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CLIMATE CHANGE TRENDS IN THE RED RIVER DELTA

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Abstract. The Red River Delta (RRD) is one of the regions most significantly impacted by climate change (CC) in Vietnam. This study utilizes correlation assessment methods and regression equations to evaluate the trends of certain meteorological factors and extreme weather events during the period 1961 - 2020 in the RRD. Overall, climate factors across the region exhibit quite clear trends of change. The highest trends in annual average temperature and maximum annual average temperature are observed in the northwestern part of the RRD, especially in major cities such as Ha Noi (the increase in mean annual temperature ranges from 0.0317 - 0.0336 ºC/year). The lowest trends in these temperatures are found in coastal, island, and mountainous areas (the increase in mean annual temperature ranges from 0.0133 - 0.0224 ºC/year). The annual rainfall reports a decreasing trend at 17 out of 23 meteorological stations in the RRD, varying from -11 to 9 mm/year. Extreme weather phenomena report little significant change, with maximum daily rainfall records a decreasing trend, varying from -3.119 to 1.395 mm/year; the number of days with rainfall exceeding 50 mm also reports a decrease, varying from -0.058 to 0.017 days/year. The results of this study will serve as a basis for developing action plans to respond to CC in the RRD.

Keywords: climate change trends, mean annual temperature, annual rainfall, extreme weather, Red River Delta.

1. Introduction

According to the Law on Meteorology and Hydrology (2015), "CC is a change in climate over a long period due to the impact of natural conditions and human activities, manifested by global warming, rising sea levels, and increasing extreme meteorological and hydrological phenomena" [1]. Human economic and social activities have increasingly intensified greenhouse gas emissions, leading to more severe global CC [2].

According to the IPCC (2023), the global surface temperature trend during 2011 - 2020 was 1.09 ºC higher than the 1850 - 1900 period; sea levels rose by 0.15 - 0.25 m between

1901 - 2018 [3]. According to the 2022 Annual Global Climate Report, the ten warmest years in history occurred between 2010 - 2022 [4]. In Russia, the average temperature trend from 1981 - 2020 increased by 0.61 ºC/10 years, 2.5 times the global increase; annual rainfall generally increased across Russia, especially in the central parts of the Asian territory, while rainfall decreased slightly in the central and southern parts of the European territory [5]. In China, the mean annual temperature has been increasing compared to the 1961 - 1990 period, with a potential rise of 1.5 - 2.8 ºC by 2030 and 2.3 - 3.3 ºC by 2050; annual rainfall is also expected to increase by 5 - 7% by 2050 [6]. In Saudi Arabia, the mean annual temperature trend is expected to rise by approximately 0.8 - 1.6 ºC, 0.9 - 2.7 ºC, and 0.7 - 4.1 ºC during the periods of 2025 - 2044, 2045 - 2064, and 2065 - 2084, respectively, compared to the 1986 - 2005 period under the RCP8.5 scenario [7]. In Central and South America, the air temperature trend is in accordance with global warming, with an expected increase of 1 - 2 ºC by 2100 under the RCP2.6 scenario and 5 - 6 ºC under the RCP8.5 scenario [8].

According to the 2020 Climate Change Scenarios by the Ministry of Natural Resources and Environment, the mean annual temperature in Vietnam is expected to increase compared to the 1986 - 2005 period. Under the RCP4.5 scenario, by the end of the 21st century, northern temperatures are expected to rise by 1.9 - 2.4 ºC and southern temperatures by 1.5 - 1.9 ºC; while under the RCP8.5 scenario, northern temperatures may increase by 3.5 - 4.2 ºC, and southern temperatures by 3.0 - 3.5 ºC [9]. Annual rainfall is also expected to increase by 10 - 20% under the RCP4.5 scenario compared to the 1986 - 2005 period [9]. During the first half of the 21st century, a study [10] indicates that Vietnam's mean annual temperature trend has been rising by approximately 0.3 ºC/10 years, and annual rainfall has generally been increasing nationwide. In the RRD, Ha Noi, Thai Binh, and Nam Dinh are among the localities most affected by CC; between 1958 - 2014, rainfall in the RRD has been decreasing by 12.5%/57 years, while average temperatures have been notably increasing, particularly in Nam Dinh (with a 1 ºC increase between 2001 - 2014 compared to 1981 - 1990) [11]. Due to urbanization, CC impacts in Ha Noi have become more pronounced, resulting in a growing temperature difference of 1 - 2 ºC between the inner city and its vicinity [12].

CC has also intensified natural disasters. Between 1976 - 2020, both the RCP 4.5 and RCP 8.5 scenarios indicate that, in the future, from 2021 to 2050, drought in Hai Duong will increase in both frequency and intensity, with extreme droughts occurring in cycles of about 9 - 10 years [13]. Sea levels are expected to rise fairly uniformly across localities; by the end of the 21st century, sea levels along the coastal areas from Mong Cai to Hon Dau may rise by 44 cm under the RCP2.6 scenario, 52 cm under the RCP4.5 scenario, and 72 cm under the RCP8.5 scenario [9]. According to the 2020 Climate Change Scenarios, if sea levels rise by 100 cm, the RRD risks losing approximately 15% of its natural land area (about 340 thousand hectares); some localities, such as Nam Dinh (43.67%), Thai Binh (38.22%), and Hai Phong (25.06%), are projected to lose significant land [9]. The RRD is also severely impacted by saltwater intrusion; on the Day River, saltwater intrusion may extend an additional 15 km, reaching 45 km by 2030; on the Red River, it may reach 47 km, increasing by about 5 km; and on the Van Uc River, it may reach 35 km, increasing by 3-5 km. Several other rivers are also expected to experience increased saltwater intrusion [14].

CC greatly impacts human life and production activities. Rising temperatures lead to more frequent heat stress events. A study [15] reports that in Ha Noi, the ET (effective temperature index) of the hottest month has been increasing by about 0.014 ℃/year - 0.018 ℃/year, with higher ET values observed in urban Ha Noi, Ha Dong, and Son Tay, potentially causing people to feel hotter, leading to heat exhaustion and sunstroke if exposed to the sun for extended periods. Due to changes in temperature, rainfall, and humidity, a study [16] indicates that, in the context of CC, while winter tends to be milder, sudden cold snaps are increasing, facilitating the spread of influenza viruses and respiratory diseases during the cold season.

According to Resolution No. 81/2023/QH15 "On the National Master Plan for the period 2021 - 2030 with a vision to 2050", Viet Nam currently has six economic regions, including the RRD, which comprises 11 provinces and cities [17]. The RRD is and will continue to be the nation's leading economic region, which is densely populated; and heavily impacted by CC. Researching the trends of meteorological factors and phenomena in the RRD is of practical significance as a basis for developing CC response strategies in the locality.

2. Content

2.1. Study area, data, and research methods

2.1.1. Study area

The RRD is located between the Northern Midlands and Mountainous Region to the north and west, the North Central Region to the southwest, and the East Sea to the east and southeast. The RRD comprises 11 provinces and cities: Ha Noi, Hai Phong, Hai Duong, Hung Yen, Vinh Phuc, Bac Ninh, Thai Binh, Nam Dinh, Ha Nam, Ninh Binh, and Quang Ninh. The area of the RRD is 21,278.6 km², accounting for about 6.4% of the country's total area. The terrain consists of a triangular-shaped delta with its apex at Viet Tri (Phu Tho) and its base along the coastline from Hai Phong to Ninh Binh, as well as the Quang Ninh region to the northeast. The RRD has a tropical monsoon climate. The mean annual temperature is about 23 - 25 ℃, with an annual temperature amplitude of 9 - 12 ℃. The annual rainfall in the RRD ranges from 1,400 - 2,000 mm. Rainfall is seasonal, with the rainy season from May to September or October accounting for 75 - 85% of the annual rainfall, and the dry season from November to April of the following year.

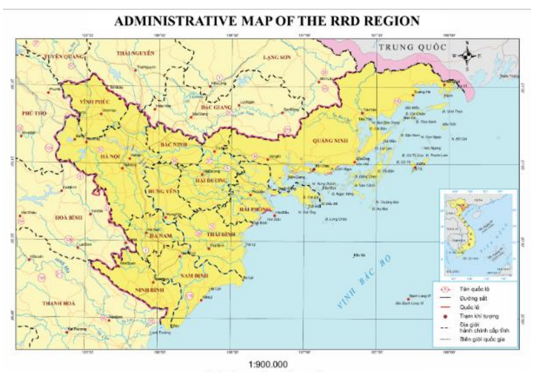

Figure 1. Administrative map of the RRD

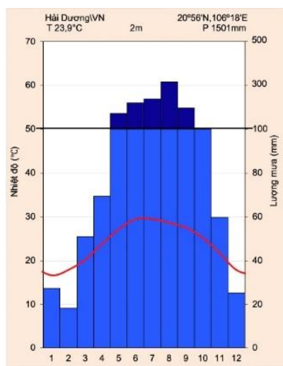

Figure 2. Climatic chart at the Hai Duong weather station

As of 2022, the population of the RRD reached 23,454.1 thousand people, making it the most populous region in Vietnam. The RRD has the highest population density among the six economic regions, reaching 1,102 people/km² (in 2022), 3.7 times the national average figure [18]. The RRD has 7 out of 11 provinces and cities within the planning of the Northern Key Economic Region, with an economy ranking second in size nationwide, reaching 2.37 trillion VND in 2020, accounting for 29.4% of the country's GDP structure [19].

2.1.2. Research Data

This study uses meteorological data series, including factors such as mean annual temperature, annual rainfall, rainfall during the three driest months, number of rainy days, maximum annual average temperature, maximum daily rainfall, and number of days with rainfall exceeding 50 mm during the period 1961 - 2020. Data was collected from 23 meteorological stations in the RRD (Ba Vi, Bach Long Vi, Bai Chay, Co To, Cua Ong, Ha Dong, Ha Nam, Hai Duong, Hon Dau, Hung Yen, Lang, Mong Cai, Nam Dinh, Nho Quan, Ninh Binh, Phu Lien, Quang Ha, Son Tay, Tam Dao, Thai Binh, Tien Yen, Uong Bi, Van Ly) and 20 surrounding stations (Dinh Lap, Son Dong, Luc Ngan, Lang Son, Huu Lung, Bac Giang, Hiep Hoa, Thai Nguyen, Tuyen Quang, Phu Ho, Viet Tri, Minh Dai, Hoa Binh, Kim Boi, Mai Chau, Lac Son, Chi Ne, Hoi Xuan, Yen Dinh, Bai Thuong).

2.1.3. Key research methods

**** Correlation assessment method***

To determine the trend of certain climate factors Y, it is necessary to test whether the climate factor exhibits a trend and establish the trend equation. The correlation between the meteorological factor y and time t (in this study, time is the independent variable) is tested using the following formula [20]:

$$r = \frac{\overline{y * t} - \bar{y} * \bar{t}}{\sqrt{\overline{y^2} - (\bar{y})^2} * \sqrt{\overline{t^2} - (\bar{t})^2}}$$

where y is the climate factor, t is time, and r is the correlation coefficient. The correlation degree of r is specified as follows:

- If $r < 0.5$, the correlation degree is weak;
- If $0.5 \le r < 0.7$, the correlation degree is moderate;
- If $0.7 \le r < 0.9$, the correlation degree is relatively strong;
- When $0.9 \le r < 1$, the correlation degree is strong;
- If $r = 1$, the correlation is perfect.

**** Regression equation method***

The regression equation and trend line will have significance if, after testing, the correlation degree is relatively strong or higher ($r > 0.7$ or $r^2 > 0.5$). From there, the regression equation is established to calculate the trend of factor y over time. The trend of the study object over time is expressed by a linear regression equation as follows [20]:

$$y_t = at + b$$

Where y is the climate factor, t is time, $a = \frac{\overline{y * t} - \bar{y} * \bar{t}}{\overline{t^2} - (\bar{t})^2}$ and $b = \bar{y} - a\bar{t}$

**** Inverse distance weighting (IDW) interpolation method***

This method was used to create a map of the change in mean annual temperature and maximum annual average temperature in the RRD. In the interpolation process, sample points are weighted so that the influence of one point over another decreases with distance from the unknown point. The weight of each point is calculated using the following formula [21]:

$$Z_0 = \frac{\sum_{i=1}^{N} Z_i \,.\, d_i^{-n}}{\sum_{i=1}^{N} d_i^{-n}}$$

Where Z_i is the value at a known point, d_i is the distance to the unknown point, Z_0 is the value at the unknown point, N is the total number of sample points, and n is the exponent value.

2.2. Research results

2.2.1. Trends in meteorological factors

The trend of mean annual temperature

During the period 1961 - 2020, the mean annual temperature in the RRD records an increasing trend, ranging from 0.013 to 0.034 ºC/year. At the Ha Dong meteorological station, the trend averaged 0.034 ºC/year, 1.66 times the average trend of the entire region and 2.32 times that of the Phu Lien station in Hai Phong (0.015 ºC/year).

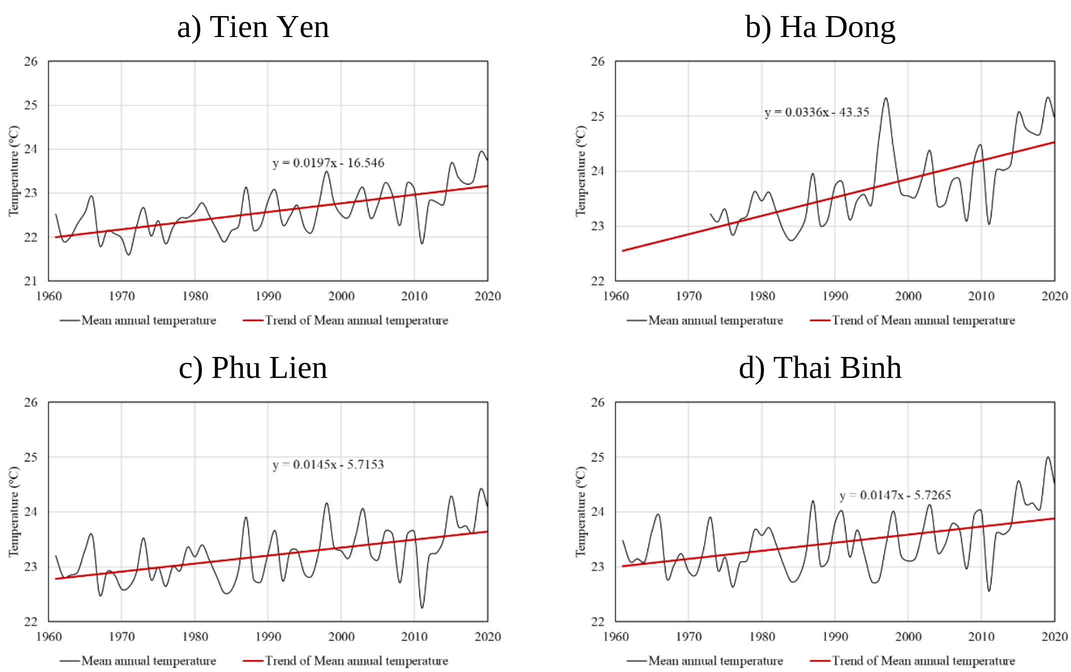

Figure 3. Long-term variation and trend of the mean annual temperature changes from 1961 to 2020 in the RRD

According to the spatial distribution, the average annual temperature tends to decrease gradually towards the west and east of Ha Noi. In the eastern part, the trend of decreasing average annual temperature is slower compared to the western part.

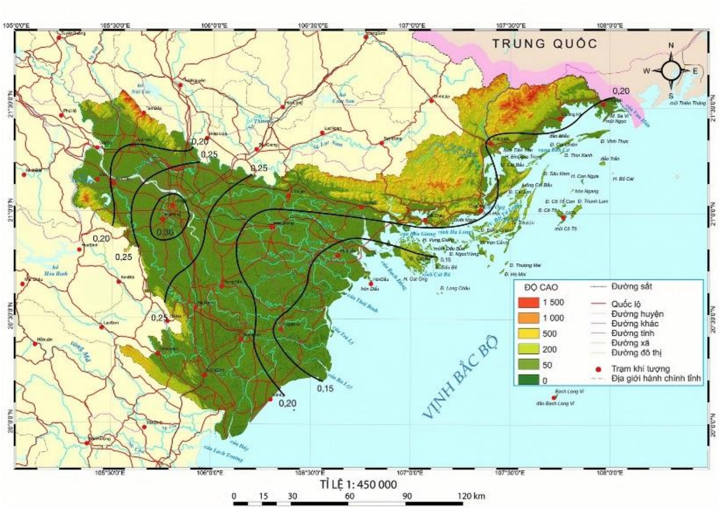

Figure 4. Map of the trend in mean annual temperature changes (ºC/decade) in the RRD from 1961 to 2020

Trend of Maximum annual average temperature

During the period 1961 - 2020, all 23 meteorological stations in the RRD report an increasing trend in maximum annual average temperature, ranging from 0.010 ºC/year to 0.049 ºC/year.

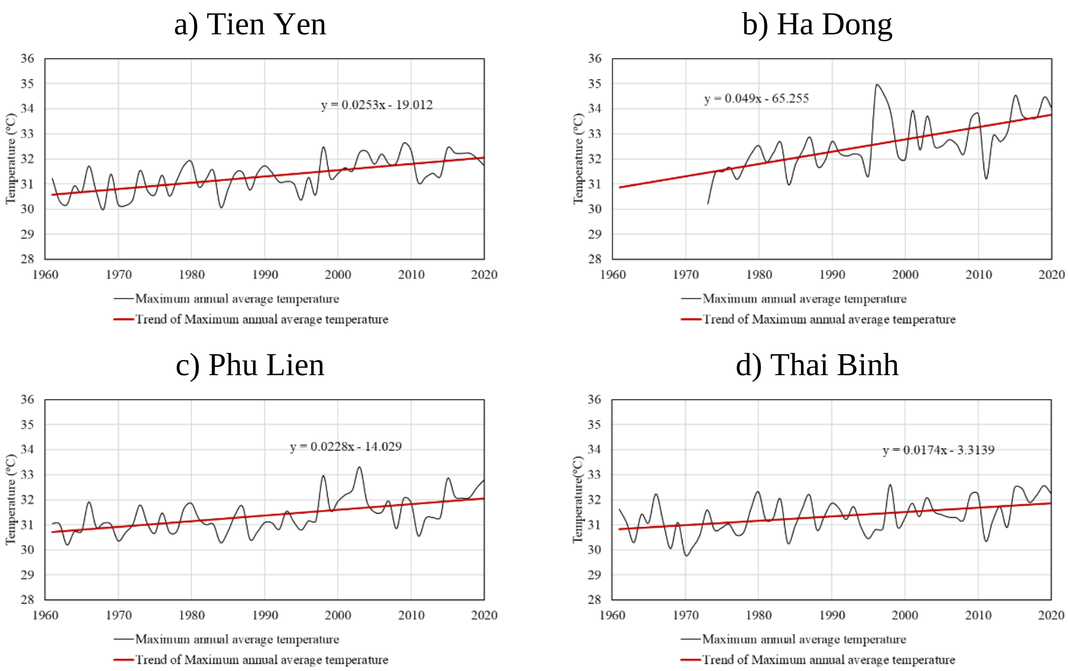

Figure 5. Long-term variation and trend of the maximum annual average temperature changes from 1961 to 2020 in the RRD

The average annual maximum temperature shows a clear spatial variation similar to the trend in average annual temperature - the trend of increasing average maximum temperature decreases gradually towards both the west and east of Ha Noi.

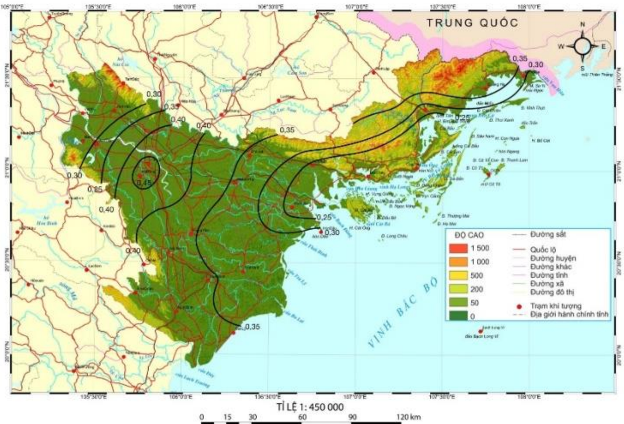

Figure 6. Map of the trend in maximum annual average temperature changes (ºC/decade) in the RRD from 1961 to 2020

Trend of annual rainfall

During the period 1961 - 2020, the annual rainfall across the RRD shows a decreasing trend, varying between -11 mm/year (at Ba Vi station) and 9 mm/year (at Quang Ha station). Spatially, the annual rainfall trend in the RRD correlates with the trend of mean annual temperature. Notably, in the northeast coastal strip of the region, rainfall at several stations records a significant increase during the period 1961 - 2020.

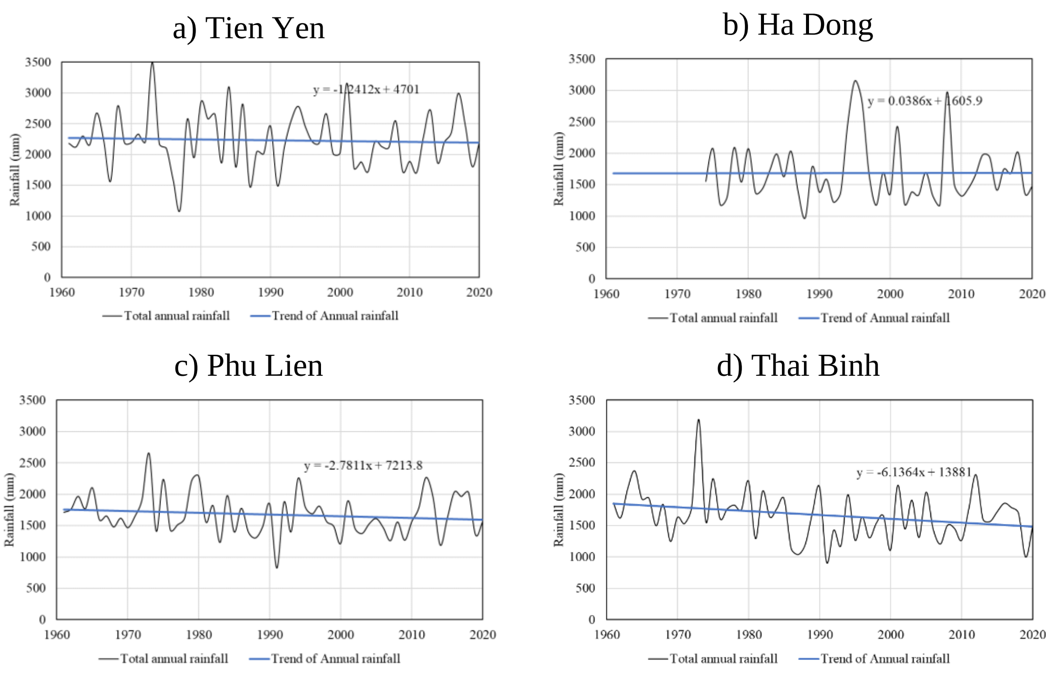

Figure 7. Long-term variation and trend of the annual rainfall changes from 1961 to 2020 in the RRD

The trend of rainfall in the three driest months

Contrary to the decreasing trend of annual rainfall across the RRD during 1961 - 2020, the rainfall in the three driest months reports a slight increase at most meteorological stations, varying from -0.150 to 1.154 mm/year.

The average annual maximum temperature shows a clear spatial variation similar to the trend in average annual temperature - the trend of increasing average maximum temperature decreases gradually towards both the west and east of Ha Noi.

The trend of rainy days

During the period 1961 - 2020, the number of rainy days in the RRD generally records a slight increasing trend, varying from -0.134 to 0.566 days/year. Spatially, the trend of rainy days increases the slowest in the central plain and more rapidly towards the east and west of the RRD.

2.2.2. Trend of extreme weather phenomena

The trend of maximum daily rainfall

The general trend of maximum daily rainfall in the RRD records a decrease over the years, averaging 4.61 mm/year. Spatially, this trend is similar to the trend in annual rainfall.

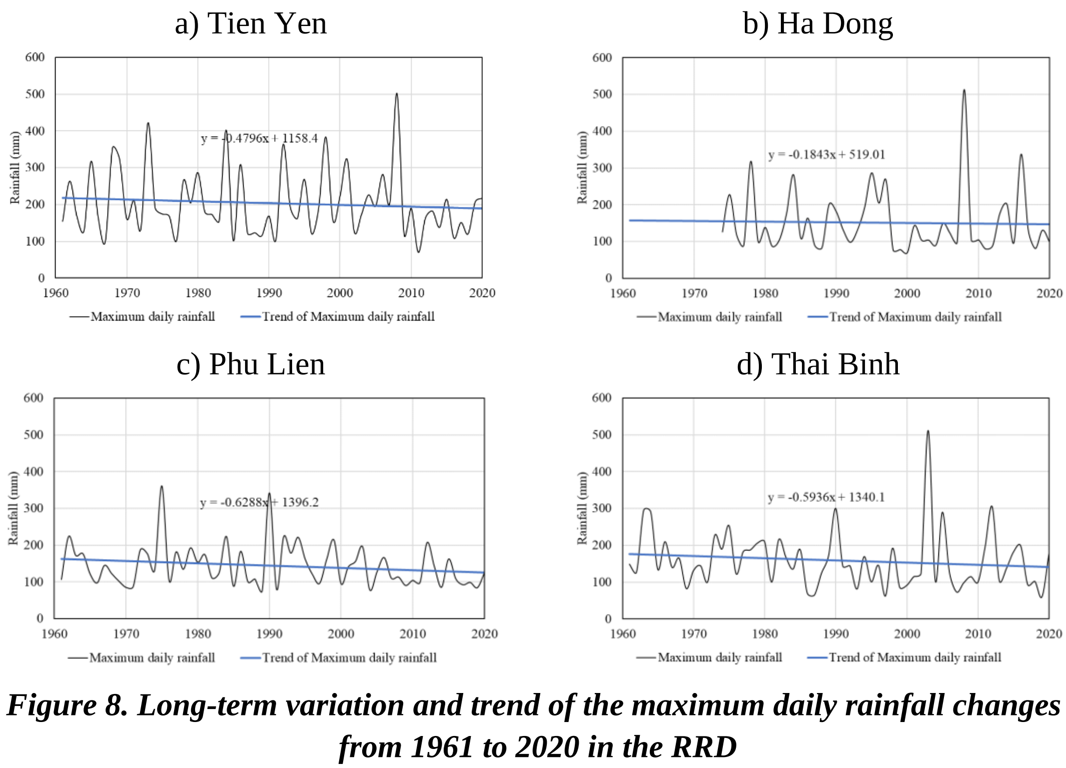

Figure 8. Long-term variation and trend of the maximum daily rainfall changes from 1961 to 2020 in the RRD

Trend of the Number of days with rainfall exceeding 50 mm

During the period 1961 - 2020, the number of days with rainfall exceeding 50 mm in the RRD reports no significant change, decreasing by an average of 0.008 days/year. This trend tends to increase in the eastern coastal areas and the western hilly regions, while the rest of the RRD records a decreasing trend.

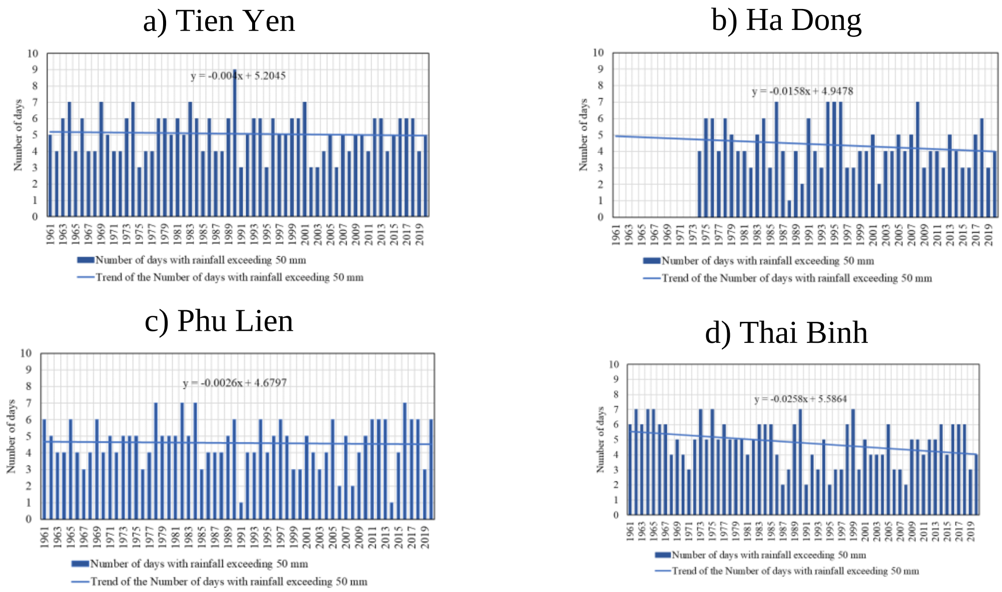

Figure 9. Long-term variation and trend of the number of days with rainfall exceeding 50 mm changes from 1961 to 2020 in the RRD

2.3. Discussion

The study reports that the trend of CC in the RRD aligns with the general global climate change trends, although there are varying changes of degrees between areas. The highest trends in mean annual temperatures and maximum annual average temperatures are observed in Ha Noi (at the Ha Dong station, 0.0336 ºC/year and 0.049 ºC/year, respectively; at the Lang station, 0.0317 ºC/year and 0.0455 ºC/year, respectively), and decrease towards the east and west of the region. This is mainly because Ha Noi is the most developed locality in terms of economy and is a major economic, political, and cultural center of the country, with significant industrial production, high population density, and a high degree of urbanization. Climate factors and phenomena show a faster-decreasing trend towards the west compared to the east, primarily due to the topography, where the western region is mostly composed of low-lying hills and midlands with greater elevation changes, while the eastern region is mainly flat coastal land with less topographical variation. The coastal and island regions of the RRD exhibit the lowest trends in mean annual temperatures and maximum annual average temperatures (at Co To station, 0.0133 ºC/year and 0.0251 ºC/year, respectively; at Phu Lien station, 0.0145 ºC/year and 0.0228 ºC/year, respectively), primarily due to limited industrial development and lower levels of urbanization. For the trend of rainfall and certain extreme weather phenomena, spatial differentiation is not evident, but there is a significant temporal variation.

CC in the RRD has a considerable impact on all sectors. As mean annual temperatures rise, while rainfall shows little variation, evaporation trends increase, leading to more severe drought conditions in the RRD. Drought has significantly impacted natural ecosystems and production activities, especially agriculture in the RRD. CC in the RRD has increased the frequency and intensity of natural disasters. The rising trend in maximum annual average temperatures leads to an increased risk of heat stress and a rise in diseases, significantly affecting public health.

The RRD needs to develop CC response solutions based on its existing advantages, particularly focusing on mechanisms and policies (developing renewable energy, participating in the carbon credit market, etc.); promoting science and technology solutions; and enhancing education and awareness about CC.

3. Conclusions

In the RRD, the trend of climate change is quite evident through the changing trends of climate factors and phenomena. The trend of mean annual temperatures increases by 0.013 to 0.034 ºC/year, with a decreasing trend towards the outskirts of Ha Noi. The trend of annual rainfall generally records a decrease, ranging from -11 to 9 mm/year; spatially, the trend of annual rainfall is similar to the trend of mean annual temperatures. In the RRD, the most prominent manifestation of CC is through temperature factors, where rising temperatures correspond to global warming. The changing trend of annual rainfall is also consistent with the temperature trend. Therefore, CC manifestations through these two main meteorological factors are quite clear in the RRD.

Certain extreme weather phenomena studied in this research, including maximum annual average temperatures, maximum daily rainfall, and the number of days with rainfall exceeding 50 mm, have shown variations over the study period, though trends differ across stations. The trend of maximum annual average temperature reports a significant increase at all meteorological stations in the RRD, varying from 0.010 ºC/year to 0.049 ºC/year, leading to severe consequences such as increased drought, heat stress, and related diseases. Other factors show trends but are not as significant.

To proactively and effectively respond to CC in the RRD in the future, it is necessary to strengthen regional linkages, enhance cooperation between provinces and cities in the RRD, and develop appropriate and effective action plans in response to CC. Emphasis should be placed on education, enhancing the capacity and awareness of management personnel regarding CC, and focusing on communication and outreach about CC issues. It is also crucial to increase scientific research activities on CC at the local level and across the RRD.

The research results of this study will serve as a reference for local authorities and relevant agencies to devise CC response strategies in the RRD and to develop sustainable development strategies for the locality in the background of increasing global CC.

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