour in the atmosphere. This results in a decrease in water vapor concentration (lower humidity if the air is dry). Water vapor load increases when the wind passes over a body of water (higher humidity). For example, on coasts, offshore winds increase humidity, while winds coming from land usually reduce it. Conversely, humidity affects wind, as moist air is lighter than dry air because water vapor molecules (H_2O) are lighter than N_2 and O_2. This difference in density contributes to the formation of additional pressure differences that affect wind movement. Therefore, humid areas (such as oceans and forests) are more susceptible to the formation of air currents and convection. As for the equations that link humidity and wind speed, there is no direct equation that links humidity to wind speed (because the relationship is nonlinear and depends on other factors such as temperature and pressure). However, there are physical equations that link them through evaporation and cooling. The higher the wind speed (U), the greater the evaporation, the more the amount of water vapor in the air, and the higher the humidity, as shown in Equations 5 and 6:

Bulk aerodynamic formula:

$$E = \rho C_e U(q_s - q_a) \qquad (5)$$

Where E is the evaporation rate (kg/m²/s), ρ is the air density, Ce is the transfer coefficient, U is the wind speed at altitude (m/s), qs is the saturation humidity at the water surface, and qa is the specific humidity in the air.

Moisture Flux:

$$E = \rho C_e U(q_s - q_a) \qquad (5)$$

Where Fq is the moisture flux, ρ is the air density, U is the wind speed at altitude (m/s), and q is the specific humidity.

3.4 Relationship between wind speed and relative humidity

The general physical relationship between humidity and wind speed is that there is often an inverse relationship between wind speed and relative humidity. This is because wind increases evaporation, thus decreasing relative humidity. When winds decrease, water vapor builds up in the atmosphere, leading to higher humidity. Figure 3 shows that, at most stations, there are periods of time when higher wind speeds (red line) are accompanied by lower humidity (green line), and vice versa. However, the relationship is not always linear or 100% clear, as other variables, supporting the hypothesis of an inverse relationship, factors control humidity, such as temperature, rainfall, topography, and vegetation. Some graphs, such as those of (Baghdad and Karbala), show an opposite annual fluctuation between the two variables.

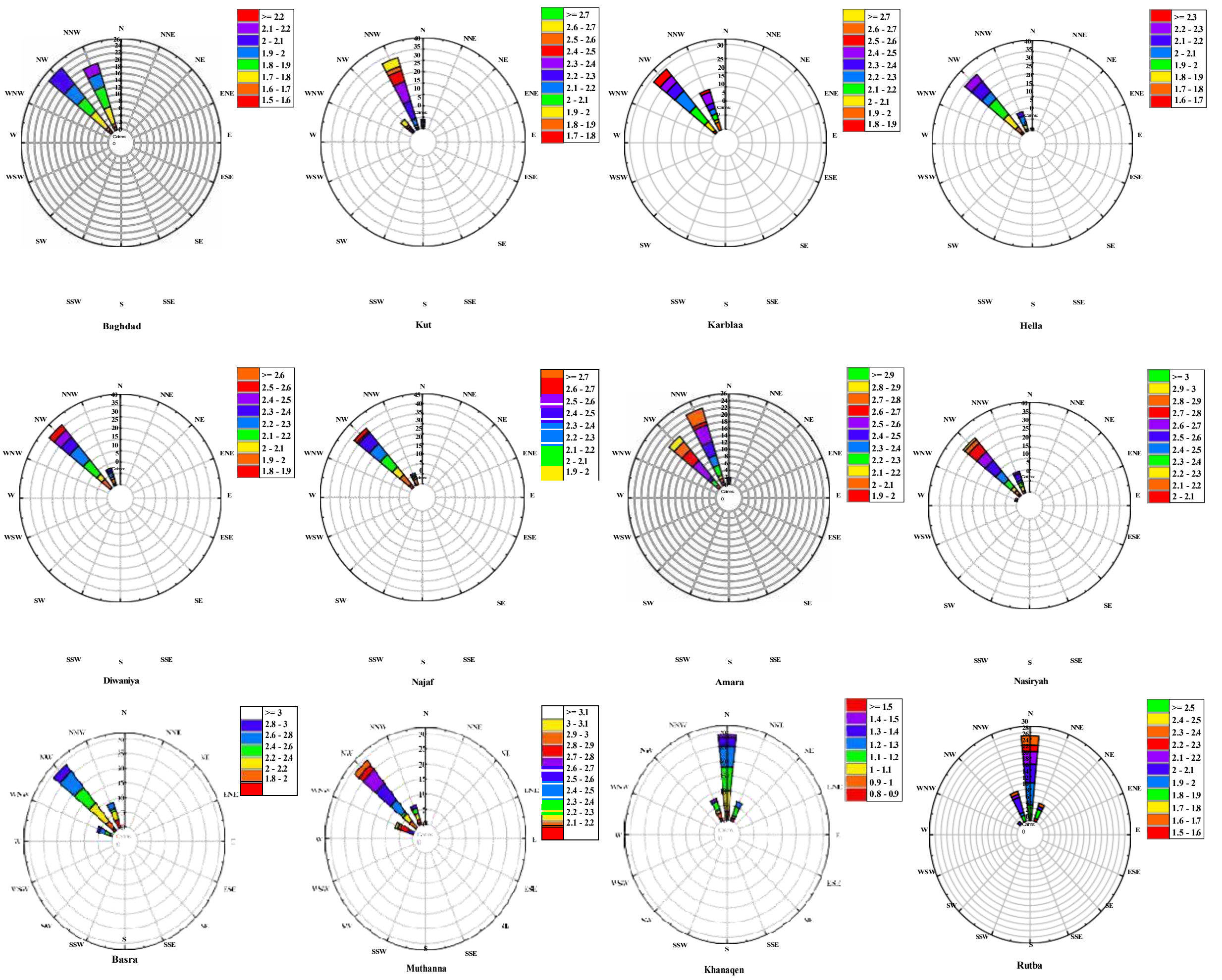

Figure 2: Annual average wind speed for all stations.

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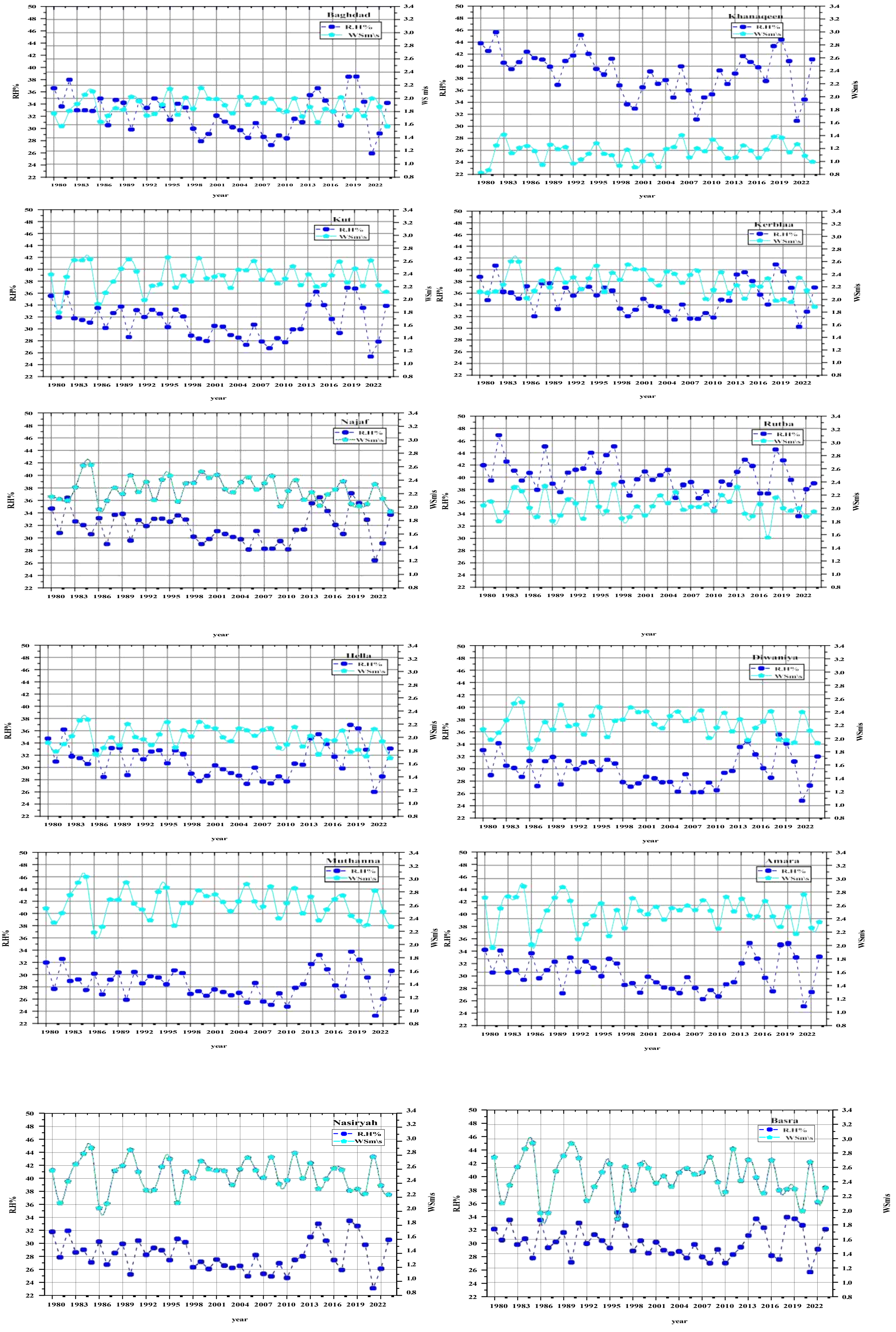

Figure 3: Relationship between wind speed and relative humidity.

Table2: Correlation coefficient of wind speed and relative humidity

RH % / WS m\s	Bag	Kanq	Kut	Kerb	Naj	Hella	Rut	Diw	Muth	Amar	Bas	Nas
r	-0.4	0.01	-0.2	-0.4	-0.5	-0.5	0.	-0.5	-0.4	-0.2	-0.	-0.
p-value	0.0013	0.898	0.074	0.002	0.001	0.005	0.077	0.007	0.003	0.164	0.013	0.008

3.5 Influence of wind and humidity on dew point temperature

The basic concept of dew point temperature (Td) is the temperature at which air (at constant pressure) cools to saturation (RH = 100%). It is directly related to the water vapor content of the air. Its relationship with wind does not directly affect the dew point, as the dew point depends on the amount of water vapor. However, wind does transport different air masses. For example, if the wind brings humid air (from the sea), the dew point rises. However, if it brings dry air (from the desert), the dew point decreases. As the wind speed increases over a water surface, evaporation and water vapor in the atmosphere increase, and the dew point may increase. Conversely, the dew point is directly related to humidity: the more humid the air, the higher the dew point.

$$Td = \frac{b.\gamma(T, RH)}{a - \gamma(T, RH)} \qquad (7)$$

Where:

$$\gamma(T, RH) = \frac{\alpha.T}{b + T} + \ln(\frac{RH}{100}) \qquad (8)$$

Wind speed is related to atmospheric systems (depressions, highs, and jet streams) as well as to spatial temperature variations. Dew point temperature is a direct measure of the water vapor content in the atmosphere; the higher the dew point, the higher the absolute humidity. Figure 4 shows a clear annual fluctuation in both variables, but they are not identical. Some stations show an inverse relationship (when wind speed increases, the dew point temperature decreases and vice versa), while other stations show a weak or irregular relationship. In recent years, at some stations, an increase in wind speed has been associated with a slight increase in the dew point, which may indicate climatic influences or a change in the properties of the influencing air masses. An inverse relationship is often observed: When wind speed increases, strong mixing occurs between dry air from the upper layers and moist surface air, lowering the dew point. Sometimes a direct relationship occurs. In some seasons, especially summer, southerly or southeasterly winds may be laden with moisture from the Arabian Gulf, so the increase in wind speed coincides with an increase in the dew point.

In Tables 1 and 2, the results showed that there is an inverse relationship between wind speed, relative humidity, and dew point temperature at most stations with respect to the correlation coefficient and probability value, as shown in the table. It should be noted that the probability function value must range between (0-1) for there to be a relationship.

3.6 Spatial distribution and temporal variability of wind speed over Iraq

Figure 5 Climate change plays a significant role in influencing the atmosphere in general, which is a set of factors that change throughout the year, day by day, and during the known seasons. The primary source of energy for this universe is the sun, which is responsible for supplying the Earth's surface with energy, through which these changes occur, considering the increase and decrease in energy. To guide our understanding of these changes, it was necessary to study some climatic variables. For example, wind speed and direction are shown in Figure 5. The general and prevailing direction is northwesterly over Iraq, and it may also be northerly. As for wind speed, we found variations in its intensity according to the given color gradient. The variation in wind intensity depends primarily on the nature of the terrain in the study area. It was observed that the intensity is concentrated in the northern region, which is mountainous in nature. The annual average in central and southern Iraq, a flat area free of friction factors, also ranges between 3.5 and 0.3 m/s. The intensity of this gradient depends on the nature of the climate during that period. The study period covered the period from 1980 to 2023, a period and a half in length. A significant increase in intensity was observed in 1985, in contrast to the preceding years, which were less severe. The intensity then increased again from 1990 to 2000. A clear difference was also observed in the central and southern regions during the period from 2005 to 2010. The study sites were selected based on areas where the wind intensity was most pronounced.

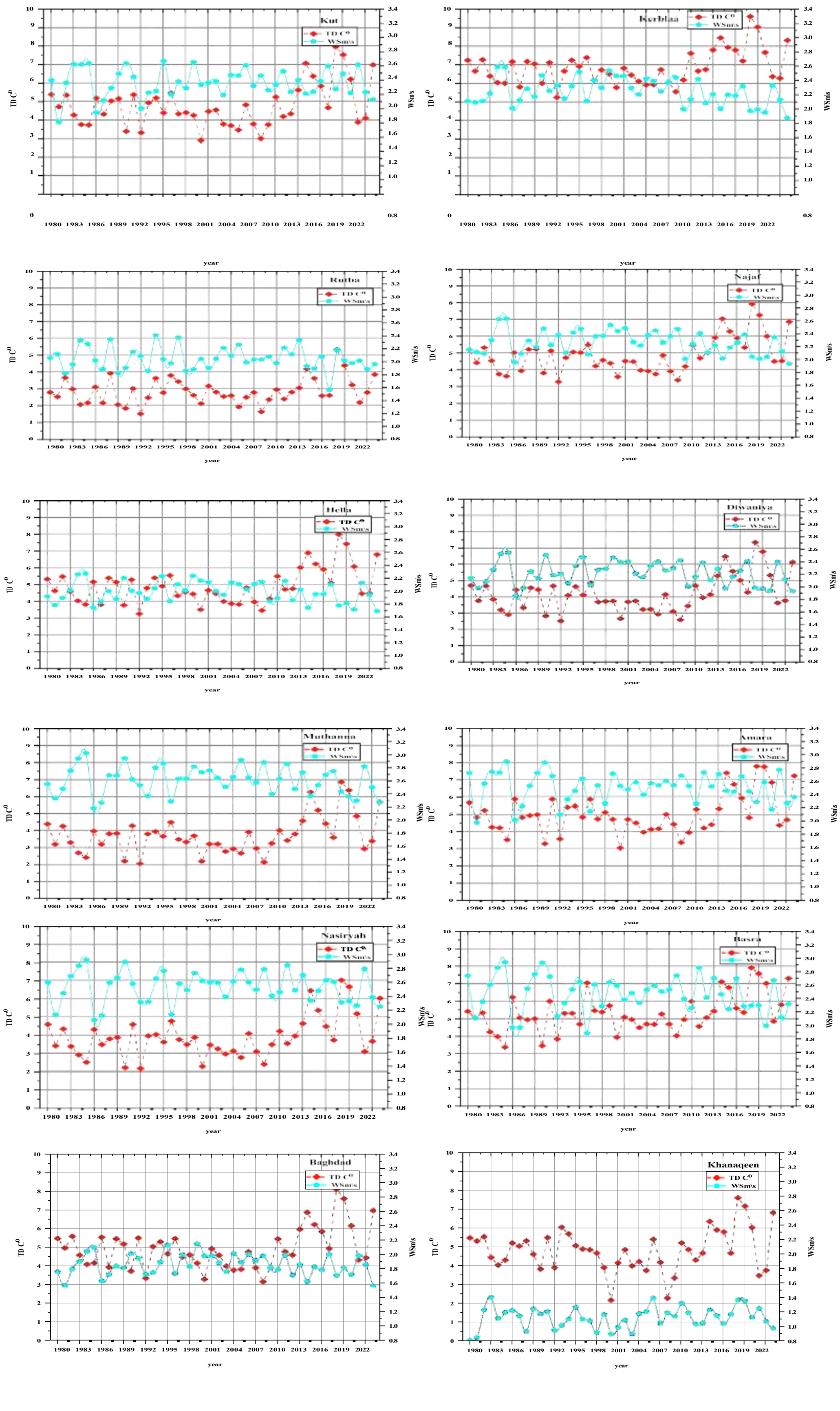

Figure 4: Relationship between wind speed and dew point

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Table 3: Correlation coefficient of wind speed and dew point

Dwp ºC / WS m\s	Bag	Kanq	Kut	Kerb	Naj	Hella	Rut	Diw	Muth	Amar	Bas	Nas

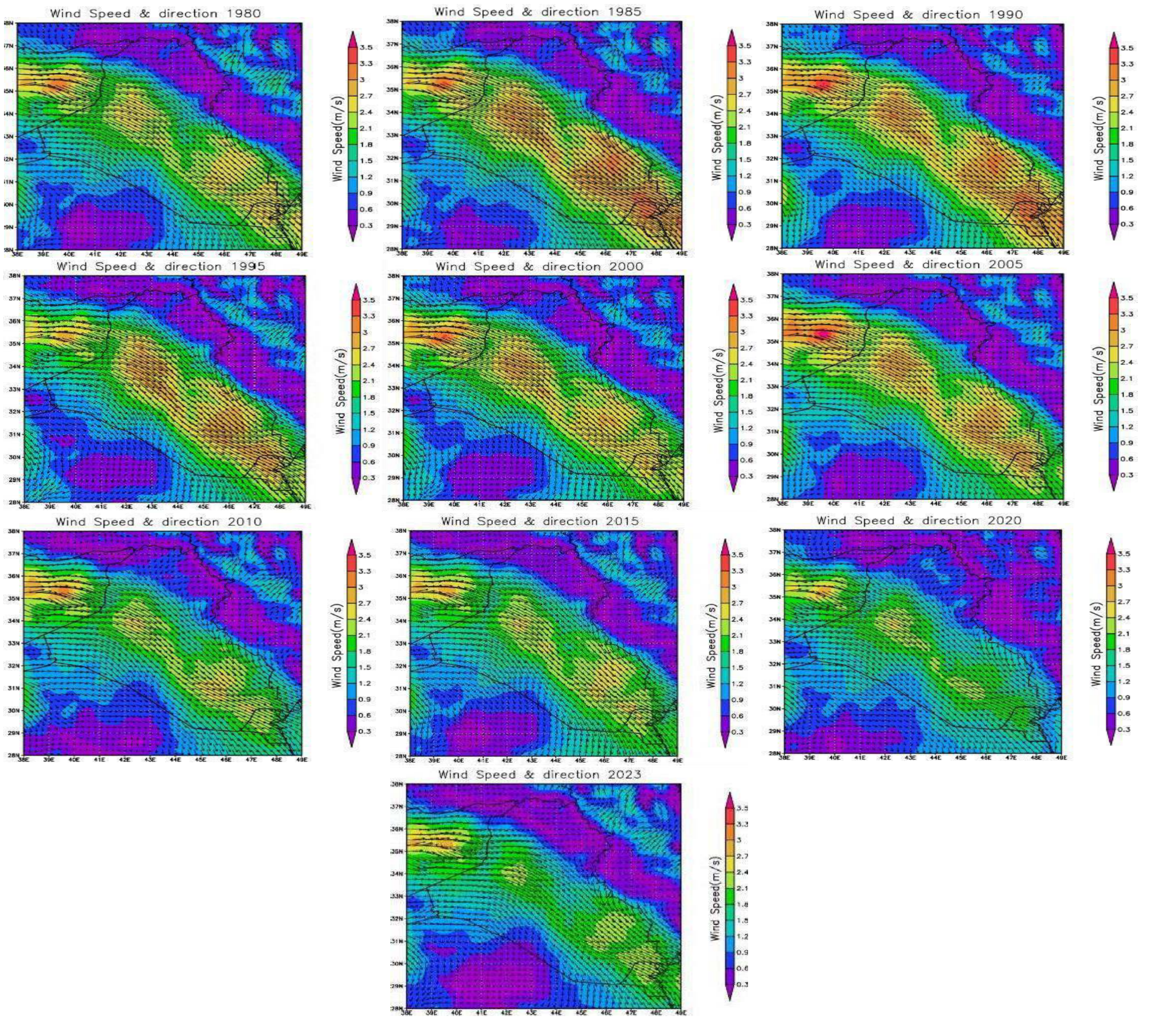

Figure 5: Wind speed overall in Iraq for the chosen year.

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3.7 Overall trend of relative humidity

Figure 6 illustrates the overall trend of relative humidity changes by relating the maps to annual averages. The results show that the blue areas represent high humidity, and this decreased over the years, representing a decline in humidity levels. These areas increase as relative humidity rises. Despite this, humidity levels fluctuate. Some years have experienced sudden increases followed by decreases, which may be attributed to temporary climatic variations, such as heavy rainy seasons or El Niño years. The geographical distribution of humidity also varies by region. Some areas were more affected than others, such as the north or south, which experienced greater changes in humidity. This may be linked to changes in water resources or the effects of human factors, such as expansion or desertification. Areas near bodies of water are also affected, and the maps can be compared to determine if there are changes in humidity near rivers or lakes due to changes in water flow or drought. Therefore, the relationship between these changes and rising temperatures is also evident in global climate change. This continuous decrease in humidity over the years may be related to rising temperatures and increased evaporation.

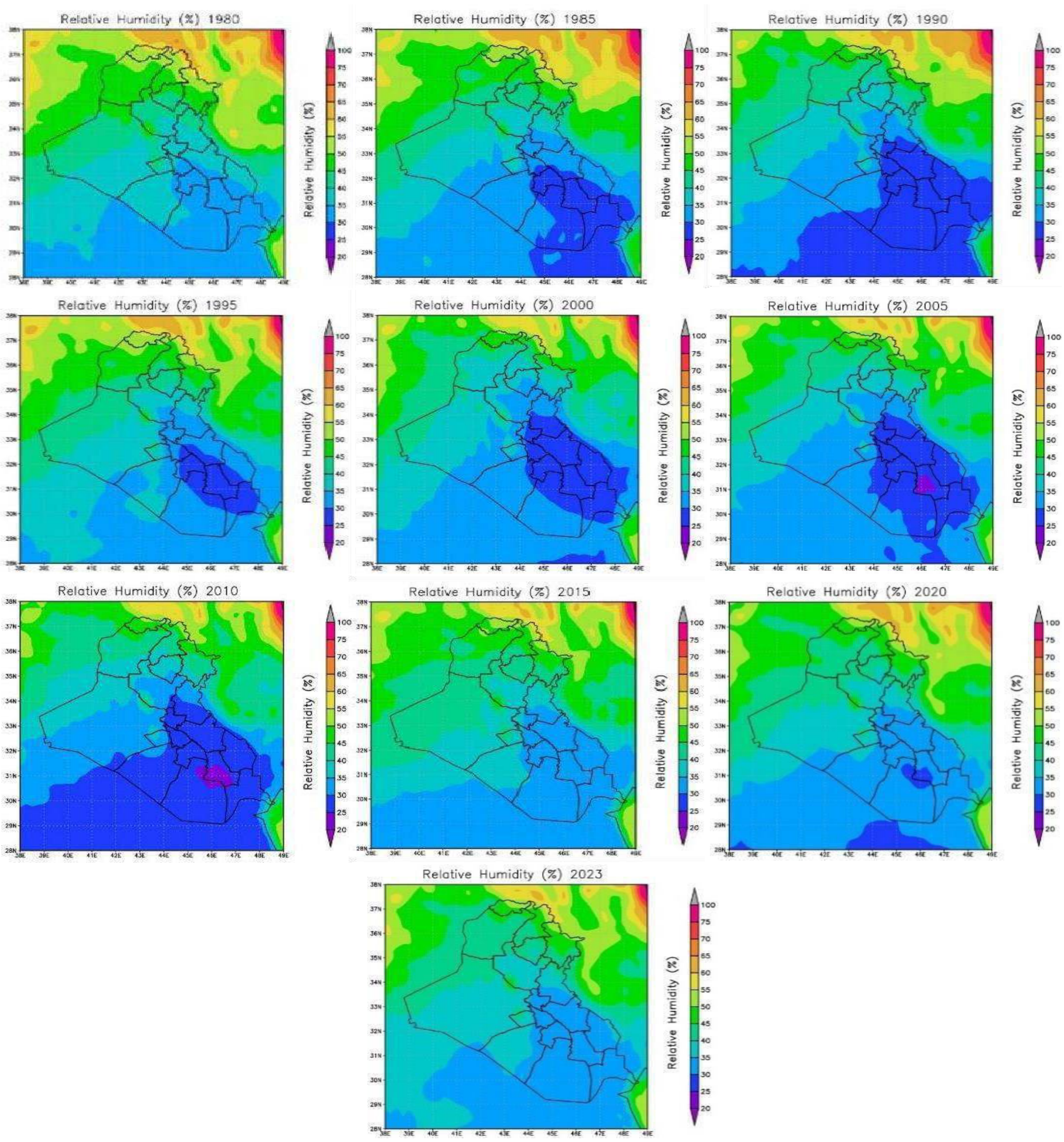

Figure 6: Relative Humidity overall in Iraq for the chosen year.

One indicator of atmospheric humidity is the dew point temperature, a good indicator of the air's ability to hold water vapor, which leads to fluctuations. These fluctuations significantly affect climate, agriculture, and the overall ecological distribution. To evaluate the spatial and temporal variations in dew point temperatures in Iraq between 1980 and 2023, using annual climate data, a series of climate maps was created representing the distribution of dew point temperatures (in degrees Celsius) for each year. A color gradient was used on the maps to illustrate these changes, with cool colors (green and blue) indicating lower temperatures and warm colors (red, orange, and yellow) indicating higher temperatures. The data indicate annual fluctuations in dew point temperatures, without a consistent pattern observed across all years. Notable increases were recorded in 1985 and 1995. However, some years recorded notably lower dew point temperatures, with 1990 exhibiting the lowest value. While there was a clear rise in temperatures in 2015 and 2023, the remaining years fluctuated between rise and fall, as the eastern and southeastern regions of Iraq, close to the Iranian border and the Arabian Gulf, showed higher temperature gradients compared to other regions. These regions tend to be more humid and may be more affected by climate change or winds, especially in the last years of the series. The western and northwestern regions, however, were cooler in most years, indicating stability or slower changes.

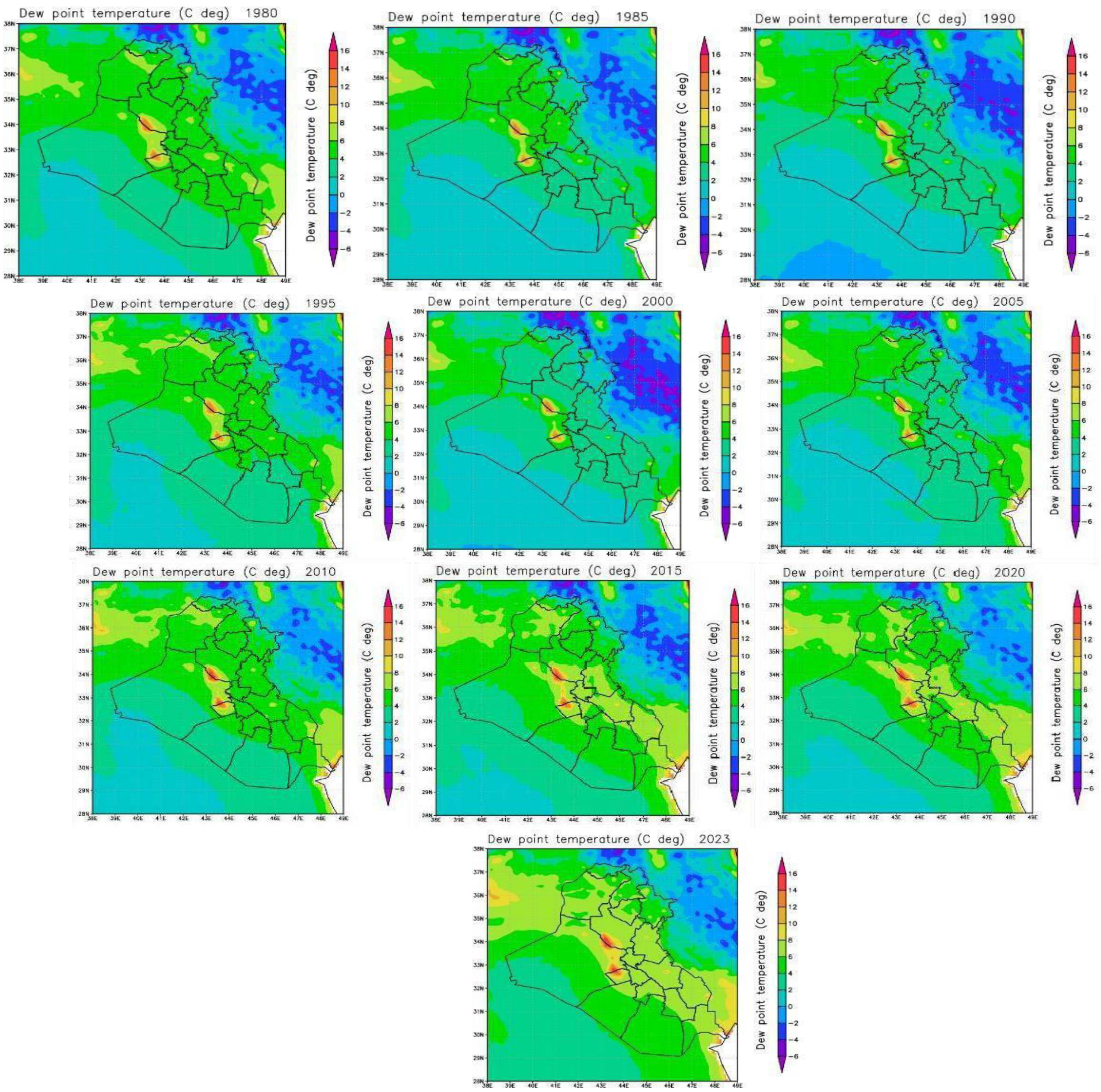

Figure 7: Overall dew point in Iraq for the chosen year.

CONCLUSIONS

The findings of this study provide important insights into the spatiotemporal variations of wind speed, relative humidity, and dew point temperature across Iraq. The analysis revealed that wind patterns are generally consistent throughout the country, with only localized variations, indicating favourable conditions for wind energy development and a potential contribution to improving the urban microclimate. The findings also demonstrate a gradual long-term decline in relative humidity, suggesting an increasing tendency toward drought and desertification. This trend is consistent with global reports highlighting the depletion of water resources and the growing impacts of climate change in the region. The spatial distribution maps further confirmed a general reduction in humidity over the study period, which is likely associated with rising temperatures and enhanced evaporation. If current climatic trends persist, several regions of iraq may experience increasingly dry conditions. In contrast, dew point temperature exhibited a slight upward trend, with the most pronounced increases occurring in the eastern and southeastern parts of the country, indicating localized increases in atmospheric moisture. Although the present study provides valuable evidence of the temporal and spatial patterns of these climatic variables, a more detailed analysis using high-resolution daily observations from representative locations is recommended to better quantify the relationships among wind speed, relative humidity, and dew point temperature. Such analyses would provide a deeper understanding of the interactions among these variables and improve climate assessment and environmental planning in iraq.

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