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Managing Green and Sustainable Technologies: Climate-Informed Corrosion Prediction for Steel Structures

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Abstract

The unpredictability of atmospheric circumstances is one of the major elements that contribute to the capability to anticipate the corrosion growth in metal structures over time accurately. Climate shifts can potentially modify the long-term attributes of these factors throughout the operational life of metal structures, both those currently in existence and those newly developed. The impact of climate irregularity on the probabilistic nature of atmospheric variables, which significantly impact corrosion situations, can add intricacy to corrosion predictions in these constructions. This project presents an incorporated framework to quantify the impact of climate alteration on the corrosion rates of steel structures in Jordan. It considers the changes in environmental conditions, specifically temperature, relative humidity, and wind speed, and their impacts on atmospheric corrosion. Global Climate Models are employed to assess the long-term effects of climate transformation on these environmental circumstances. An analytical model for anticipating corrosion rate is integrated with climate transformation models to predict modifications in the corrosion rates of steel parts relative to historical situations. This project also examines the impact of climate transformation on the fluctuations of these climatic parameters and offers a contrast between historical data and projected conditions across the country. The findings indicate a significant increase in corrosion rates across Jordan, which calls for localized green building codes and standards to ensure that future infrastructure is sustainable and capable of withstanding the new climatic norms. This approach addresses the immediate challenges posed by climate change and contributes to the broader goals of sustainable urban development and managing green technology adoption in Jordan.

Keywords: Steel Corrosion; Global Climate Change; Humidity Change; Temperature Change; Wind Speed Change.

1. Introduction

Civil and marine constructions face an array of mechanical and environmental failure mechanisms over their operational lifespans. Some of these can precipitate sudden structural collapses through yielding or buckling, while others induce insidious deterioration, such as corrosion. Thus, developing robust analytical techniques to bolster structural resilience against extreme and progressive events and to extend the service life of aging assets is imperative. Steel, renowned for its adaptability and durability, is fundamental in many applications, including infrastructure, industrial machinery, and equipment. However, steel degradation due to atmospheric corrosion in coastal, terrestrial, or polluted industrial settings has become an urgent global issue. Steel deterioration poses significant environmental,

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safety, and financial risks. A zinc coating is often applied to structural steel surfaces to mitigate this deterioration and protect steel from corrosion. Remarkably, the zinc coating industry consumes half of the world's zinc production, specifically for steel construction [1].

Several factors influence the pace and severity of atmospheric corrosion on steel structures, including environmental conditions such as humidity, temperature, rainfall, and salinity; atmospheric pollutants like sulfur dioxide, chlorides, and nitrogen oxides; and exposure settings ranging from urban to rural and industrial areas [2, 3]. Traditional structural steel design and evaluation approaches often assume that historical atmospheric data will represent future conditions [4]. However, climate change is poised to alter the frequency and severity of average and extreme weather events, rendering historical records insufficient for future projections [5]. This necessitates a paradigm shift in how we approach the durability and resilience of steel structures in an era of unprecedented climatic variability.

Unfavorable climate change is linked to steadily climbing global temperatures and sea levels, resulting in more frequent, intense, extensive, and prolonged extreme weather events across the planet. Events such as heat waves, fierce storms, heavy downpours, and floods can significantly impact infrastructure and buildings' safety and service life. Similarly, changes in pollutant concentrations and climatic parameters such as temperature, relative humidity, precipitation, and wind patterns can have comparable effects. Recent comparisons between current climate trends and historical norms have revealed significant disparities in various climatic factors, including temperature, relative humidity, precipitation, and wind speeds across different global regions [6]. These environmental shifts can accelerate the rate of corrosion in steel construction.

Civil and marine structures are continually exposed to various mechanical and environmental stressors that compromise their integrity and longevity. Particularly, the corrosion of steel structures poses significant challenges due to its pervasive nature and the substantial safety, environmental, and economic implications associated with it. The acceleration of corrosion processes due to changing climatic conditions, such as increased temperatures, humidity, and altered wind patterns, further exacerbates these challenges. Understanding and predicting the impact of climate change on corrosion rates is critical for developing strategies to enhance the resilience and service life of infrastructural assets.

This study seeks to address several pressing research questions to better understand and mitigate the impact of climate change on structural degradation. Key inquiries include examining how projected changes in temperature, humidity, and wind speed influence the rate of atmospheric corrosion of steel structures. The role of Global Climate Models (GCMs) in predicting future environmental conditions and their impact on corrosion processes is also critical. Additionally, the study aims to explore how current corrosion prediction models can be adapted to incorporate the effects of changing climatic conditions to provide more accurate forecasts. A comparative analysis of historical corrosion data versus future projections will be conducted to understand the implications for structural maintenance and design standards, ensuring that these standards evolve to meet future environmental challenges.

While existing research has extensively documented the general effects of climate change on environmental conditions, there is a significant gap in localized studies that link these changes directly to the corrosion rates of steel structures. Most studies focus globally or on broader regional impacts without addressing specific local environments, which may experience significantly different climatic changes. Furthermore, the integration of advanced climate modeling with corrosion prediction methodologies remains underexplored. Current literature often relies on historical data to predict future conditions, a method increasingly inadequate due to the rapid pace of climatic changes and their non-linear impacts on corrosion processes.

This research proposes to narrow these gaps by integrating state-of-the-art GCMs with corrosion prediction analytics to develop a more dynamic and predictive framework for assessing the corrosion rates of steel structures under future climatic scenarios. By focusing on the specific variables of temperature, humidity, and wind speed, which are critical to corrosion processes, and comparing these with historical data, this study aims to provide a detailed analysis of expected changes and their implications. The use of localized data further refines the predictions and makes them more applicable to specific regions, thus enabling targeted and effective mitigation strategies. This approach not only enhances the understanding of corrosion processes under future climates but also contributes to the development of more resilient infrastructure systems, aligning with broader sustainability and safety goals.

This paper significantly contributes to the field of civil engineering and climate resilience by providing a detailed analytical framework to predict the impact of climate change on the corrosion rates of steel structures in Jordan. It merges climatic data from GCMs with corrosion prediction models to offer a comprehensive understanding of how changing environmental factors—specifically temperature, humidity, and wind speed—affect steel corrosion over time. This work not only enhances our ability to predict and mitigate the risks associated with the long-term deterioration of steel infrastructures under climate change scenarios but also aids in the formulation of localized building codes and standards. By incorporating projected climatic impacts into structural planning and maintenance, the paper supports more sustainable infrastructure development and helps prepare for the increasing challenges posed by global climate change.

2. Literature Review

GCMs are crucial for simulating atmospheric conditions and forecasting future climatic variations. GCMs are computational representations of the atmosphere, sea ice, land surfaces, and oceans, integrating the global climate system's physical, biological, and chemical aspects [7]. These models predict long-term trends in precipitation, temperature, and wind patterns. GCMs have been applied in numerous fields, including predicting long-term flooding [8], evaluating bridge vulnerability [9, 10], and conducting land use studies [11].

While many studies have explored the impacts of climate change on temperature, humidity, and wind patterns globally, less is known about how these climatic shifts influence corrosion at a local level. According to the fundamental Arrhenius equation, which relates reaction rates to environmental conditions, warming is expected to accelerate the breakdown of materials. Empirically, it has been observed that each 10-degree Celsius increase in temperature tends to roughly double corrosion rates across various settings [12]. Climate data reveals that temperatures have risen approximately 0.09 degrees per decade since 1880, but this rate has more than doubled since 1981 to 0.18 degrees per decade [13]. A seminal U.S. report on 21st-century projections indicates that if emissions continue unabated, warming could reach 2.8 to over 5.7 degrees above early 20th-century norms by 2100. However, curbing annual emissions to decline by 2050 significantly could stabilize the temperature increase between 1.3 to 3.3 degrees compared to preindustrial levels, thereby mitigating the impacts. This nuanced understanding underscores the critical need for localized studies to effectively predict and manage corrosion rates under varying climatic scenarios.

Indeed, relative humidity also significantly influences the atmospheric corrosion process among climatic parameters. Projections of heightened emission levels under climate change predict increases in humidity, as warmer air can hold more moisture [14]. Several investigative efforts have evidenced that corrosion rates rise alongside relative humidity [15-17]. For example, a notable acceleration of magnesium alloy deterioration was observed when humidity escalated from 75 to 95% [15]. Other examinations [16, 18] signaled that corrosion similarly amplified following an exponential curve as moisture soared from 53% to 92% or 40% to 90%. Wind velocity also substantially impacts calculated corrosion severity since aerosol salinity primarily originates from surf activities commonly governed by wind forces [19]. The consequences of climate change on wind patterns vary across locations, with some regions experiencing increased wind speeds while others retain relative stability.

Recent studies have emphasized the rising challenges posed by climate change on structural materials, particularly steel, due to the increasing frequency and intensity of extreme weather events and shifting climatic patterns. For instance, Zhang et al. (2022) [20] explored the projections of corrosion and deterioration of infrastructure in United States coasts under a changing climate, highlighting the necessity for updated predictive models to account for climate-induced variations in corrosion rates. Similarly, Xu & Yang. (2023) [21] investigated the impact of climate change on the long-term regional corrosion risks of steel bridges, providing insights into the adaptation of infrastructure to new climatic conditions. Another significant study by Soliman & Frangopol (2015) [22] focused on the life-cycle cost evaluation of corrosion-resistant steel, demonstrating the economic benefits of using advanced materials in mitigating climate impacts. These advancements underscore the critical need to incorporate dynamic climatic factors into corrosion prediction frameworks.

Moreover, research by Abtahi et al. (2023) [23] emphasized the importance of accurate parameter estimation for corrosion models in reinforced concrete structures under seismic and environmental stress, which can be extrapolated to steel structures as well. Additionally, Wu (2024) [24] developed predictive artificial neural networks models for assessing the performance of pervious concrete pavement under climate change conditions, which is crucial for sustainable construction practices. These contemporary insights align with our research objective to develop an integrated framework for predicting steel corrosion under evolving climatic conditions, ensuring the resilience and sustainability of future infrastructure in the region.

Despite considerable research aimed at quantifying climate change's impacts on the atmospheric corrosion of steel reinforcement in concrete structures and variations in climatic parameters [25-27], a clear understanding gap remains regarding how climate change affects the corrosion rates of exposed steel structures. Building on the recent advancements in understanding regional and material-specific corrosion risks, this work presents an innovative forecasting approach for the atmospheric corrosion of steel structures under climate change. This approach considers the impacts of temperature, humidity, and wind speed on corrosion resulting from environmental changes, thereby addressing the identified research gap and providing a comprehensive framework for future studies. An analytical corrosion rate prediction model is used in conjunction with climate change models to project changes in the corrosion rates of steel components. This research also discusses variations in climatic parameters due to climate change and compares Jordan's historical data and projected conditions. Global Climate Models (GCMs) are employed to quantify the effect of climate change on these parameters. Various model types and levels of greenhouse gas emissions are utilized to establish multiple scenarios forecasting future temperature, humidity, and wind speed.

3. Research Methodology

Our methodology follows a structured approach, starting with the collection and analysis of historical climate data to establish a baseline for atmospheric conditions, including temperature, relative humidity, and wind speed. This baseline data is then used to calibrate the climate models, ensuring their accuracy in reflecting historical weather patterns. Next, we incorporate the outputs from the CMIP5 models, which include over 50 distinct general circulation models capable of simulating a range of climate-related parameters. These models are used to project future climate conditions based on different Representative Concentration Pathways (RCPs) scenarios—RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5—each representing different levels of greenhouse gas emissions by the year 2100. To account for internal variability in the climate system, we apply differing initial conditions, resulting in multiple output sets for each global climate model and scenario. This approach allows us to evaluate the influences of model types, greenhouse gas trajectories, and natural fluctuations on the projected climate conditions. The next step involves calculating corrosion rates using the derived climate variables—temperature, relative humidity, and wind speed—both from historical data and future projections. We employ diverse general circulation models, ensembles, and RCPs to encompass the inherent uncertainties in the climate forecasting process. Finally, we apply these calculated corrosion rates to our case study, focusing on the country of Jordan. This allows us to compare historical corrosion data with future projections, highlighting any significant differences and their implications for structural maintenance and design standards. By detailing each step of our research approach in a sequential format, we ensure that our methods are reproducible and clear to our readers, providing a comprehensive understanding of how climate change impacts structural degradation.

3.1. Global Climate Model

The substantial increase in greenhouse gas emissions has prompted significant climatic changes [28]. These changes immediately impact several atmospheric and oceanic conditions, such as rising sea levels, increased global temperatures, shifts in relative humidity, and variations in rainfall patterns and wind velocities [29, 30]. Recent studies have focused on developing models and methodologies to better understand the anticipated impacts of climate change on the global atmosphere. Within this context, the Coupled Model Intercomparison Project Phase 5 (CMIP5) introduces numerous global climate simulations predicting the consequences of climate change both in the near future (up to 2035) and the long term (up to 2100). These models are typically calibrated by aligning their forecasts with historical short-term weather records [31].

The CMIP5 archive includes over 50 distinct general circulation models capable of simulating a range of climate-related parameters. To project potential future climate conditions, a set of radiative forcing scenarios are established, relating to anticipated greenhouse gas emissions by 2100. The CMIP5 models produced their climate output data using the radiative forcing scenarios proposed by the Intergovernmental Panel on Climate Change (IPCC) [28]. These scenarios, known as Representative Concentration Pathways (RCPs), include RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5. The numerical values in the RCPs represent anticipated levels of radiative forcing in watts per square meter by the end of the century. Variability intrinsic to Earth's climate, independent of radiative factors, is termed internal variability [32]. To account for this, differing initial conditions were applied, yielding multiple output sets for each global climate model and scenario. Accurately representing uncertainties necessitates evaluating the influences of model types, greenhouse gas trajectories, and natural fluctuations. Therefore, to comprehensively address doubts affecting corrosion projections, various ensembles were formed by merging different models, pathways, and starting points.

In this study, key atmospheric parameters—temperature, relative humidity, and wind speed—were derived from global models and historical data. These climate variables were then applied to calculate past and future corrosion rates. Diverse general circulation models, ensembles, and RCPs were employed to encompass inherent uncertainties in the climate forecasting process. The case study for this analysis focused on the country of Jordan.

3.2. Corrosion of Steel Structures

Atmospheric corrosion of structural steel is a prominent topic that has attracted significant research efforts to investigate. Steel is a commonly utilized material in construction practices. Thus, its degradation due to corrosion necessitates extensive studies in locations where exposure to harsh climate conditions is anticipated. Both experimental testing and field monitoring research yielded various equations that model long-term atmospheric corrosion processes [33-38]. The following equation expresses one such model:

$$c_{atm} = c_0 t^n \tag{1}$$

where c_{atm} is the depth of atmospheric corrosion (μm) after t years in service, c_0 is the depth of corrosion at t = 1 year (μm), t is the number of years in service, and n is a power factor <1.0. Following the same description as Nguyen et al. (2013b) [1], c_0 is referred herein as the "corrosion rate parameter". Several research efforts have been focused on determining the corrosion rate parameter (c_0) and the power factor (n) through short-term and long-term testing. For carbon steel, a specific exponent value of power factor (n) 0.623 is advocated [34-37, 39]. Generally, the factors governing the corrosion rate parameter (c_0) are diverse in their complexity and influence. Foremost, the surface wetness time estimates the annual percentage wherein the steel is encapsulated by moisture as environmental humidity exceeds eighty percent and temperature rises above freezing. Additionally, airborne salinity is quantified through chloride concentration in the atmosphere. Furthermore, airborne pollution measured by airborne sulfide levels is a significant factor. The interplay of these intricately interconnected elements collaboratively constructs the corrosion landscape confronted by structural steel. In summary, a multifaceted approach is necessary to fully portray the dynamics dictating the CRP, incorporating the wetness time's role in facilitating corrosive reactions and surrounding salinity and pollution as aggressive outsiders perturbing the normally protective air-steel interface.

3.2.1. Effect of Relative Humidity

Regardless of the time of surface wetness, the increase in relative humidity (RH) is expected to increase the size of surface aerosols, thus increasing salt deposits. This issue is mainly a concern in the marine environment [38, 40-45]. Thus, increased RH is expected to greatly affect the corrosion rate (e.g., structural steel in reinforced concrete structures [46, 47].

3.2.2. Effect of Temperature

Even though atmospheric corrosion is fundamentally an electrochemical process, it is hypothesized in this study that the corrosion rate is influenced by ambient temperature following the Arrhenius law

$$c_0 = \alpha e^{-E_a/RK} \tag{2}$$

where c_0 is corrosion rate parameter, α is a frequency factor, K is the absolute temperature (kelvin), E_a is the activation energy, and R is the Boltzmann gas constant (R = 8.31 J.K^{-1}.mol^{-1}). In light of the Arrhenius equation, the ambient temperature is suggested to have a major effect on the corrosion rate [48]. The general rule elaborates that a 10°C increase in temperature will result in twice the corrosion rate when the temperature is within 20-30°C [12]. It is important to highlight that some research efforts suggested that the temperature change has a secondary effect on corrosion rate in laboratory and field conditions [36, 38, 39, 45, 48-50] however since the surface wetness has a cyclic nature (i.e., in daytime, the RH decreases and the temperature increases, while in nighttime, the RH increases and the temperature decreases), it is believed that the temperature effect is major when combined with the RH and thus is considered herein, this is supported by the finding that an increase of 2 K (from 293 to 295 K) is expected to increase the rate of corrosion by 0.6% [50].

3.2.3. Effect of Wind Speed

The effect of wind speed is characterized by airborne salinity [42, 51]. It is assumed that the air salinity comes from the action of surf, which is affected by the wind characteristics. Thus, the projected wind speed variation is considered as the third major variable. McKay et al. (1994) [52] suggested the following equation to correlate volumetric airborne salinity, $S_{air,vol}$ (μg/m^3) to mean wind speed, U (m/s):

$$\ln(S_{air,vol}) = 0.23U + 3.05 \tag{3}$$

The airborne salinity S_{air} is stated in terms of deposit on a salt candle [53] and needs to be related to the volumetric airborne salinity $S_{air,vol}$. Cole & Corrigan (2009) [54] expressed the relationship by:

$$S_{air} = \eta S_{air,vol} U A_s \tag{4}$$

where η is a deposition efficiency factor and A_s is the area of the salt candle surface that the salinity aerosol impacts on.

By using climate change projections for wind speed and by employing Equations 3 and 4, the changes in volumetric airborne salinity, $S_{air,vol}$, can be estimated.

3.2.4. Projections of Change in Steel Structures Corrosion Rate

The three key parameters previously mentioned—temperature, relative humidity (RH), and wind speed—are incorporated into the atmospheric corrosion model developed by Nguyen et al. (2013a) [19]. The climate change factor due to temperature change, C_{temp}, is defined using Equation 5:

$$C_{temp} = \frac{c_{0,T_{projected}}}{c_{0,T_{reference}}} = e^{260\left[\left(\frac{1}{T_{reference}}\right)-\left(\frac{1}{T_{projected}}\right)\right]} \tag{5}$$

where $T_{reference}$ is the absolute yearly average temperature for the years 1956 to 2006, $T_{projected}$ is the projected absolute yearly average temperature due to climate change at any year, and $c_{0,T_{reference}}$ and $c_{0,T_{projected}}$ are corrosion rate parameters at $T_{reference}$ and $T_{projected}$, respectively.

In a similar manner, the climate change factor for the surface wetness time due to the change in RH, $C_{t_{wet}}$ is defined as:

$$C_{t_{wet}} = \frac{t_{wet,projected}}{t_{wet,reference}} = \frac{a \times RH_{projected} + b}{a \times RH_{reference} + b} \tag{6}$$

where $RH_{reference}$ is the average RH for the years 1956 to 2006. $RH_{projected}$ is the projected RH due to climate change. $t_{wet,reference}$ and $t_{wet,projected}$ are the surface wetness times at $RH_{reference}$ and $RH_{projected}$, respectively.

Using Equations 3 and 4, the climate change factor, $C_{S_{air}}$ can be expressed as:

$$C_{S_{air}} = \frac{S_{air,projected}}{S_{air,reference}} = \frac{\sum_{m=1,2,\ldots 12} U_{projected,m} \exp(0.23 U_{projected,m})}{\sum_{m=1,2,\ldots 12} U_{reference,m} \exp(0.23 U_{reference,m})} \tag{7}$$

where $S_{air,projected}$ is the projected airborne salinity due to climate change and $S_{air,reference}$ is the average airborne salinity for the years 1956 to 2006. $U_{reference,m}$ is the mean wind speed for month m of the years 1956 to 2006; $U_{projected,m}$ is the projected mean wind speed for month m of the projected year under climate change. Thus, the monthly change is used to reflect the effect of yearly changes in wind speed on the airborne salinity.

Using previous equations leads to C_{rate}, thus the projected relative corrosion rate of steel is:

$$C_{rate} = C_{temp} C_{t_{wet}}^{\ 0.8} C_{S_{air}}^{\ 0.5} \tag{8}$$

The term $C_{rate,steel}$ is used to indicate a change in the corrosion rate parameter. If this term is >1.0, the corrosion rate has increased, while if this term is <1.0, the corrosion rate has decreased, all relative to the average of the year 1956 to 2006 [1, 19].

3.3. Framework for Quantifying Corrosion of Steel Structures Considering Climate Variability

This research proposes a novel methodology for anticipating atmospheric corrosion rate conditions for steel infrastructures concerning climate transformation. The suggested framework establishes the time-varying alteration in corrosion pace for steel structures under changing atmospheric climate circumstances through two interconnected modules. As depicted in Figure 1, Module I is accountable for cultivating the historical and projected future atmospheric parameters across the realm. This module splits the territory of Jordan into northern, southern, and central districts. Climatic factors like temperature, relative moisture, and wind velocity related to each section are adopted from worldwide climate designs and records. Several general circulation models, ensemble runs, and representative concentration pathways situations are utilized to account for uncertainties linked to climate expectation modeling. Module II is in charge of carrying out the corrosion analysis essential for quantifying the time-variant corrosion rate related to every Region in Jordan. An analytical model is applied jointly with climate transformation predictions to project the modification in the atmospheric corrosion rates of steel infrastructure using Equations 1 to 8.

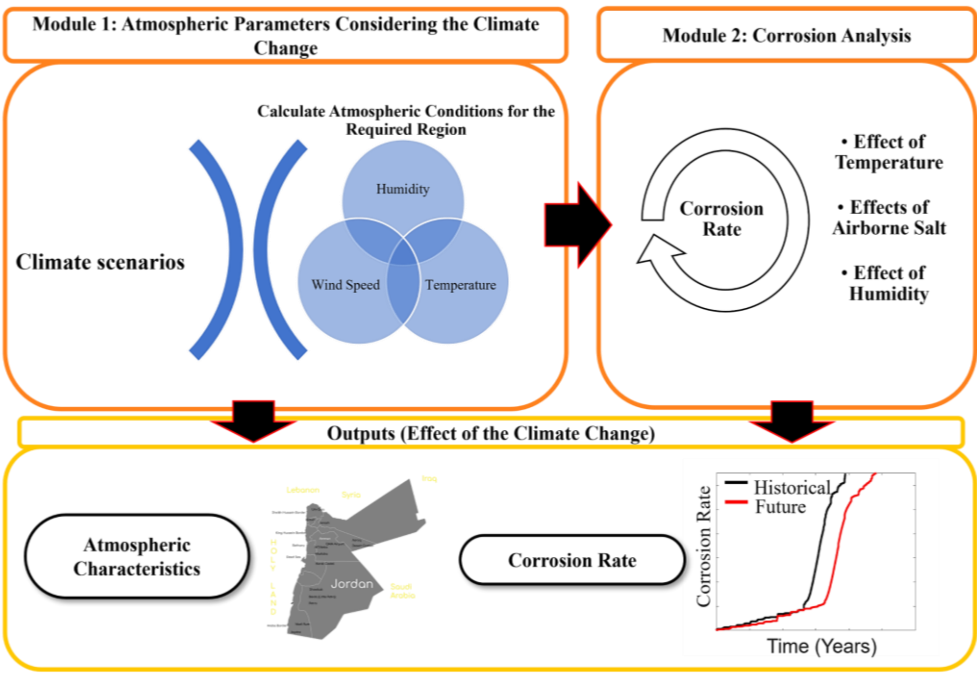


Figure 1. Schematic representation of the proposed framework

4. Results and Discussion

The novelty of this research lies in its integrated approach that combines atmospheric science with materials engineering to forecast corrosion rates under changing climate conditions. Unlike traditional models that rely on historical data presumed to represent future conditions, this paper utilizes forward-looking climate modeling to assess the future corrosive environments steel structures will face. It introduces an innovative method that factors in the variability and uncertainties of projected climatic conditions, providing a more dynamic and accurate prediction model. Furthermore, the study extends its originality by proposing the use of green technologies and intelligent monitoring systems in construction, positioning it at the forefront of sustainable and adaptive civil engineering practices. This approach not only addresses immediate corrosion challenges but also aligns with broader environmental sustainability goals by promoting the adoption of advanced, eco-friendly materials and construction techniques.

The methodology proposed was demonstrated on steel structures across all Jordan cities. Eleven municipal areas were taken into account: four municipalities in the North, namely Irbid, Ajlun, Jarash, and Mafraq; three cities in the central region, including Amman, Al-Salt, and Al-Zarqa; and four urban districts in the South, specifically Al-Tafialh, Al-Karak, Ma'an, and Al-Aqaba. These cities studied are depicted in Figure 2. Five diverse GCMs alongside RCP 8.5 greenhouse gas emission scenarios were adopted from the CMIP5 dataset [31] to project average temperature, relative humidity, and wind velocity for the predefined regions. It bears noting that models employing the RCP 8.5 forcing scenario represent more aggressive conditions than models utilizing RCP 4.5 forcing, which was considered in this study. Table 1 presents comprehensive details regarding the climate scenarios viewed as significant. Each GCM provides data with a specific spatial resolution (see Table 1). The scenarios embraced provide climatic data at monthly intervals, then projected annual averages of the climatic parameters are computed from the projected monthly averages and displayed in Figures 3 to 11. The adopted atmospheric data is then used to project climate change factors C_{temp}, $C_{t_{wet}}$, and $C_{S_{air}}$ from 2020-2100 associated with each of the defined regions, which are used ultimately to calculate the change in the atmospheric corrosion rate for the same period (using Equation 8).

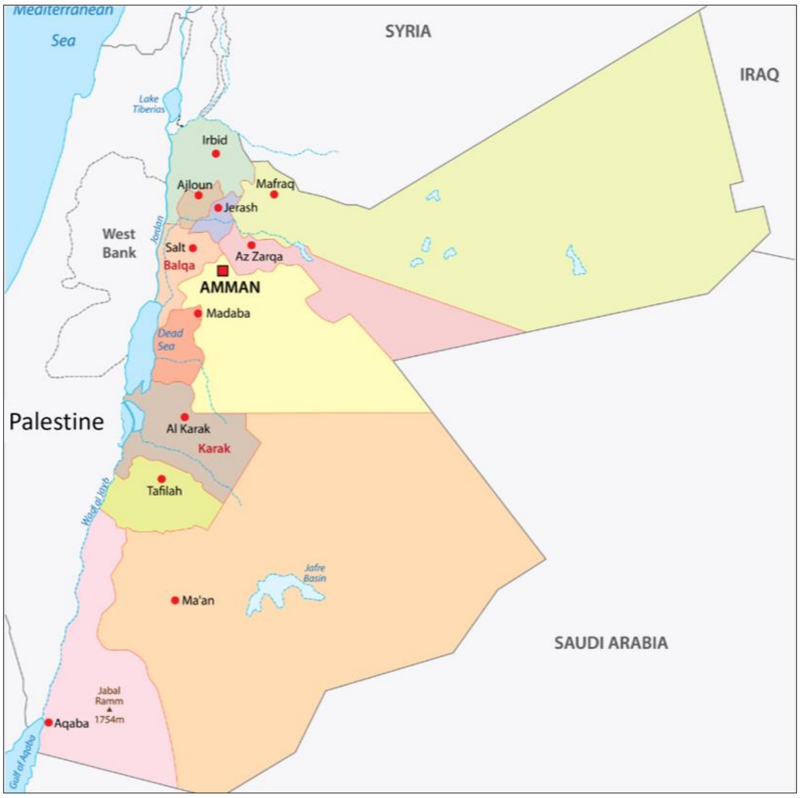


Figure 2. Geographic segmentation of Jordan into major cities

Table 1. Adopted CMIP5 climate models

Modeling Center (or group)	Model Name	RCP (W/m^2)	Resolution (lat × lon)
Beijing Climate Center, China Meteorological Administration	BCC-CSM1-1	8.5	64 × 128
Canadian Centre for Climate Modelling and Analysis	CanESM2	8.5	64 × 128
Australian Commonwealth Scientific and Industrial Research Organization	CSIRO-QCCCE	8.5	96 × 192
Institute Pierre Simon Laplace, Paris, France	IPSL	8.5	96 × 96
Model for Interdisciplinary Research on Climate, Japan	MIROC-ESM	8.5	64 × 128

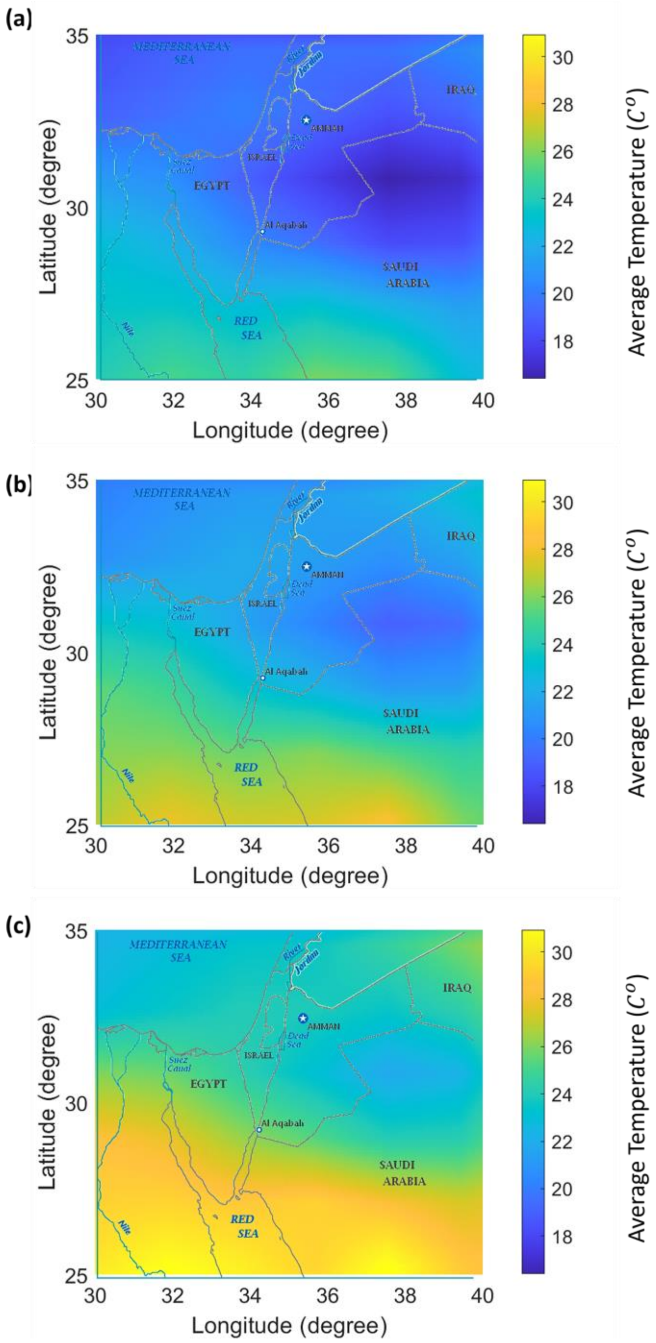


Figure 3. Heat map showing Current and projected temperature of Jordan from (a) 1956-2006; (b) 2020-2060; and (c) 2060-2100

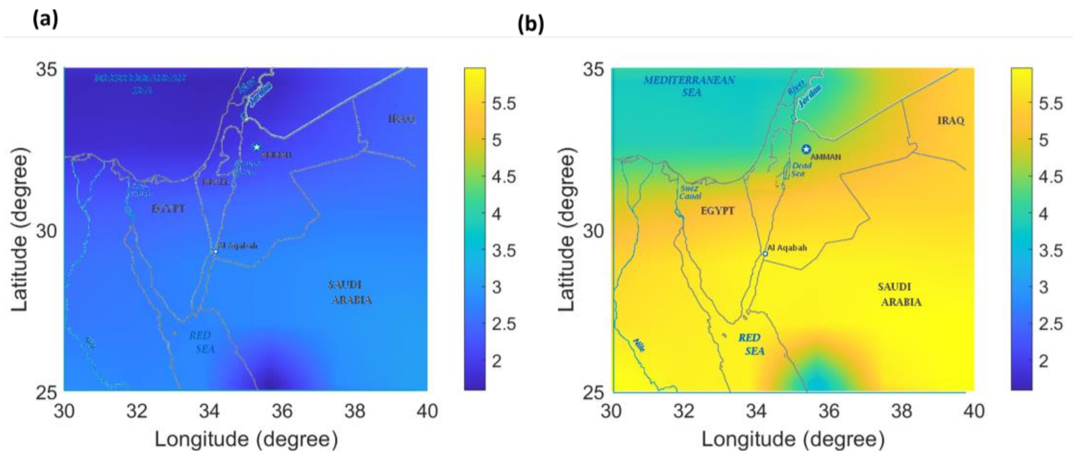
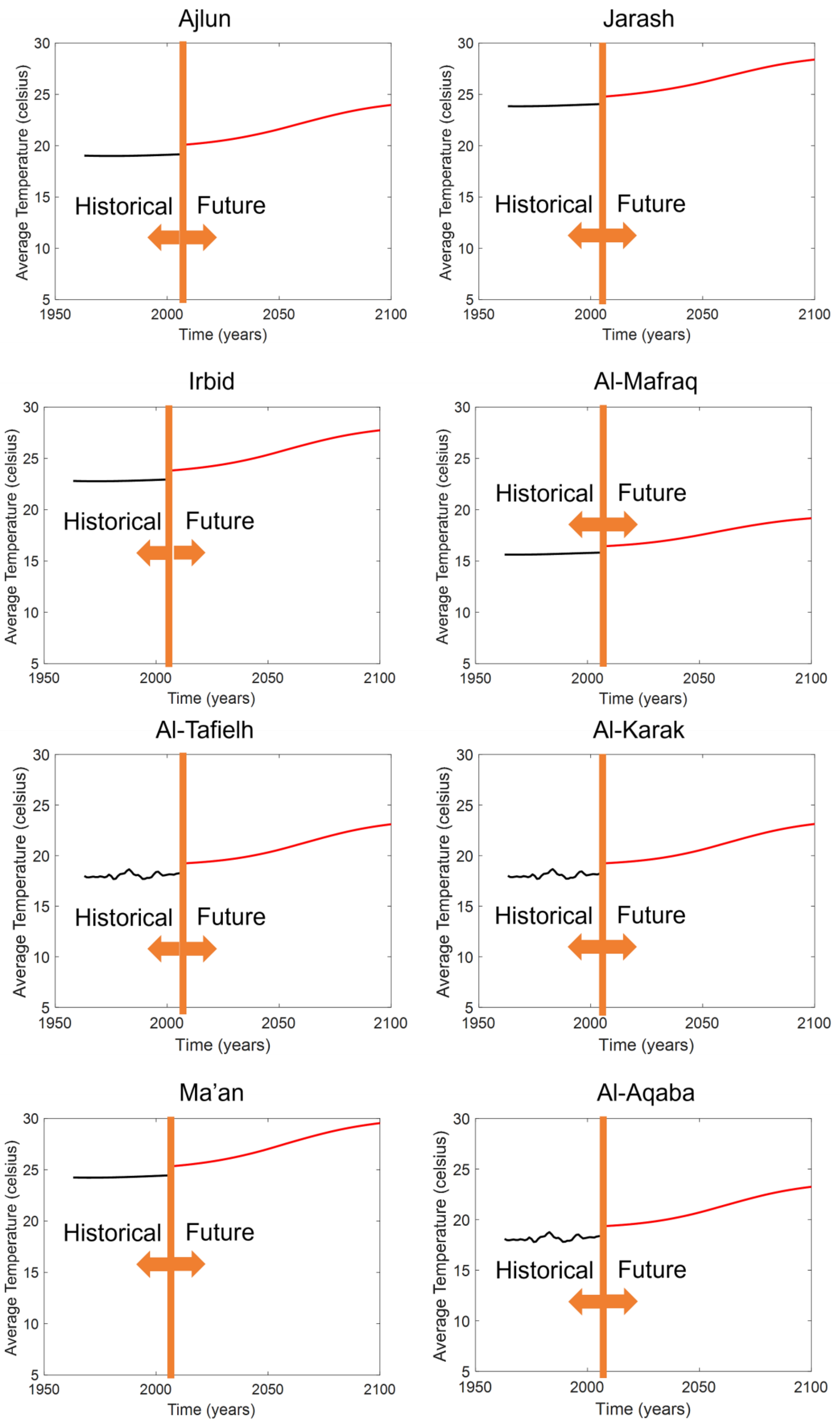


Figure 4. Comparative Heat Maps of Temperature Changes between the historical period (1956-2006) and two future intervals in Jordan (a) 2020-2060 and (b) 2060-2100


Ajlun
Average Temperature (celsius)
Historical
Future
Time (years)
Jarash
Average Temperature (celsius)
Historical
Future
Time (years)
Irbid
Average Temperature (celsius)
Historical
Future
Time (years)
Al-Mafraq
Average Temperature (celsius)
Historical
Future
Time (years)
Al-Tafielh
Average Temperature (celsius)
Historical
Future
Time (years)
Al-Karak
Average Temperature (celsius)
Historical
Future
Time (years)
Ma'an
Average Temperature (celsius)
Historical
Future
Time (years)
Al-Aqaba
Average Temperature (celsius)
Historical
Future
Time (years)

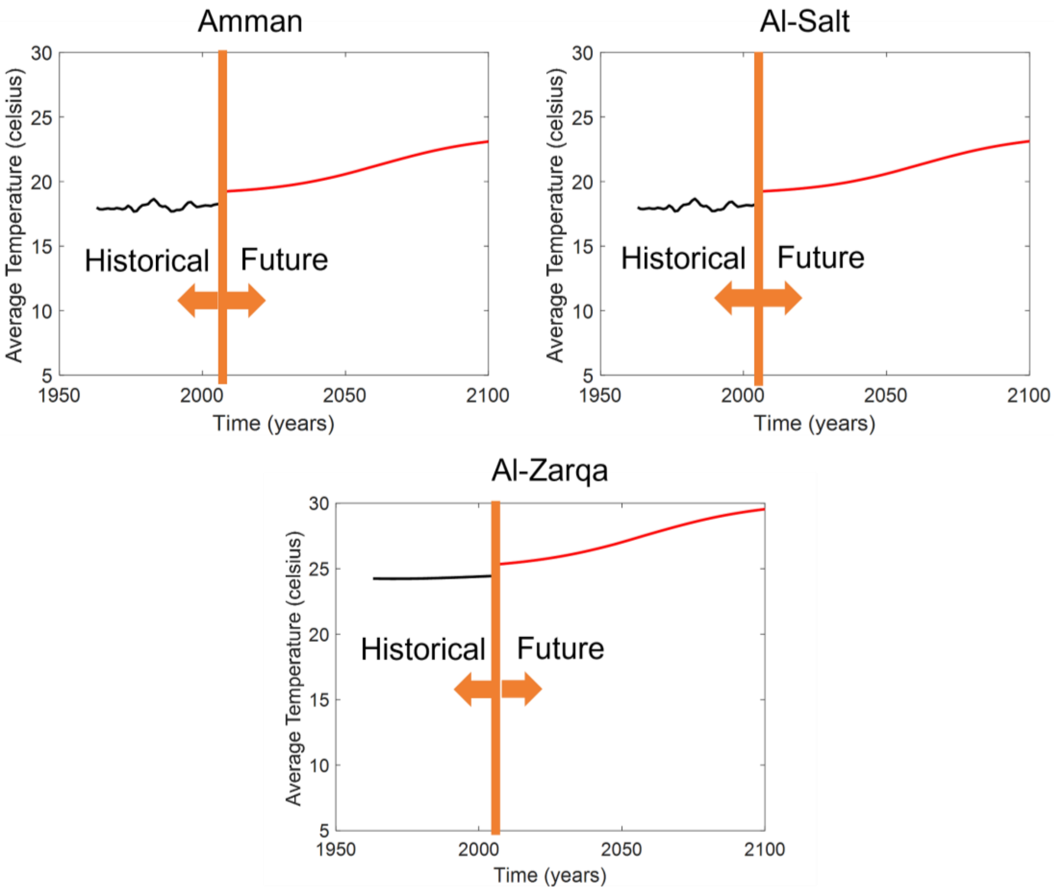
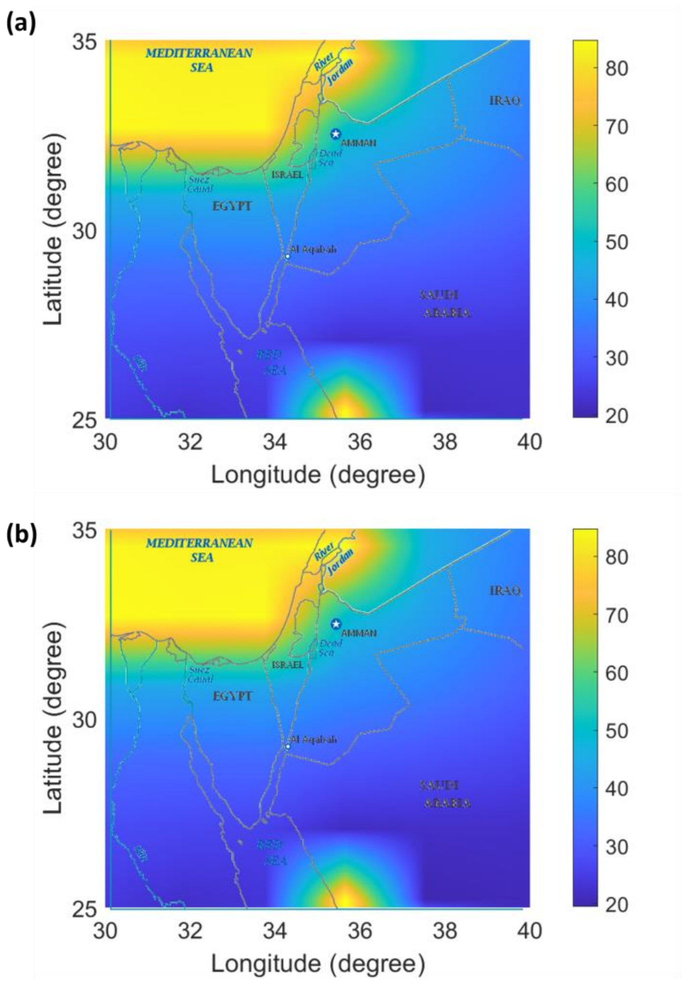


Figure 5. Average Yearly Temperatures Across Cities (1965-2100)



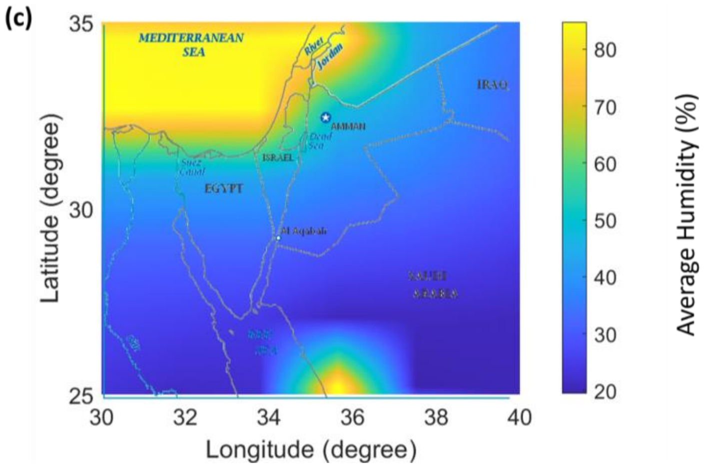


Figure 6. Heat map showing current and projected relative humidity across Jordan from (a) 1956-2006, (b) 2020-2060, and (c) 2060-2100

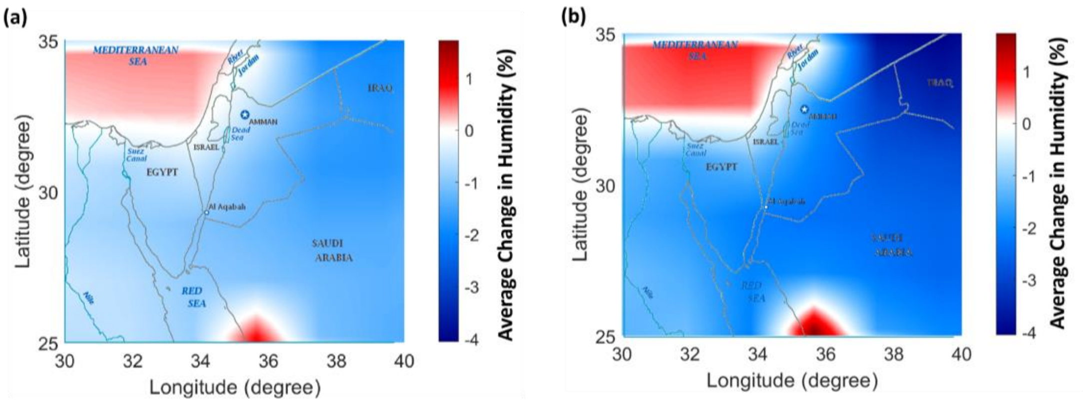
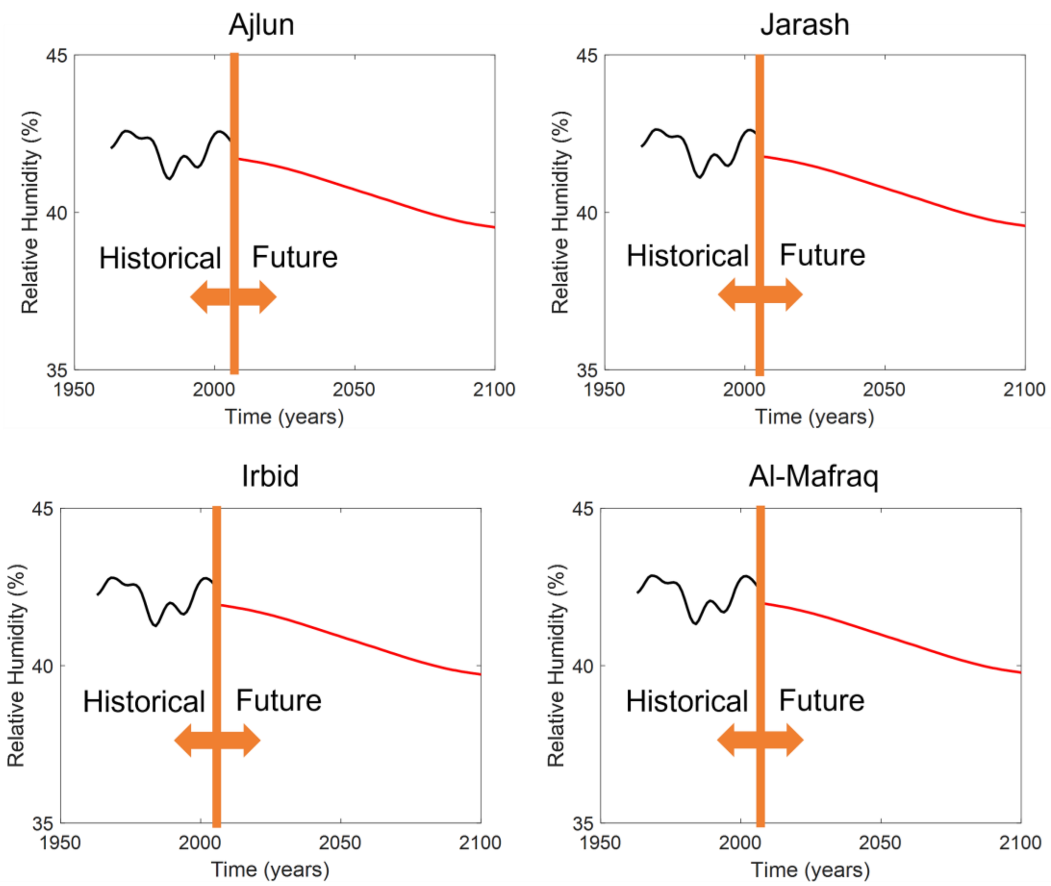


Figure 7. Comparative heat maps of the relative humidity changes between the historical period (1956-2006) and two future intervals across Jordan (a) 2020-2060 and (b) 2060-2100



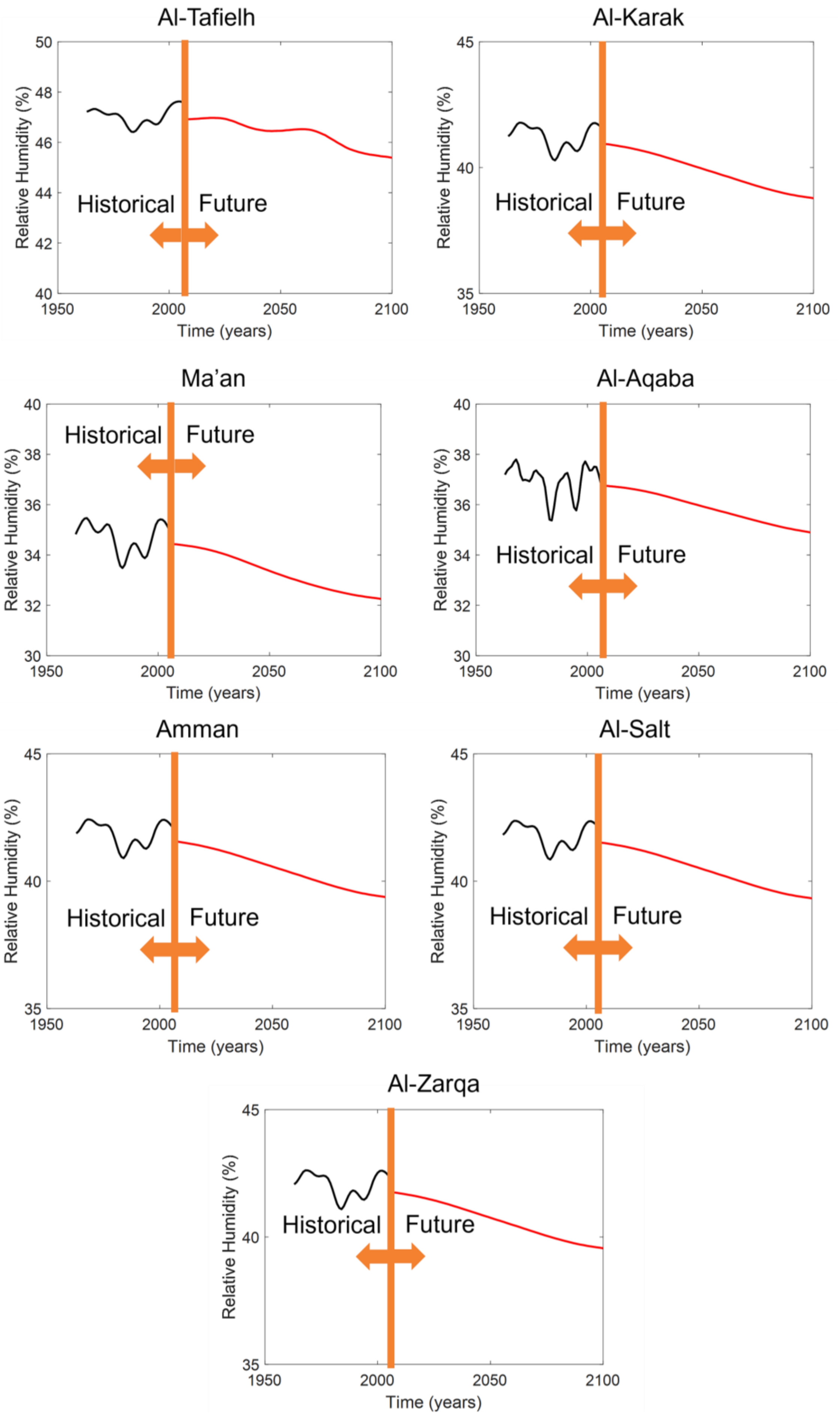


Figure 8. Average yearly relative humidity across main cities of Jordan (1965-2100)

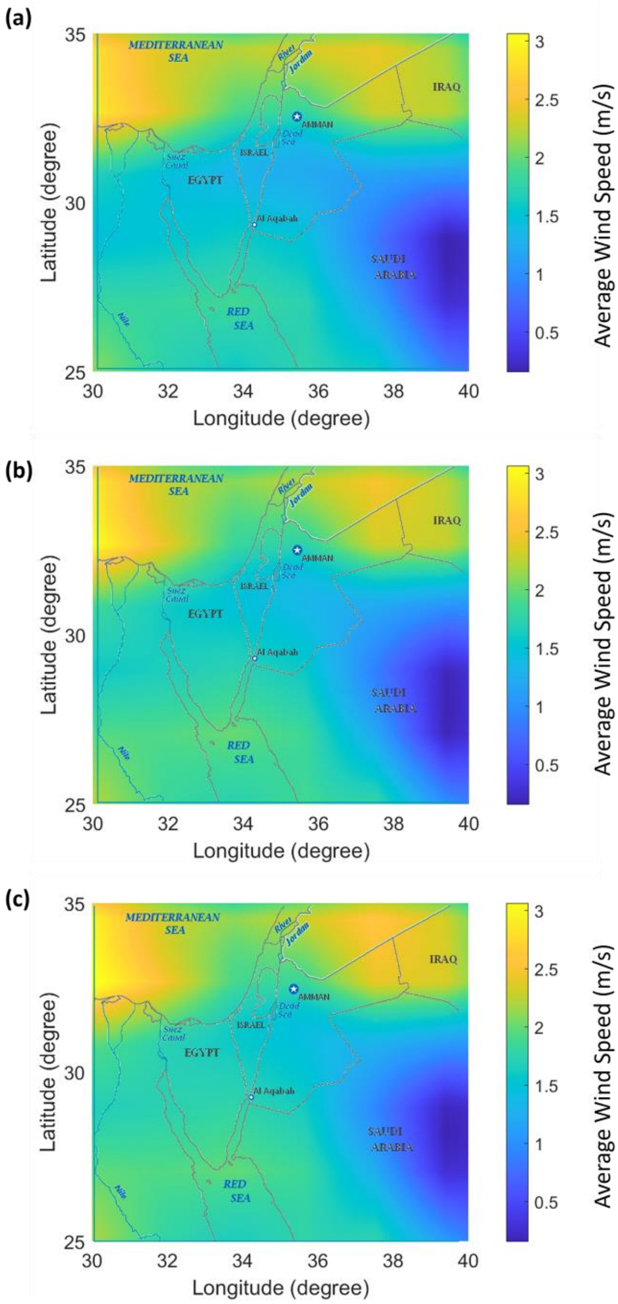


Figure 9. Heat map showing current and projected wind speed across Jordan from (a) 1956-2006, (b) 2020-2060, and (c) 2060-2100

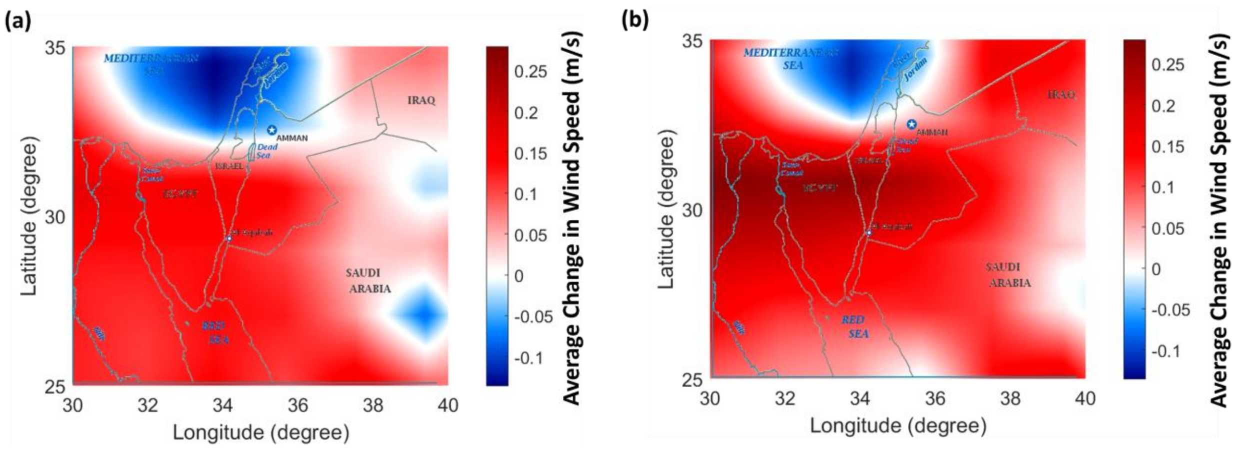
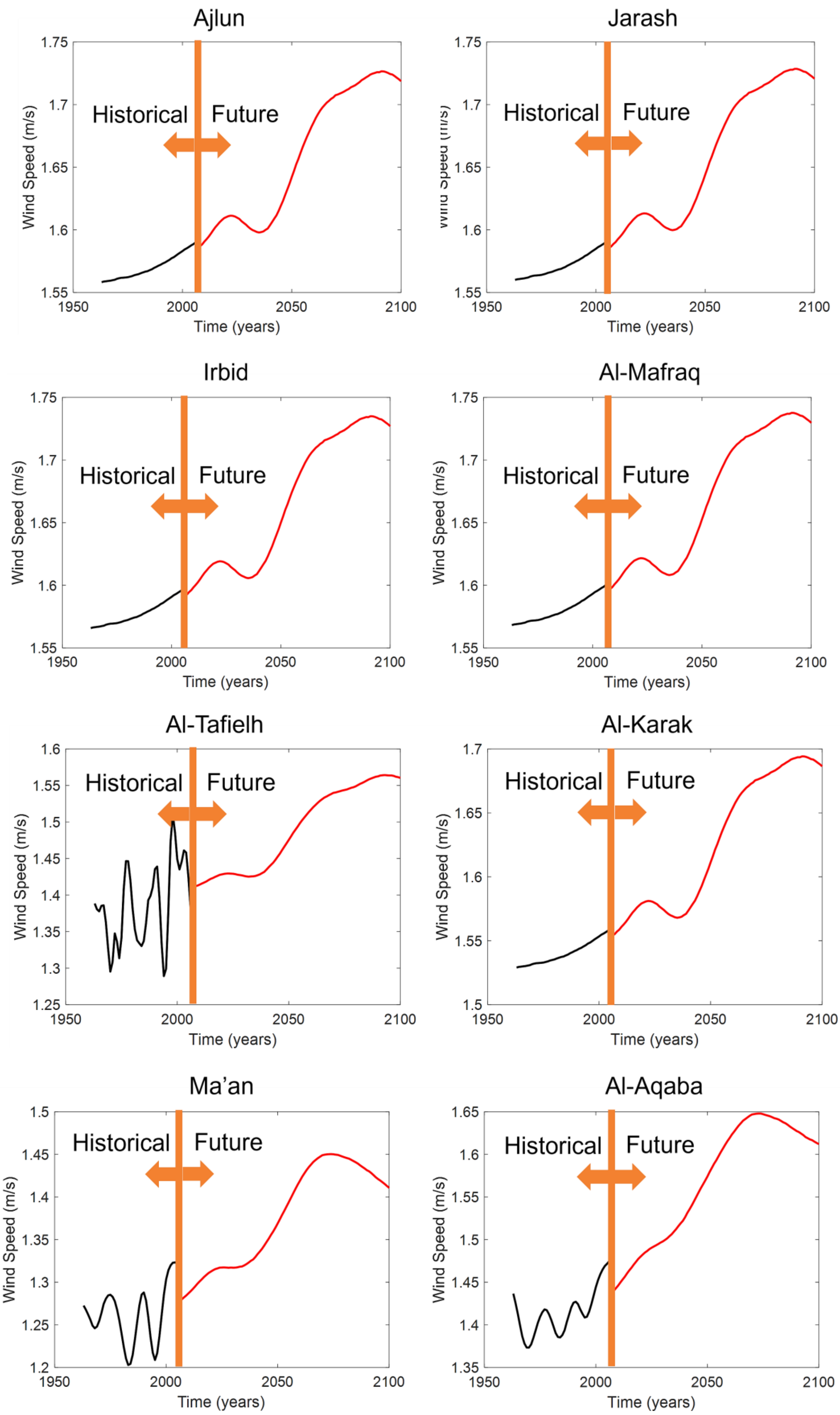


Figure 10. Comparative heat maps of wind speed changes across Jordan between the historical period (1956-2006) and two future intervals (a) 2020-2060 and (b) 2060-2100


Ajlun
Historical
Future
Wind Speed (m/s)
Time (years)
Jarash
Historical
Future
Time (years)
Irbid
Historical
Future
Wind Speed (m/s)
Time (years)
Al-Mafraq
Historical
Future
Wind Speed (m/s)
Time (years)
Al-Tafielh
Historical
Future
Wind Speed (m/s)
Time (years)
Al-Karak
Historical
Future
Wind Speed (m/s)
Time (years)
Ma'an
Historical
Future
Wind Speed (m/s)
Time (years)
Al-Aqaba
Historical
Future
Wind Speed (m/s)
Time (years)

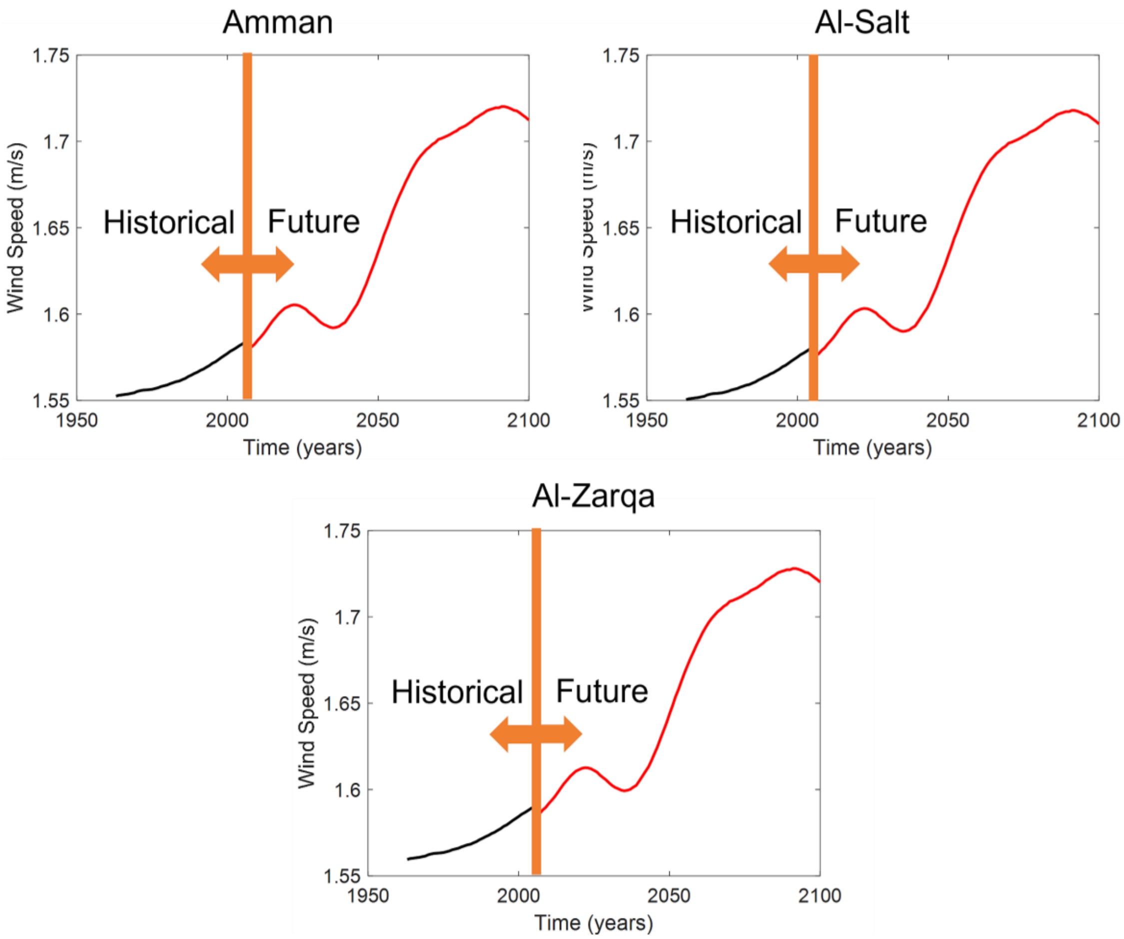


Figure 11. Average yearly wind speed across the main cities in Jordan (1965-2100)

The study's comprehensive analysis, utilizing five diverse GCMs under the RCP 8.5 scenario, has provided detailed projections of how climatic parameters such as temperature, humidity, and wind speed are expected to evolve across Jordan from 2020 to 2100. These parameters directly influence the rate of corrosion in steel structures, making this data crucial for future planning and mitigation strategies.

4.1. Impact of Climate Change on the Climatic Parameters

To thoroughly gauge climate change's impact on specific climatic aspects, this analysis systematically evaluated the effects on ambient temperature, humidity levels, and wind speed across Jordan. Projections for average temperature, relative humidity, and wind velocity across these predefined cities were formulated using five global climate models under the severe RCP 8.5 emission scenario within the comprehensive CMIP5 dataset. A comparison was then made between projected data from 2020 to 2100 and historical data spanning 1956 to 2006 to provide a well-rounded assessment. Downscaling was applied to achieve a high-resolution spatial dimension of approximately 15 arc-seconds (~1/2 km^2) for the climatic variables, seen as crucial to capture subtle territorial variations effectively. The downscaling methodology adhered to was discussed in detail within WorldClim (2023) [55].

4.2. Global Change in Ambient Temperature

The temperature variations across three timeframes – historically from 1956 to 2006, shortly from 2020 to 2060, and in the far future from 2060 to 2100 – are depicted in Figures 3-a to 3-c. These illuminating heat maps comprehensively visualize existing and projected temperature patterns across Jordan. Figure 3-a notably presents the baseline temperatures from 1956 to 2006, establishing the foundation for comparisons with future projections shown in Figures 3-b and 3-c. These latter figures display the expected temperatures in the near and far future periods, permitting an evaluation of climate change's immediate and long-term effects. Given the study's focus on assessing the impacts of climate change by contrasting historical and projected temperatures, the difference between these timeframes was further analyzed in intricate detail. The consequent alterations in temperature, a direct consequence of variations in climate, are prominently highlighted in Figure 4. This difference heat map is an illustrative tool, emphasizing the regions most afflicted by evolving climate conditions. Figure 4 depicts a heat map of temperature deviations between the two intervals of 1956 to 2006 and 2020 to 2100. The shift in color intensity from blue to red was used to indicate decreases to sharp rises in temperature, respectively. Most parts of the country have been experiencing warmer average temperatures, as evidenced by the heat map, especially later in the century, from 2060 through 2100. By 2100's end, all regions are predicted to see temperature increases ranging from 5 to 5.5 degrees Celsius when viewing historical benchmarks. Figure 5 provide detailed descriptions and projections of average annual temperatures across the cities in Jordan from 1965 to 2100. These figures illustrate the consistently upward trajectory of temperatures over the decades from 1956 through 2100. For instance, the temperatures in Al-Tafielh, usually around 18 degrees Celsius, are anticipated to reach 24 degrees by the end of the century. These conclusions underscore the pervasive warming theme and highlight the pressing need to address climatic changes' implications urgently.

To conclude, the heat maps represented in Figures 3 to 5 illustrate a consistent upward trajectory in temperatures across all regions in Jordan. For example, Al-Tafielh, typically experiencing average annual temperatures around 18 degrees Celsius, is projected to reach 24 degrees Celsius by the end of the century. This rise in temperature is expected to accelerate the corrosion process, as higher temperatures generally increase the rate of chemical reactions. The data suggests that by 2100, regions might experience temperature increases ranging from 5 to 5.5 degrees Celsius compared to historical benchmarks, significantly impacting structural integrity and increasing maintenance needs.

4.3. Global Change in Humidity

The relative humidity variations across three timeframes in Jordan - from 1956 to 2006, 2020 to 2060, and 2060 to 2100 - are shown in Figures 6-a to 6-c. Figure 6-a presents the historical baseline humidity patterns from 1956 to 2006 for comparison with future projections shown in Figures 6-b and 6-c. These latter figures illustrate the expected relative humidity from 2020 to 2060 and the future from 2060 to 2100 under climate change. As with temperature, the difference between these periods was further examined. Figure 7 highlights the areas most impacted by the changing humidity levels through a heat map of relative humidity deviations between 1956-2006 and 2020-2100. Similar to Figure 4's depiction of temperature changes, darker colors in this map indicate a larger decrease or increase in relative humidity from blue to red. Most regions will see lower humidity over land and higher humidity over water towards the late 21st century. By 2100, it is anticipated that all parts of Jordan will experience a 1-4% reduction in humidity compared to historical records, as depicted in Figure 8. For example, relative humidity in Irbid, which was around 43% in the past, may drop to 39% by 2100. These findings underscore the significant projected decline in humidity and emphasize the pressing need to address climate change implications.

To sum up, there is a general decline in relative humidity across the country, with some areas witnessing more pronounced changes. This decrease in humidity could potentially slow down corrosion rates in certain areas; however, the increased temperatures might offset this effect. The projected decrease in humidity could lead to drier conditions that affect the time of wetness of steel surfaces, a critical factor in the rate of corrosion.

4.4. Global Change in Wind Speed

This section aims to comprehend the variations in wind speed attributable to climate change across Jordan. Wind speeds were explored throughout three pivotal timeframes: historical times (1956-2006), near-future (2020-2060), and far future (2060-2100), illustrated in Figure 9. This figure provides a heat map portraying current and anticipated wind velocities globally across the specified periods (a) 1956-2006, (b) 2020-2060, and (c) 2060-2100. Identical to prior sections, the divergence between these spans was further analyzed. The resultant changes in wind speed, a direct consequence of climate variations, are highlighted in Figure 10. This figure presents comparative heat maps explaining wind velocity alterations between the historical period (1956-2006) and the two future intervals (a) 2020-2060 and (b) 2060-2100 in Jordan. Similar to previous heat maps, the color intensity differences reflected wind speed changes. Reductions were denoted in darker blue shades communicating more notable reductions, whereas increases were presented in deeper red shades indicating higher elevations. Figures 10(a) and 10(b) plainly exhibit a general trend of increasing wind velocities across Jordan. By 2100, it is anticipated that all parts of Jordan will experience a 0.2-0.3 m/s increase in wind speed compared to historical records, as depicted in Figure 11. For example, wind speed in Irbid, which was around 1.55 m/s in the past, rose to 1.75 m/s by 2100. These findings underscore the significant projected increase in wind speed and emphasize the pressing need to address climate change implications.

The increase in wind speeds could lead to more abrasive conditions that physically impact structures and increase the deposition of corrosive agents like salts and industrial pollutants. This factor is particularly concerning for coastal and industrial regions where windborne saline particles are prevalent.

4.5. Projections of Changes in Corrosion Rates

To evaluate the potential effect of climate change on corrosion rates, researchers projected climatic parameters using historical data from 1956 to 2006 alongside global climate model data from 2020 to 2100. Figures 3 through 11 thoroughly compare past and anticipated climatic conditions. As the figures demonstrate, the studied regions experience notable variations in temperature, humidity, and wind speeds across different areas and eras. Some localities may encounter elevated occurrences and severities of average and extreme weather, unlike records from the past, whereas others may encounter diminished frequency due to climate change impacts.

The influences of temperature, relative humidity, and wind speeds on the corrosion rate are represented by C_{temp}, C_{twet}, and $C_{S_{air}}$, respectively. Using Equations 8 to 12, the three climate change factors C_{temp}, C_{twet}, and $C_{S_{air}}$ and the relative corrosion rates for steel (C_{rate}) were estimated annually from 2020 to 2100, all relative to the average of 1956 to 2006. The estimated relative corrosion rate (C_{rate}) was based on the climate change effects projected from the six GCMs under the RCP 8.5 emission scenario, as depicted in Figure 12. Due to the time-varying nature of the projected climate data (as seen in Figures 3 to 11), the climate change factors and relative corrosion rates also change over time. Figure 12 displays the average relative corrosion rate projected using RCP 8.5 scenarios relative to historical data for 2020-2060 and 2060-2100. Notably, compared to historical data, GCM projections indicate an accelerated corrosion rate in all regions across Jordan of approximately 15%.

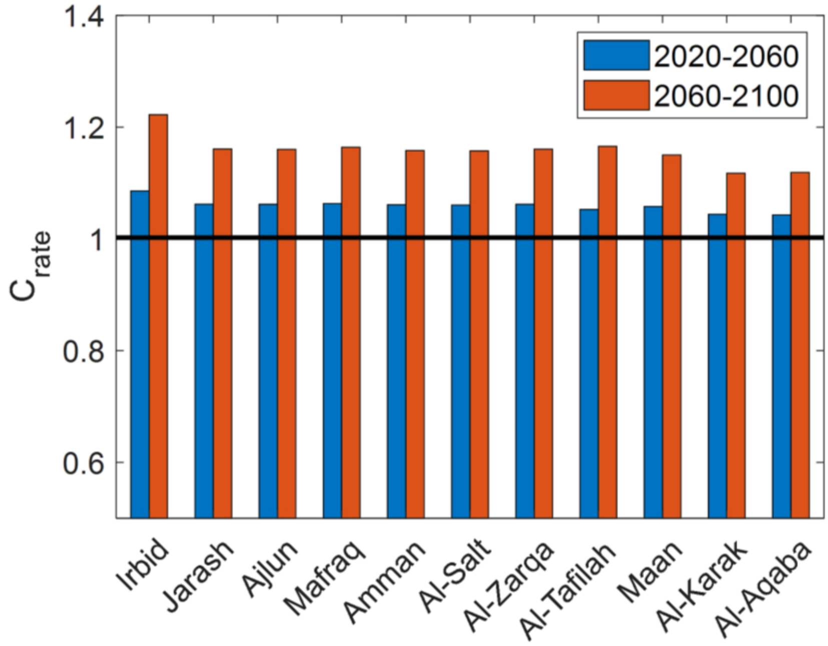


Figure 12. Comparison of the average corrosion rate projected using RCP 8.5 forcing scenarios with the historical data along the main cities in Jordan for 2020-2060 and 2060-2100

To mitigate the worrisome corrosion rates expected to plague Jordan, this work proposes cultivating and integrating progressive, sustainable materials uniquely designed to withstand the deteriorative impacts of environmental change. Capitalizing on green technologies, such as corrosion-resistant alloys or coatings constructed from recycled refuse, offers a twofold advantage: prolonging the longevity of steel infrastructures while adhering to ecological sustainability principles. Furthermore, incorporating smart sensors within these constructions to monitor corrosion in real-time could inform maintenance schedules and prevent catastrophic failures, harmonizing with intelligent utility and energy-efficient systems for sustainable infrastructure administration. By concentrating on these groundbreaking solutions, we address the immediate issues of amplified corrosion and contribute to the more comprehensive goals of sustainable and resilient infrastructure progression. To provide a comprehensive context for our study and illustrate how it advances the field of corrosion rate predictions under climate change scenarios, we have reviewed key literature on the subject. Table 2 presents a comparison of our findings with those of recent studies.

Table 2. Comparative Analysis of Key Studies on Corrosion Under Climate Change

Study	Focus	Key Findings	Comparison with Current Study
Iannuzzi & Frankel (2023) [56]	Carbon footprint of steel corrosion	Highlighted the environmental impact of steel corrosion and the need for updated predictive models	Aligns with the necessity for enhanced corrosion mitigation strategies and updated models in the current study
Soliman & Frangopol (2015) [22]	Life-cycle cost evaluation of corrosion-resistant steel for bridges	Demonstrated economic benefits of using advanced materials to mitigate climate impacts	Complements the current study by providing practical implications of using advanced materials in climate-affected regions
Abtahi et al. (2023) [23]	Parameter estimation for corrosion models in reinforced concrete structures	Emphasized the importance of accurate parameter estimation for corrosion models	Extends the approach by integrating detailed climatic data into corrosion predictions for steel structures
Ozkan et al. (2023) [57]	Atmospheric corrosion of steel infrastructure in Canada under climate change	Demonstrated the feasibility of using quantitative models to predict corrosion rates	Extends the quantitative approach to the specific climatic conditions of Jordan

5. Practical Implications of the Proposed Model

The projected increase in corrosion rates necessitates the redesign of current infrastructure plans to incorporate materials and coatings that are more resistant to the changing climate conditions. This might include the use of advanced zinc coatings or alternative alloys that offer better resistance to temperature fluctuations and humidity changes. With the acceleration of corrosion rates, particularly in areas projected to experience the most significant climatic shifts, there will be a need for more frequent and detailed inspections. Proactive maintenance will become crucial to prevent structural failures, especially in critical infrastructure such as bridges and high-rise buildings. The findings support the call for updated building codes that consider future climatic impacts on structural materials. These codes should encourage the use of materials and construction techniques that are suited to withstand harsher conditions and reduce the long-term environmental and economic costs associated with corrosion. Integrating smart sensor technologies into structural components can provide real-time data on the condition of the infrastructure, allowing for timely interventions. This technology not only aids in monitoring but also helps in gathering large-scale data to further refine predictive models.

The results of this study demonstrate a significant increase in corrosion rates of steel structures across Jordan due to climate change. The integrated framework, which considers the impacts of temperature, humidity, and wind speed, provides a comprehensive approach to predicting atmospheric corrosion under changing environmental conditions. Our findings align with the study by Iannuzzi & Frankel (2022) [56], which emphasized the critical role of reducing steel corrosion to combat climate change. Their research highlights the environmental impact of steel corrosion, estimating that the steel industry could contribute significantly to global carbon emissions if corrosion is not effectively managed. This underscores the necessity for updated predictive models and enhanced corrosion mitigation strategies. Similarly, the research by Soliman & Frangopol (2015) [22] focused on the life-cycle cost evaluation of corrosion-resistant steel for bridges under climate change scenarios. Their study demonstrated the economic benefits of using advanced materials in mitigating climate impacts. Our research complements their findings by providing detailed predictions of corrosion rates based on climatic factors, thereby highlighting the practical implications of adopting advanced materials in regions experiencing significant climatic shifts.

Moreover, the study by Abtahi et al. (2023) [23] emphasized the importance of accurate parameter estimation for corrosion models in reinforced concrete structures. While their focus was on reinforced concrete, our approach of integrating detailed climatic data into corrosion predictions for steel structures expands the scope and provides a robust framework for assessing environmental impacts on different structural materials. The work by Ozkan et al. (2023) [57] on atmospheric corrosion of steel infrastructure in Canada under climate change demonstrated the feasibility of using quantitative models to predict corrosion rates. Our study extends this approach by applying it to the specific climatic conditions of Jordan, offering localized insights that are crucial for developing targeted mitigation strategies. Overall, our study contributes to the existing literature by providing a localized analysis of climate change impacts on steel corrosion in Jordan, utilizing advanced predictive models and comprehensive climatic data. The findings emphasize the necessity for updated building codes and standards that account for the changing environmental conditions, ensuring the resilience and sustainability of future infrastructure.

6. Conclusions

This study presents an innovative framework for predicting the atmospheric corrosion rate of steel structures considering climate change. The effects on atmospheric corrosion due to changes in the environmental temperature, relative humidity, and wind speed are considered. The presented results focus on the following findings:

- The proposed framework effectively influences the long-term impact of climate change on the corrosion rate in steel structures across Jordan.
- An upward trajectory of temperatures is consistently observed across all studied regions. For instance, temperatures in Amman, historically around 19°C, are anticipated to reach 23°C by 2100. Similarly, temperature increases are projected for Irbid, Maan, AL-Aqaba, and across the country.
- A downward trajectory of relative humidity is consistently observed across all cities. For instance, relative humidity in Irbid, historically around 43%, was anticipated to drop to 39% by 2100.
- A general trend of wind speed increase over the cities is observed.
- The combined effect of climate change (and on climatic parameters) on the corrosion rate depends on the considered region. For instance, specific regions like Irbid have an increase of 22%. However, other cities increase (13–15%).
- There is a critical need for enhanced protective measures for steel structures in all cities in Jordan.
- The unpredictable effects of climate change on corrosion necessitate factoring sophisticated modeling and real-time analytics into forecasts to optimize predictive accuracy over time. AI and machine learning promise to refine expectations as environmental inputs evolve in complex, non-linear ways.
- Immediate code revisions are imperative to embed climate-conscious standards addressing expected corrosion escalation into new builds and overhauls. Strategically incentivizing cutting-edge, eco-friendly materials and methods proven to bolster resiliency ensures infrastructure endures amid fluctuation.

7. Declarations

7.1. Author Contributions

Conceptualization, M.F.T., A.S., and O.A.; methodology, M.F.T., A.S., O.A., K.A., G.T., S.T., M.F., E.H., A.A., and M.N.; software, M.F.T.; formal analysis, M.F.T., A.S., O.A., K.A., G.T., S.T., M.F., E.H., A.A., and M.N.; investigation, M.F.T., A.S., and O.A.; writing—original draft preparation, M.F.T., A.S., and O.A.; writing—review and editing, M.F.T., A.S., and O.A.; visualization, M.F.T., A.S., O.A., K.A., G.T., S.T., M.F., E.H., A.A., and M.N.; supervision, M.F.T.; project administration, M.F.T. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available in the article.

7.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

7.4. Conflicts of Interest

The authors declare no conflict of interest.

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