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من نحن

المجلة العربية للعلوم الإنسانية والاجتماعية مجلة علمية الكترونية محكمة ، ربع سنوية، تصدر عن مركز السنبلة للبحوث والدراسات، عمان - الأردن ، تعنى بنشر البحوث والدراسات ، وملخصات رسائل الماجستير والدكتوراه ، ونشر فصول من الرسائل العلمية ، ومراجعة الكتب ، ونشر التقارير والندوات والمؤتمرات العلمية ، والحوارات واللقاءات العلمية في مجالات العلوم الإنسانية والاجتماعية بجميع فروعها : التاريخ ، والتربية ، وعلم الاجتماع ، والفلسفة ، والأديان ، وعلم النفس ، والقانون والعلوم السياسية ، والعلوم الادارية ، والتنمية البشرية ، وعلم الجريمة ، وعلم الانثربولوجيا، اللغة العربية وآدابها ،الجغرافيا الآثار، الإعلام والصحافة ،المكتبات والمعلومات.

الأهداف

تسعى المجلة العربية للعلوم الإنسانية والاجتماعية لتحقيق الأهداف التالية:

- نشر البحوث المبتكرة التي يقدمها الباحثون في المجالات العلمية المتعلقة بالآداب والعلوم الإنسانية ،وذلك بعد عرضها على المقوّمين العلميّين.
- نشر تقارير الندوات والمؤتمرات العلمية بالجامعات العربية ، والمعاهد العلمية ، ومراكز البحوث.
- توثيق ونشر الثقافة العلمية بين الباحثين، والتواصل العلمي فى مختلف مجالات العلوم الانسانية والاجتماعية.
- التعاون العلمي بين المجلة والباحثين والعلماء العرب في مجالات تخصّص المجلة.
- تشجيع الباحثين العرب على إنجاز بحوثهم المبتكرة.
- التميز في تقديم البحوث ذات الأفكار المبتكرة و التى لم يسبق نشرها بمجلات علمية أخرى والمحكمة بواسطة نخبة من العلماء والمتخصصين ،والإسهام في إخراج بحوث علمية متميزة , من خلال الالتزام بالمعايير العالمية للتميز في مجالات البحث العلمي.
- ضبط أمور البحث العلميّ ،بعرض البحوث المقدّمة إلى المجلة على المختصين والخبراء والتطوير المستمر فى أساليب النشر والتحكيم.
- الإسهام في إثراء البحث العلمي والمناهج العلمية و التزام معاييرها، ونشر المعرفة في مجال الآداب والعلوم الإنسانية ،وتعميمها في الوطن العربي خدمةً للمجتمع العربي وتقدّمه.
- نشر البحوث وأخبار المؤتمرات والندوات والمراجعات وملخصات الرسائل الجامعية، وفصول من الرسائل العلمية للتعريف بقيمتها العلمية.
- تعميم الفائدة المرجوّة من نشر البحوث والدراسات، بوضع أعداد المجلّة بين أيدي القراء والباحثين على موقع المجلة في شبكة(الإنترنت)وتطوير الموقع وتحديثه.

خطوات النشر :

-يقوم الباحث بتنسيق البحث حسب شروط المجلة المذكورة أدناه.

-يقوم الباحث بإرسال البحث المنسق على شكل ملف مايكروسوفت وورد، إلى البريد الإلكتروني :
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-يجب أن يكون البحث مكتوباً بلغة سليمة،

-يجب أن تكون المادة المرسلة للنشر أصيلة ولم ترسل للنشر في أي جهة أخرى.

-يلتزم الباحث بالأصول العلمية المتعارف عليها في إعداد وكتابة البحوث.

-يجب إثبات مصادر المعلومات وتوثيق الاقتباس واحترام الأمانة العلمية في الإحالات والمراجع والمصادر.

–يتمّ تقويم البحث من محكّمين.

–يتم إبلاغ الباحث بنتائج التحكيم خلال اقل من اسبوع، بالقبول أو الرفض أو إجراء التعديلات للبحث بعد التحكيم.

–يقوم الباحث بالتعديلات المطلوبة ثم يتم متابعة التعديلات من قيل لجان التحكيم . يتم إرسال البحث مع تقرير بقبول البحث بشكل نهائي من لجان التحكيم.

-يتم إرسال خطاب رسمي من المجلة بقبول البحث للنشر.

-يقوم الباحث بدفع رسوم النشر والتحكيم .ويرسل ذلك عبر البريد الالكتروني editor@arabjhs.com، أو الواتسب على الرقم **962790260197**

-يتم إبلاغ الباحث بإيميل رسمي بإتمام عملية النشر في حال إكمال كافة الإجراءات السابقة وإنجاز عملية النشر الفعلي في عدد المجلة .

يراعي الباحث ما يلي:

–اسم الباحث (الباحثين) ، الوصف الوظيفي ، المؤسسة التي يعمل بها ، .

–الملخّص باللغة العربية ثم الكلمات المفتاحية

–الملخّص باللغة الانجليزية ثم الكلمات المفتاحية

ترتيب المحتوى: محتوى البحث حسب شروط المجلة العربية للعلوم الإنسانية والاجتماعية : المقدمة ،مشكلة الدراسة ،أسئلة الدراسة ، أهمية الدراسة ، أهداف الدراسة ، مصطلحات الدراسة الإطار النظري والدراسات السابقة ، منهج الدراسة، أداة الدراسة ، نتائج الدراسة، ومناقشة النتائج ، التوصيات ،المصادر والمراجع

تنسيق البحث :يتم تنسيق الورقة على) قياس(A4 ، بحيث يكون نوع وحجم الخط وفق شروط محددة، وهي:– نوع الخط في الابحاث باللغة العربية هوSimplified Arabic ، حجم الخط 16 غامق للعنوان الرئيس، 14 غامق للعناوين الفرعية، 14 عادي لباقي النصوص وترقيم الصفحات و المسافة بين الأسطر يجب أن لا تقل عن 1.5.

–نوع الخط في الأبحاث باللغة الإنجليزية هوTimes New Roman ، حجم الخط 14 غامق للعنوان الرئيس، 12 غامق للعناوين الفرعية، 12 عادي لباقي النصوص وترقيم الصفحات و المسافة بين الأسطر يجب أن لا تقل عن 1.5.

حجم البحث والملخص :ألا يزيد عدد صفحات البحث على (30) صفحة و ذلك لكي لا يتم زيادة رسوم التحكيم. ويجب أرفاق ملخص مكون من 200 – 250 كلمة باللغتين العربية والانجليزية ، بالإضافة إلى كلمات مفتاحية لا تقل عن 6 كلمات.

التوثيق : يتم التوثيق وفقا لأسلوب الجمعية الأمريكية السيكولوجية APA)) وعلى النحو التالي داخل البحث إذا كان المرجع كتابا يكتب اسم العائلة والسنة ، مثال(السرهيد ، 2005).وإذا كان المرجع بحثا في مجلة علمية يراعى ما سبق ، أما إذا كان موقعا على الأنترنت فيكتب : اسم المؤلف ، عنوان المقال ، السنة ، الموقع ، السنة ، التاريخ ،.بالنسبة للمصادر والمراجع ، ترد المصادر العربية ، ثم المصادر الأجنبية.

الهوامش: تستخدم هوامش الصفحات السفلية لذكر أي ملاحظة، أو لتوضيح أي معلومة واردة في متن البحث، أو للتوثيق في بعض الأبحاث ولا مانع من ذلك ، وتوضع بين قوسين في أسفل الصفحة ، أو يعمل لها ملحق للهوامش توضع في نهاية البحث.

المراجع:

-ترتب أرقام المراجع في قائمة المراجع بالتسلسل، وذلك بعد مراعاة ترتيب المراجع هجائياً في القائمة حسب اسم المؤلف وفقاً للآتي:

أ. إذا كان المرجع بحثاً في دورية:

—اسم الباحث (الباحثين) بدءاً باسم العائلة،. "عنوان البحث،" اسم الدورية ، رقم المجلد، رقم العدد، ، سنة النشر.

ب.إذا كان المرجع كتاباً:

—اسم المؤلف (المؤلفين) بدءاً باسم العائلة، عنوان الكتاب ، اسم الناشر، سنة النشر.

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د.إذا كان المرجع نشرة أو إحصائية صادرة عن جهة رسمية:

—يكتب اسم الجهة، عنوان التقرير ، المدينة، ، سنة النشر.

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—يكتب اسم المؤلف، عنوان الموضوع ، سنة النشر والتاريخ ، الرابط الالكتروني.

و- وقائع المؤتمر:

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رسوم النشر والتحكيم: 140 دينار أردني ،ما يعادل 200 دولار.

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الرسوم

رسوم النشر والتحكيم والدفع

تسعى المجلة العربية للعلوم الانسانية والاجتماعية بنشر الأبحاث العلمية وتطوير البحث العلمي في الوطن العربي ، وتطلب المجلة رسوم رمزية مقدارها 140 دينار أردني أو ما يعادل 200 دولار لنشر البحوث المكونة من 25 – 30 صفحة بحد أقصى ويتم إضافة رسوم في حال زيادة عدد الصفحات عن 30 صفحة.

التحويل البنكي:

يمكنك تحويل رسوم النشر من خلال البيانات البنكية التالية:

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ESJI Eurasian Scientific Journal Index	
RESEARCHBIB ACADEMIC RESOURCE INDEX	
ADVANCED SCIENCE INDEX	
CITE FACTOR Academic Scientic journal	
DRJI Directory of Research Journal Indexing	
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EBSCO قاعدة بيانات ابسكو العالمية	

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Projected Changes in Temperature and Precipitation over the Imam Turki bin Abdullah Royal Reserve using CMIP6 Global Climate Models

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Abstract

Understanding future climate change is essential for the sustainable management of protected dryland ecosystems. This study assessed projected changes in maximum temperature (Tmax), minimum temperature (Tmin), and annual precipitation across the Imam Turki bin Abdullah (ITBA) Royal Reserve, Saudi Arabia, using the Coupled Model Intercomparison Project Phase 6 (CMIP6) multi-model ensemble under two Shared Socioeconomic Pathways: SSP2-4.5 and SSP5-8.5. Climate projections were analyzed for five representative stations (Al-Jouf, Gassim, Rafha, Hail, and Qaisumah) for the period 2015–2100, with changes also evaluated relative to the historical baseline (1985–2014). Results indicate that temperature is the most robust climate change signal across the ITBA reserve. Under SSP2-4.5, annual Tmax is projected to increase by approximately 2.4–2.6 °C by 2100, while Tmin rises by about 2.8–2.9 °C. Under SSP5-8.5, warming intensifies substantially, with Tmax increasing by 5.7–6.4 °C and Tmin by 6.8–7.2 °C. Tmin increases exceed those of Tmax under both scenarios, indicating a progressive reduction in diurnal temperature range (DTR) and increasing nighttime heat stress. Warming is spatially coherent across all stations, although northern and interior locations generally exhibit slightly stronger increases than southern stations. In contrast, annual precipitation projections show no statistically robust long-term increasing or decreasing trends under either scenario. Projected anomalies remain small, spatially mixed, and highly uncertain, reflecting the dominant influence of natural variability. However, stable precipitation totals do not imply hydroclimatic stability, as rising temperatures are likely to increase evapotranspiration and intensify aridity, drought risk, and water-resource stress. Overall, the findings demonstrate that the reserve is highly vulnerable to future warming, particularly under SSP5-8.5. The results highlight the need for proactive adaptation strategies focused on heat-risk management, ecosystem resilience, sustainable water planning, and climate-resilient infrastructure, while also emphasizing the benefits of emissions mitigation in reducing long-term regional climate risks.

Keywords: Climate Change; CMIP6; Shared Socioeconomic Pathways; Imam Turki bin Abdullah Royal (ITBA) Reserve; Maximum temperature (Tmax); Minimum temperature (Tmin); precipitation; Arid ecosystems; Diurnal Temperature Range (DTR); Saudi Arabia.

1. Introduction:

Climate change has emerged as one of the most significant environmental challenges of the twenty-first century, with profound implications on ecosystems, water resources, biodiversity and socio-economic sustainability around the globe. Rising greenhouse gas emissions have contributed to increasing global temperatures, shifting precipitation patterns and increasing frequency of extreme weather events. Recent assessments indicate that arid regions are projected to experience amplified warming, increased frequency of extreme heat events, and heightened precipitation variability, with important consequences for ecological resilience and resource management (Mansour Almazroui et al., 2021; Abdirahman Ismail Dhaqane et al., 2025; Giorgi, 2006; Wilson et al., 2010).Arid and semi-arid regions are more vulnerable to these changes because of limited water availability, fragile ecosystems and strong sensitivity to climate variability (Abdirahman I Dhaqane et al., 2025; Abdirahman Ismail Dhaqane et al., 2025; Zhongming et al., 2021). Among such regions, the Arabian Peninsula has been known as a climate hotspot where warming trends are projected to exceed the global average while rainfall patterns remain highly uncertain (M. Almazroui et al., 2020; Mansour Almazroui et al., 2021; Pal & Eltahir, 2016; Zhongming et al., 2021).

Saudi Arabia occupies a large part of the Arabian Peninsula and is characterized by predominantly desert climates, sparse rainfall, high evapotranspiration rates and strong seasonal temperature contrasts. The environmental conditions make the country particularly vulnerable to intensified heat stress, prolonged droughts, desertification and increasing pressure on natural ecosystems and water resources (Chowdhury & Al-Zahrani, 2013). Understanding future climate variability over ecologically sensitive regions of Saudi Arabia is therefor essential for sustainable environmental planning and adaptation. The Imam Turki bin Abdullah Royal Reserve (ITBA) is one of the major protected reserves in northern Saudi Arabia and has substantial ecological importance because of its diverse habitats, wildlife resources and role in conservation and land restoration programs. Situate in transition zone between arid–semi-arid environments, the reserve is highly sensitive to changes in temperature and precipitation (Al-Dughairi, 2023, 2024). Despite its environmental significance limited studies has specifically examined future climate projection for this protected region.

Global Climate Models (GCMs) are widely used tools for investigating historical and future climate projections under different greenhouse gas emission pathways. The latest generation of models participating in the Coupled Model Intercomparison Project Phase 6 provides improved representations of atmospheric, oceanic, and land-surface processes compared with earlier model generations (Eyring et al., 2016). CMIP6 simulations are driven by Shared Socioeconomic Pathway (SSP) scenarios, which describe alternative future development trajectories and

associated radiative forcing levels (O'Neill et al., 2014). Among these, SSP2-4.5 represents an intermediate stabilization pathway, whereas SSP5-8.5 reflects a high-emission future associated with stronger warming. Although CMIP6 models offer valuable climate projections, their performance differs across regions, particularly in arid environments where precipitation processes are complex and spatially heterogeneous (Giorgi & Mearns, 2002; Zhongming et al., 2021). Therefore, selecting well-performing models for a specific region can improve the reliability of future projections. Previous evaluations over northern Saudi Arabia identified a subset of top-performing CMIP6 models capable of reproducing observed temperature and precipitation characteristics more realistically (Al-Shahrani et al., 2026). Building on that assessment, the use of skill-selected models provides a stronger basis for assessing future climate risks over the reserve.

The present study aims to investigate projected changes in maximum temperature (Tmax), minimum temperature (Tmin) and precipitation over ITBA using selected CMIP6 Models. Future projections are analysed under two Shared Socioeconomic Pathways (SSPs): SSP2–4.5, representing a stabilization scenario with intermediate radiative forcing, and SSP5–8.5, representing a high-emission, fossil-fuel-intensive pathway (O'Neill et al., 2016). These scenarios provide a useful framework for examining the sensitivity of regional climate responses to different future emission trajectories. Specifically the study seeks to : i) quantify future warming trends, ii) assess changes in precipitation magnitude and variability, II) compare scenario-dependent climate responses amd iv) provide scientific information relevant to ecosystem conservation, water resources planning and climate adaptation within the reserve. By comparing moderate and high-emission scenarios, this study highlights the extent to which future climate risks in the reserve depend on global mitigation pathways. The findings are expected to contribute to climate adaptation strategies, biodiversity conservation planning, and long-term environmental management within the Imam Turki bin Abdullah Royal Reserve and similar arid-region ecosystems.

2. Data and Methods:

2.1 Study Area

The Imam Turki bin Abdullah Royal Reserve (ITBA) is located in northern Saudi Arabia and represents one of the largest protected areas in the Kingdom. The reserve occupies a climatically sensitive transition zone between arid and semi-arid environments, making it highly relevant for climate variability and change assessments (Figure 1). Its geographic position within the interior Arabian Peninsula exposes the region to strong continental influences, limited moisture availability and marked seasonal contrasts in temperature and precipitation.

The climate of the reserve is predominantly continental desert in nature, characterized by extremely hot summers, relatively cool winters, low annual rainfall, and pronounced interannual variability (Al-Shahrani et al., 2026). Precipitation is sparse, irregular and highly seasonal, occurring mainly during spring and late autumn, while summer months remain largely dry. Rainfall events are often episodic and convective, producing substantial year-to-year fluctuations in total precipitation. Such climatic characteristics make the reserve particularly vulnerable to rising temperatures, prolonged droughts and occasional intense rainfall episodes.

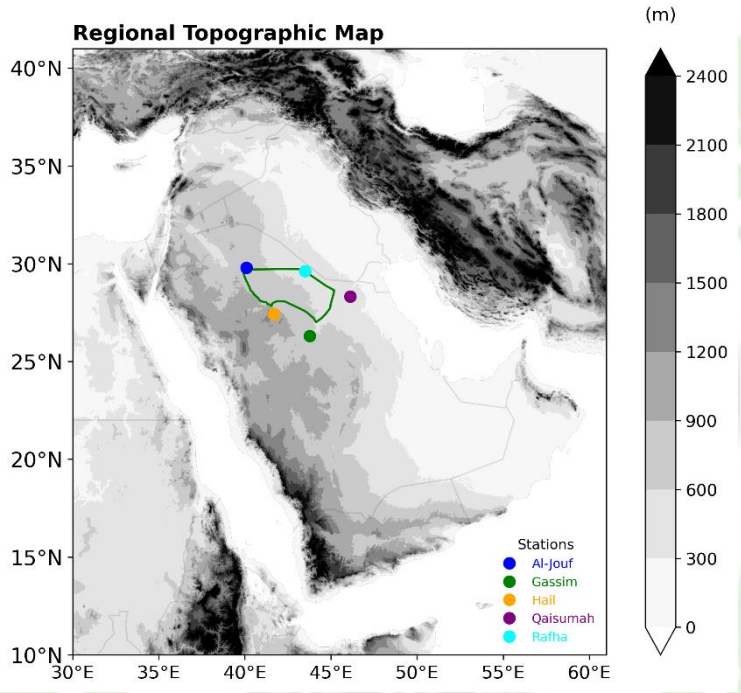

Figure 1: Topographic features of the study region.

Topographically, the study area is dominated by gently undulating terrain with moderate elevations, where most of the landscape lies between approximately 500 and 750 m above mean sea level. Lower-lying areas (<450 m) and relatively elevated terrain (>780 m) cover only a limited portion of the reserve. As a result, large-scale orographic influences on precipitation are generally weak and topographic control on surface temperature remains modest compared with mountainous regions. Nevertheless, local elevation gradients and land-surface heterogeneity may contribute to small-scale spatial differences in thermal extremes and rainfall distribution.

Considering its ecological importance, water scarcity, and sensitivity to climatic stressors, the ITBA is an important region for evaluating projected changes in temperature and precipitation under future climate scenarios using Coupled Model Intercomparison Project Phase 6 model outputs.

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This study adopts a structured methodological framework to assess projected changes in temperature and precipitation at five selected stations using outputs from the Coupled Model Intercomparison Project Phase 6 (CMIP6).

2.2 Observational Data

Observed daily data for maximum temperature (Tmax), minimum temperature (Tmin) and precipitation were obtained from National Center of Meteorology (NCM) for the five selected stations for the historical period (1985-2014) (Table 1). These station datasets were used to characterize baseline regional climate condition. Standard quality control procedures were applied to identify missing values, inconsistencies and outliers before analysis.

Table 1. Geographic characteristics of meteorological stations located within the study area.

No.	Station Code	Station Name	Latitude (N)	Longitude (E)	Elevation (m)
1	40405	Qassim	26°18'28"	43°46'03"	646.7
2	40394	Hail	27°26'04"	41°41'28"	1001.5
3	40362	Rafha	29°37'17"	43°29'41"	444.1
4	40361	Al-Jouf	29°47'19"	40°05'55"	668.7
5	40373	Qaisumah	28°19'08"	46°07'49"	357.6

2.3 CMIP6 Climate Model Data

For each station and climate variable, the baseline climatology was calculated as mean over 1985–2014, providing a reference for subsequent anomaly estimation. Historical variability was characterized using variance measures. Future projections were evaluated by calculating annual means and linear trends for Tmax, Tmin, and precipitation. Anomalies were expressed as differences between future period means and the baseline mean, enabling consistent comparison across models and timescales.

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The analysis considered one historical baseline period (1985–2014) and future projections under two Shared Socioeconomic Pathway scenarios: SSP2-4.5 and SSP5-8.5. Future projections were divided into four time slices:

- Near-term: 2015–2039
- Mid-century: 2040–2069
- Late-century: 2070–2100
- Full projection period: 2015–2100

Multi-model information was synthesized using ensemble techniques. The multi-model ensemble (MME) mean anomaly was computed based on top three best performing GCMs over each station (Al-Shahrani et al., 2026).

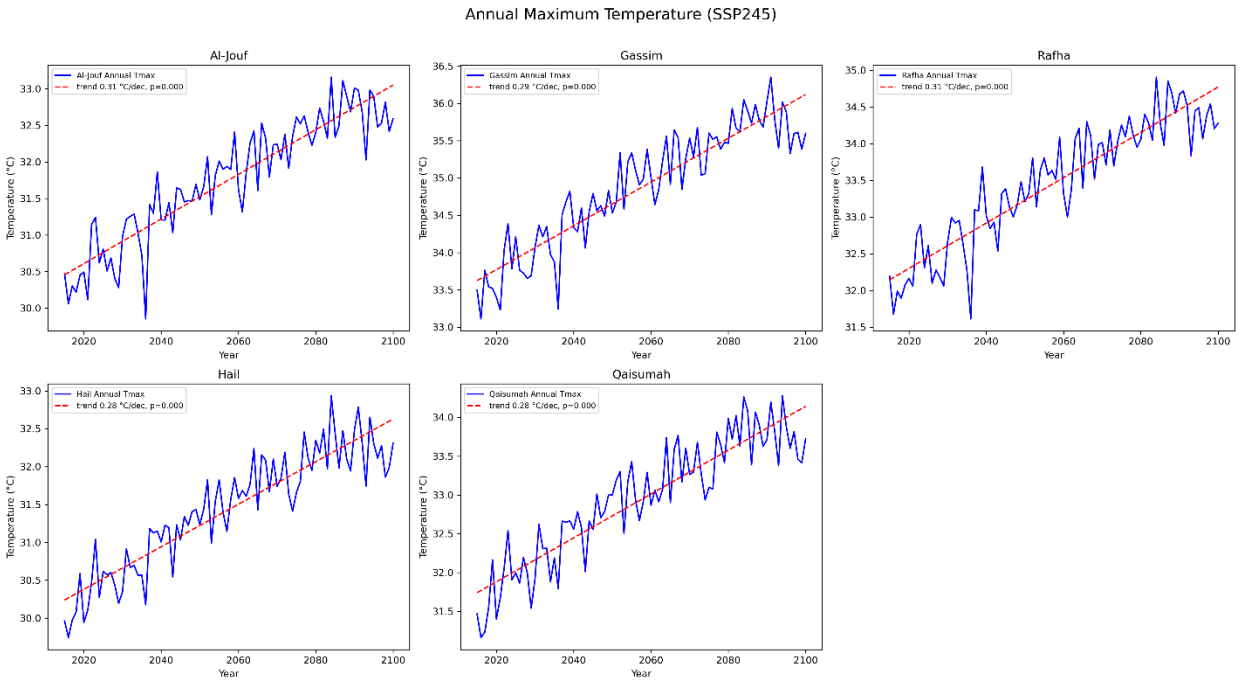
3. Results

3.1 Projected Changes in Maximum Temperature under SSP245:

Under the intermediate-emission scenario SSP2-4.5, the CMIP6 multi-model ensemble (MME) projects a clear and statistically significant increase in annual maximum temperature (Tmax) across the five representative stations of northern and central Saudi Arabia: Al-Jouf, Gassim, Hail, Qaisumah, and Rafha during 2015–2100 (Figure 2).

Figure 2. Projected annual maximum temperature (2015–2100) under SSP2-4.5 for **(a)** Al-Jouf, **(b)** Gassim, **(c)** Rafha, **(d)** Hail, and **(e)** Qaisumah based on CMIP6 GCMs. The blue line shows the annual Tmax, while the red dashed line indicates the linear trend.

Annual Tmax at all stations exhibits a pronounced upward trend superimposed on interannual variability, indicating a persistent regional warming signal. Estimated linear trends range from 0.281 to 0.309 °C decade^{-1}, suggesting a spatially coherent response to increasing greenhouse gas forcing rather than isolated station-scale anomalies. Rafha records the highest warming rate (0.309 °C decade^{-1}), followed by Al-Jouf (0.305 °C decade^{-1}) and Gassim (0.294 °C decade^{-1}), while Qaisumah (0.283 °C decade^{-1}) and Hail (0.281 °C decade^{-1}) show slightly lower trends.



When extrapolated over the study period, these rates correspond to projected increases of approximately 2.4–2.6 °C in annual Tmax by 2100 relative to baseline, with Rafha showing the largest increase (~2.63 °C) and Hail the lowest (~2.39 °C). The close clustering of projected changes highlights the dominant influence of large-scale climatic forcing, with only modest modulation by local factors such as elevation, continentality, and land-surface properties.

The robustness of these trends is supported by strong statistical relationships, with correlation coefficients ($R \approx 0.90–0.91$) and coefficients of determination ($R^2 \approx 0.82–0.84$), indicating that most of the temporal variability is explained by the long-term warming trend. Visual inspection of the time series further confirms that interannual fluctuations occur around a persistent positive trajectory.

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Spatially, the northern stations, particularly Rafha and Al-Jouf, exhibit slightly stronger warming than the other locations, possibly reflecting enhanced continentality or latitudinal amplification of thermal extremes. However, the relatively small differences among stations suggest that the study area behaves as a coherent climatic region, supporting the applicability of coordinated adaptation and resilience planning.

From an impact perspective, a 2.4–2.6 °C increase in annual Tmax by the end of the century is substantial and is likely to intensify the frequency, duration, and severity of extreme heat events, increase cooling-energy demand, and exacerbate pressures on water resources, agriculture, public health, and infrastructure.

Overall, the CMIP6 MME under SSP2-4.5 indicates steady and statistically significant warming in annual maximum temperature across northern and central Saudi Arabia, with increases of approximately 0.28–0.31 °C decade^{-1}, resulting in end-century warming of about 2.4–2.6 °C relative to baseline period.

3.2 Future Period Changes in Maximum Temperature Relative to Baseline (1985–2014)

Figure 3 shows projected changes in annual Tmax under SSP2-4.5 for three future time slices: near-term (2015–2039), mid-century (2040–2069), and late-century (2070–2100), relative to the historical baseline period 1985–2014. Across all five stations, the CMIP6 MME projects progressive warming through time. Mean anomalies averaged across the stations increase from approximately +1.34 °C in the near-term to +2.34 °C by mid-century and +3.08 °C in the late-century period.

Al-Jouf shows strong and sustained warming, with anomalies of +1.423 °C, +2.430 °C, and +3.236 °C for the three respective periods, yielding a full-period mean anomaly of +2.428 °C. Gassim exhibits a similar pattern, with projected anomalies of +1.470 °C, +2.464 °C, and +3.217 °C, and an overall mean of +2.446 °C.

Rafha records the highest warming among all stations, with anomalies of +1.465 °C, +2.480 °C, and +3.293 °C across the three periods, and a long-term mean anomaly of +2.478 °C. In contrast, Hail shows comparatively lower but still substantial warming of +1.152 °C, +2.165 °C, and +2.817 °C, while Qaisumah records +1.180 °C, +2.182 °C, and +2.851 °C, respectively.

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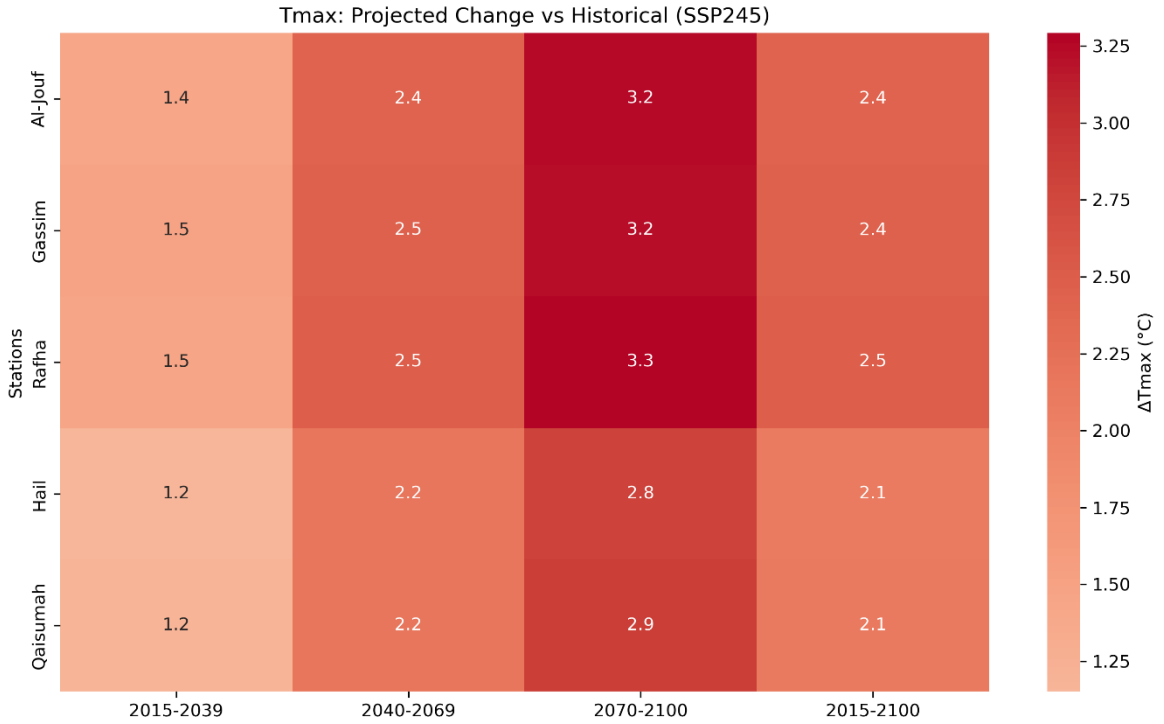

Figure 4. Heatmap of projected changes in annual maximum temperature (ΔTmax, °C) under SSP2-4.5 relative to the 1985–2014 baseline across four future periods near-term (2015–2039), mid-century (2040–2069), late-century (2070–2100), and the full period (2015–2100) for the five stations (Al-Jouf, Gassim, Rafha, Hail, and Qaisumah)

These results indicate a modest spatial gradient, with northern and more continental stations generally experiencing stronger warming than southern locations. By late century, the northern stations reach mean anomalies exceeding +3.1 °C, whereas southern stations approach +3.0 °C. Although the differences are relatively small, their persistence suggests that regional-scale forcing is slightly modified by local physiographic controls such as latitude, elevation, and land–atmosphere interactions.

The projected anomalies complement the linear trend analysis by illustrating cumulative departures from the historical climate baseline. Near-term warming exceeding +1 °C indicates that substantial warming is already underway, while mid-century anomalies approaching +2.5 °C and late-century anomalies exceeding +3 °C at several stations emphasize the growing risk of heat-related impacts. These findings highlight the urgent need for long-term adaptation measures, including heat-health management, climate-resilient infrastructure, and sustainable water and agricultural planning across northern and central Saudi Arabia.

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3.2 Projected Changes in Maximum Temperature under SSP5-8.5:

Under the high-emission scenario SSP5-8.5, the CMIP6 multi-model ensemble (MME) projects a strong and persistent increase in annual maximum temperature (Tmax) across all five study stations (Al-Jouf, Gassim, Rafha, Hail, and Qaisumah) during 2015–2100 (Figure 5). All stations exhibit statistically significant warming trends, indicating that the projected changes represent a robust externally forced climate signal rather than stochastic interannual variability.

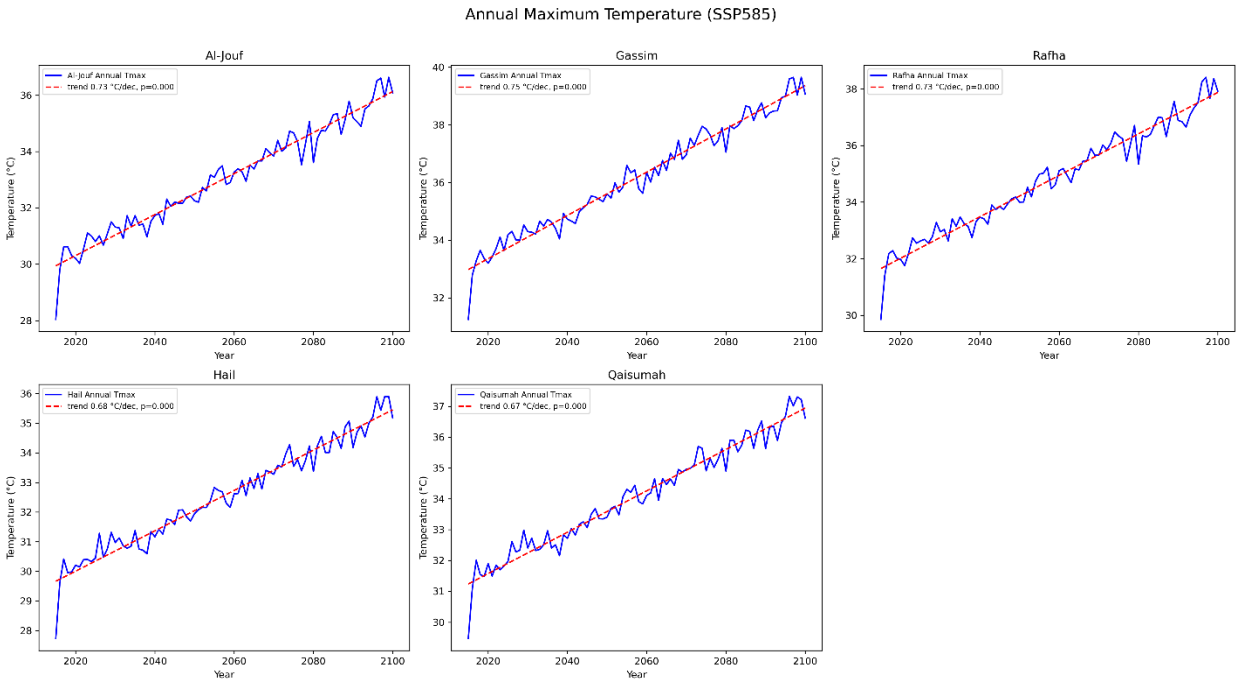

Figure 5. Projected annual maximum temperature (2015–2100) under SSP5-8.5 for **(a)** Al-Jouf, **(b)** Gassim, **(c)** Rafha, **(d)** Hail, and **(e)** Qaisumah based on CMIP6 GCMs. The blue line shows the annual Tmax, while the red dashed line indicates the linear trend.

Projected warming rates are substantial and range from 0.671 to 0.750 °C decade^{-1}. Gassim shows the steepest increase (0.750 °C decade^{-1}), followed by Rafha (0.732 °C decade^{-1}) and Al-Jouf (0.727 °C decade^{-1}). Hail (0.681 °C decade^{-1}) and Qaisumah (0.671 °C decade^{-1}) record slightly lower warming rates. Extrapolated over the study period, these trends correspond to end-century warming relative to baseline period of approximately +6.37 °C for Gassim, +6.22 °C for Rafha, +6.18 °C for Al-Jouf, +5.79 °C for Hail, and +5.71 °C for Qaisumah.

The inter-station spread in projected warming is modest (about 0.66 °C), indicating a regionally coherent response to high greenhouse gas forcing. Northern and more continental stations, particularly Rafha and Al-Jouf, together with centrally located Gassim, lie at the upper end of the

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warming range, whereas Hail and Qaisumah remain slightly lower. These differences likely reflect secondary influences of local physiographic factors such as elevation, continentality, and land-surface feedbacks. However, the magnitude of forced warming greatly exceeds these local variations, suggesting that the region may be treated as a coherent unit for climate risk assessment and adaptation planning.

From a climate risk perspective, the implications of SSP5-8.5 are severe. Increases of approximately +5.7 to +6.4 °C in annual Tmax by 2100 relative to baseline would substantially shift the upper tail of temperature distributions, leading to more frequent, intense, and prolonged extreme heat events. Such warming would also increase cooling-energy demand, intensify heat-stress risks for vulnerable populations and outdoor workers, and place significant pressure on infrastructure, water resources, agriculture, and public health systems.

Overall, the CMIP6 MME under SSP5-8.5 indicates rapid and substantial warming across northern and central Saudi Arabia, with annual Tmax increasing at rates of approximately 0.67–0.75 °C decade^{-1} and reaching around +6 °C above 2015 levels by the end of the century.

3.4 Future Period Changes in Maximum Temperature Relative to 1985–2014 Baseline

Relative to the historical baseline period (1985–2014), the CMIP6 MME projects pronounced increases in Tmax across all five stations under SSP5-8.5 (Figure 6). Near-term warming (2015–2039) ranges from approximately +1.2 to +1.6 °C, intensifies to +3.0 to +3.6 °C by mid-century (2040–2069), and reaches +5.1 to +5.8 °C in the late-century period (2070–2100). Averaged across all stations, the mean anomaly rises from +1.41 °C in the near-term to +3.31 °C by mid-century and +5.50 °C by late century, demonstrating an accelerating warming trajectory under continued high emissions.

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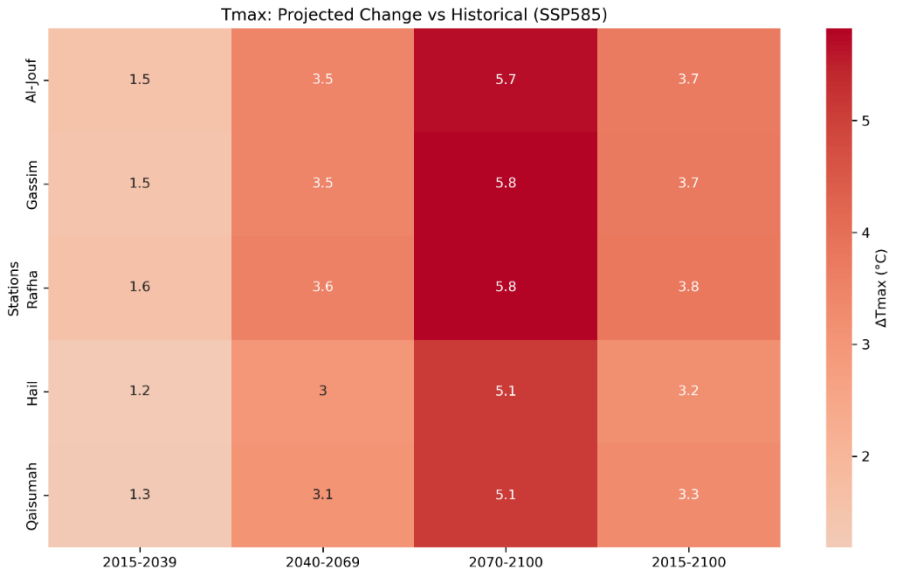

Figure 6. Heatmap of projected changes in annual maximum temperature (ΔTmax, °C) under SSP5-8.5 relative to the 1985–2014 baseline across four future periods near-term (2015–2039), mid-century (2040–2069), late-century (2070–2100), and the full period (2015–2100) for the five stations (Al-Jouf, Gassim, Rafha, Hail, and Qaisumah) .

Al-Jouf exhibits anomalies of +1.51 °C, +3.49 °C, and +5.69 °C for the three future periods, with a full-period mean anomaly of +3.71 °C. Gassim follows a similar pattern with +1.50 °C, +3.47 °C, and +5.82 °C, yielding a mean of +3.75 °C and the highest late-century anomaly among all stations. Rafha remains comparably warm throughout, recording +1.58 °C, +3.55 °C, and +5.78 °C, with the highest overall multi-decadal mean anomaly (+3.78 °C).

Hail, although slightly cooler than the northern stations, still shows substantial warming with anomalies of +1.19 °C, +3.00 °C, and +5.11 °C, corresponding to a mean of +3.23 °C. Qaisumah records +1.26 °C, +3.06 °C, and +5.10 °C, with a full-period mean of +3.30 °C. These results place Qaisumah marginally above Hail but below the northern interior stations.

A persistent spatial gradient is evident, with Rafha, Gassim, and Al-Jouf consistently experiencing the largest anomalies, while Hail and Qaisumah remain modestly lower. By late century, the northern group averages approximately +5.77 °C above the historical baseline, compared with around +5.11 to +5.12 °C for Hail and Qaisumah. This pattern likely reflects stronger continentality and enhanced land–atmosphere feedbacks in the northern interior.

These anomaly-based results closely align with the linear trend estimates of +0.67 to +0.75 °C decade^{-1} for 2015–2100. Together, the annual time series and future-period anomalies indicate that, without substantial mitigation, annual Tmax across the study region is likely to increase by

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approximately +5 to +6 °C relative to the historical climate by late century. Such warming would greatly intensify extreme heat risk, increase cooling-energy demand, and require urgent long-term adaptation planning across northern and central Saudi Arabia.

6.5 Projected Changes in Minimum Temperature under SSP2-4.5:

Under the intermediate-emission scenario SSP2-4.5, the CMIP6 multi-model ensemble (MME) projects a steady increase in annual minimum temperature (Tmin) across all five stations within the Imam Turki bin Abdullah Royal Reserve during 2015–2100 (Figure 7). The annual Tmin time series show persistent upward trends, while the fitted regression lines indicate a strong and spatially coherent warming signal throughout the study region.

Projected warming rates are tightly clustered, ranging from 0.327 to 0.336 °C decade^{-1}, suggesting limited spatial variability in nighttime warming. Gassim and Hail record the highest warming rates (0.336 °C decade^{-1} each), followed by Qaisumah and Rafha (approximately 0.332 °C decade^{-1}), while Al-Jouf shows the lowest trend (0.327 °C decade^{-1}). Over the 2015–2100 period, these rates correspond to increases in annual Tmin of approximately +2.78 to +2.86 °C relative to the baseline climate, with the highest warming at Gassim and Hail.

The narrow spread among stations highlights the strong regional consistency of the projections. Although minor local differences are evident, the results indicate that nighttime warming under SSP2-4.5 is primarily controlled by large-scale climatic forcing rather than station-specific effects.

A notable feature is that Tmin increases more rapidly than Tmax under the same scenario. Compared with projected Tmax trends (approximately 0.28–0.31 °C decade^{-1}), Tmin trends are higher by about 0.02–0.06 °C decade^{-1}. This implies a gradual reduction in the diurnal temperature range (DTR), estimated at roughly 0.19–0.47 °C by 2100. A narrowing DTR, driven by warmer nights, has important implications for human health, energy demand, agriculture, livestock productivity, and ecosystem processes that depend on nighttime thermal recovery.

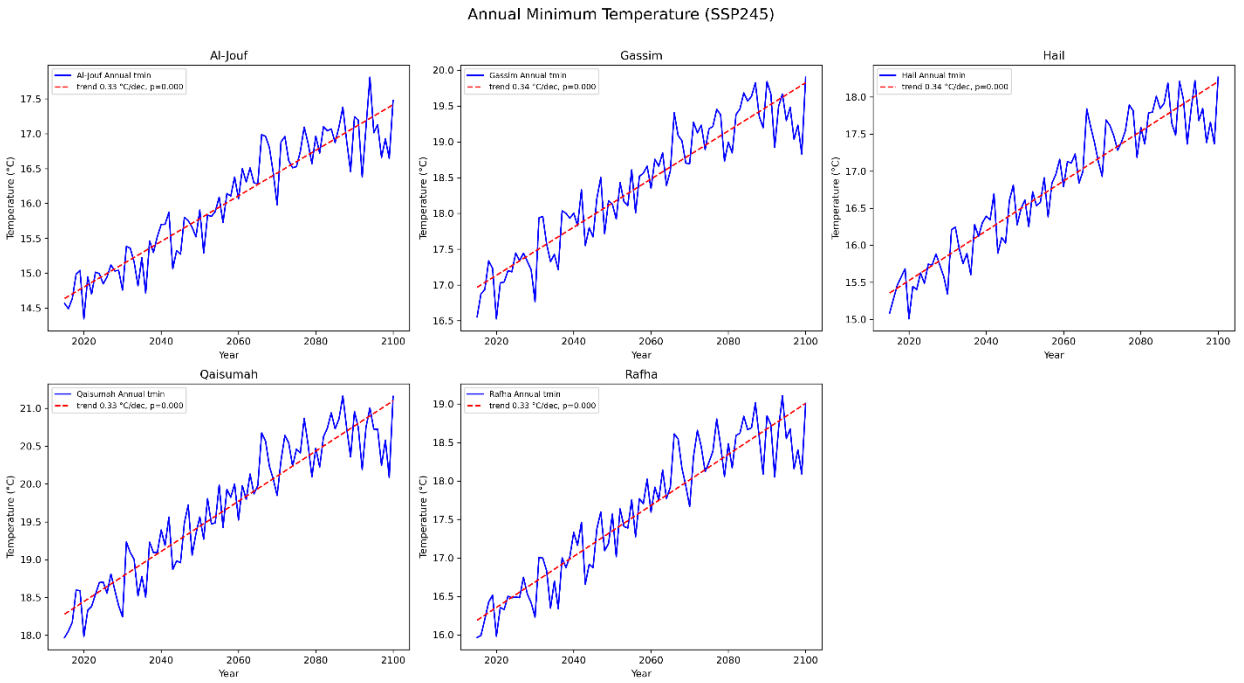

Figure 7. Projected annual minimum temperature (2015–2100) under SSP2-4.5 for **(a)** Al-Jouf, **(b)** Gassim, **(c)** Rafha, **(d)** Hail, and **(e)** Qaisumah based on CMIP6 GCMs. The blue line shows the annual Tmax, while the red dashed line indicates the linear trend.

Overall, the CMIP6 MME under SSP2-4.5 indicates robust and statistically significant nighttime warming across Al-Jouf, Gassim, Hail, Qaisumah, and Rafha, with annual Tmin projected to rise by approximately 2.8–2.9 °C by the end of the century. These findings emphasize the importance of incorporating nighttime heat stress into regional adaptation strategies, including building design, passive cooling measures, and sector-specific resilience planning.

3.6 Future Period Changes in Minimum Temperature Relative to Baseline (1985–2014)

Figure 8 summarizes projected changes in annual Tmin under SSP2-4.5 relative to the historical baseline period (1985–2014). The heatmap reveals clear time-progressive warming across all five stations. Averaged across the region, Tmin anomalies increase from approximately +1.21 °C in the near-term period (2015–2039) to +2.26 °C by mid-century (2040–2069) and +3.18 °C in the late-century period (2070–2100). The mean anomaly for the full projection period (2015–2100) is approximately +2.29 °C.

This stepwise increase indicates substantial early-century warming followed by continued but slightly slower warming after mid-century, consistent with the stabilization characteristics of SSP2-4.5.

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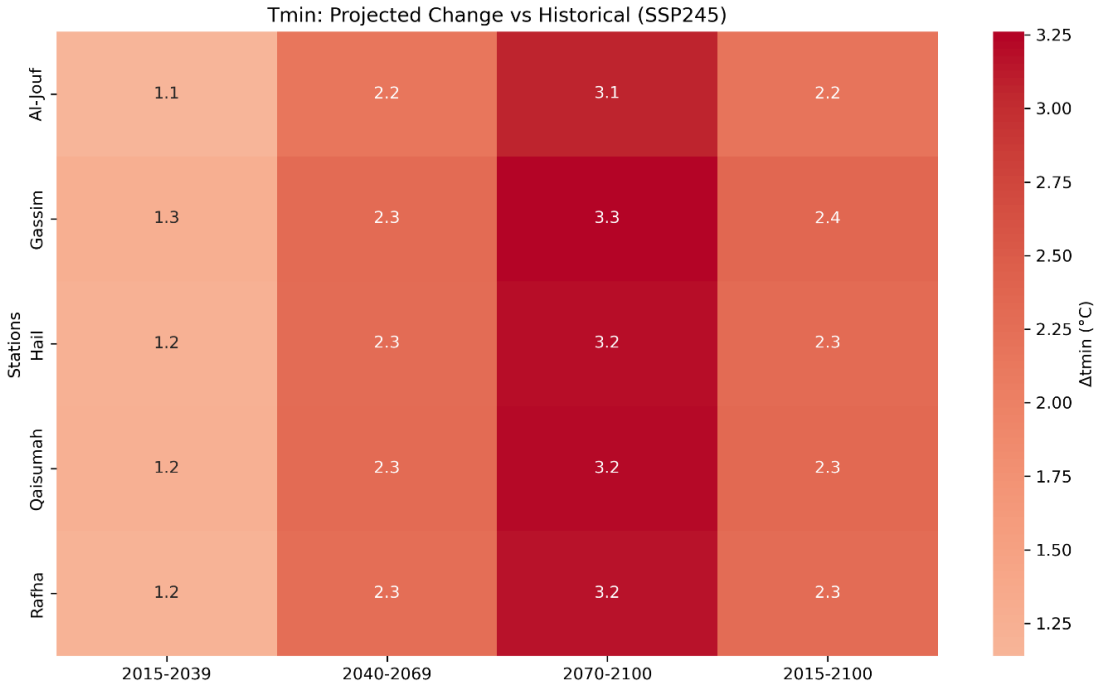

Figure 8. Heatmap of projected changes in Annual Minimum Temperature (ΔTmin, °C) under SSP2-4.5 relative to the 1985–2014 baseline across four future periods near-term (2015–2039), mid-century (2040–2069), late-century (2070–2100), and the full period (2015–2100) for the five stations (Al-Jouf, Gassim, Rafha, Hail, and Qaisumah) .

Inter-station differences remain modest throughout all future periods. Gassim records the highest anomalies in each time slice, with projected increases of +1.27 °C, +2.31 °C, +3.26 °C, and +2.35 °C for the near-term, mid-century, late-century, and full-period means, respectively. Qaisumah and Hail follow closely, whereas Rafha and Al-Jouf remain slightly lower. The spread between the warmest and coolest stations remains small, ranging from about 0.13 °C in the near-term to 0.20 °C by late century, confirming the dominance of a coherent regional warming signal.

By late century, Tmin anomalies reach approximately +3.06 to +3.26 °C across the five stations (Al-Jouf: +3.06 °C; Gassim: +3.26 °C; Hail: +3.20 °C; Qaisumah: +3.21 °C; Rafha: +3.17 °C). Such warming in nighttime temperatures is particularly significant because it limits nocturnal cooling, increases heat stress exposure, raises cooling-energy demand, and affects agricultural and ecological systems requiring nighttime recovery.

When considered alongside the stronger Tmin trends relative to Tmax, these anomalies further suggest a gradual narrowing of the diurnal temperature range by late century.

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Overall, the results demonstrate a robust and spatially consistent rise in annual Tmin across Al-Jouf, Gassim, Rafha, Hail, and Qaisumah under SSP2-4.5, with late-century warming of around +3 °C relative to the historical baseline and full-period mean anomalies ranging from approximately +2.19 to +2.35 °C among stations.

3.7 Projected Changes in Minimum Temperature under SSP5-8.5:

Under the high-emission scenario SSP5-8.5, the CMIP6 multi-model ensemble (MME) projects a pronounced and statistically robust increase in annual minimum temperature (Tmin) across all five stations within the Imam Turki bin Abdullah Royal Reserve during 2015–2100 (Figure 9). Annual Tmin values rise steadily through the century, while the fitted regression lines indicate strong and persistent nighttime warming across the region.

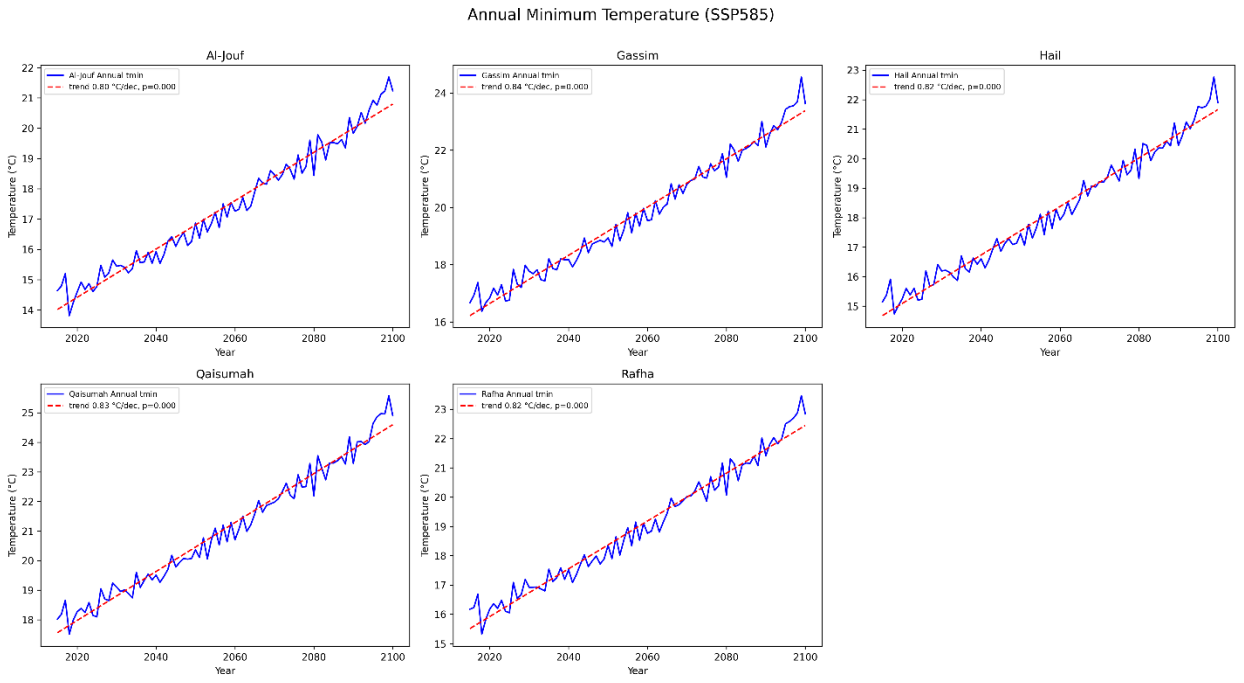

Figure 9. Projected Annual Minimum Temperature (2015–2100) under SSP5-8.5 for **(a)** Al-Jouf, **(b)** Gassim, **(c)** Rafha, **(d)** Hail, and **(e)** Qaisumah based on CMIP6 GCMs. The blue line shows the annual Tmax, while the red dashed line indicates the linear trend.

Projected Tmin trends are large and tightly clustered, ranging from 0.798 to 0.842 °C decade^{-1}. Gassim exhibits the highest warming rate (0.842 °C decade^{-1}), followed by Qaisumah (0.827 °C decade^{-1}), Hail (0.822 °C decade^{-1}), Rafha (0.816 °C decade^{-1}), and Al-Jouf (0.798 °C decade^{-1}). Over the 2015–2100 period, these rates correspond to exceptionally large increases in annual Tmin

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by late century, reaching approximately +7.16 °C at Gassim, +7.03 °C at Qaisumah, +6.99 °C at Hail, +6.94 °C at Rafha, and +6.79 °C at Al-Jouf relative to the 1985–2014 baseline.

Despite the magnitude of warming, inter-station differences remain modest, with an overall spread of only about 0.37 °C by the end of the century. This indicates a highly coherent regional response, with slightly stronger nighttime warming toward the central and northern interior.

A key feature of SSP5-8.5 is that nighttime temperatures increase faster than daytime maxima. Compared with projected Tmax trends under the same scenario (approximately 0.67–0.75 °C decade^{-1}), Tmin trends are higher by about 0.07–0.16 °C decade^{-1}. This suggests a reduction in the diurnal temperature range (DTR) of approximately 0.6–1.33 °C by 2100. A narrowing DTR implies diminished nocturnal cooling, thereby intensifying heat stress risks for human populations, livestock, crops, and ecosystems, while also increasing nighttime cooling-energy demand.

The projected Tmin time series display near-linear warming with relatively limited interannual variability around the trend line, indicating a dominant externally forced signal under sustained high emissions. Although the most pronounced warming occurs late in the century, all stations show substantial and continuous increases throughout the projection period.

Overall, the CMIP6 MME under SSP5-8.5 indicates dramatic nighttime warming across the reserve, with annual Tmin increasing by approximately +6.8 to +7.2 °C by 2100. Because Tmin rises faster than Tmax, nighttime heat risk is expected to intensify markedly across the region.

3.8 Future Period Changes in Minimum Temperature Relative to Baseline (1985–2014)

Figure 10 summarizes projected changes in annual Tmin under SSP5-8.5 relative to the historical baseline period (1985–2014). The heatmap reveals a strong and time-progressive increase across all stations. Averaged over the study region, Tmin anomalies rise from approximately +1.32 °C in the near-term period (2015–2039) to +3.23 °C by mid-century (2040–2069) and +6.01 °C during late century (2070–2100). The mean anomaly for the full projection period (2015–2100) is approximately +3.68 °C.

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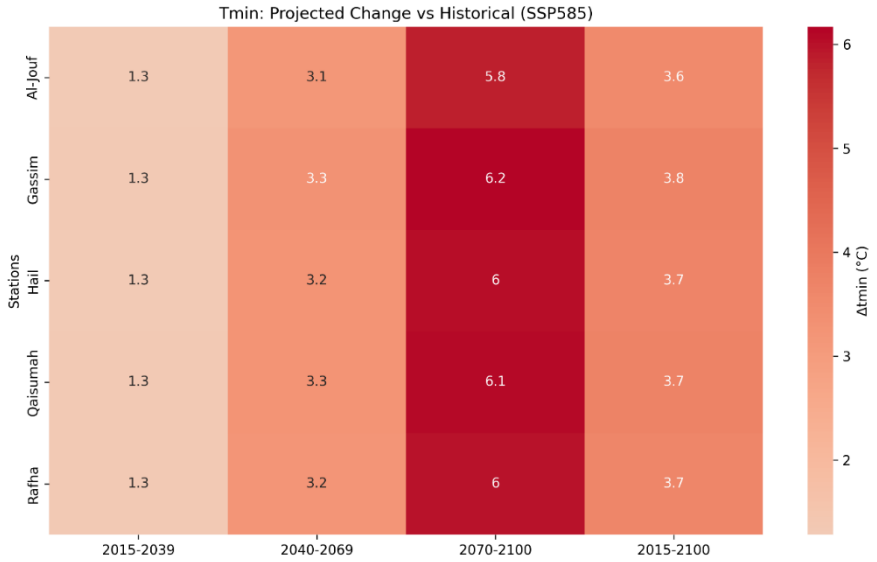

Figure 10. Heatmap of projected changes in Annual Minimum Temperature (ΔTmin, °C) under SSP5-8.5 relative to the 1985–2014 baseline across four future periods near-term (2015–2039), mid-century (2040–2069), late-century (2070–2100), and the full period (2015–2100) for the five stations (Al-Jouf, Gassim, Rafha, Hail, and Qaisumah) .

The increment from near-term to mid-century is around +1.9 °C, while the increase from mid-century to late century is larger at approximately +2.8 °C, demonstrating an acceleration of nighttime warming under continued high emissions.

Spatially, the warming pattern remains coherent, with only modest but meaningful differences among stations. Gassim consistently records the highest anomalies, with projected increases of +1.34 °C, +3.29 °C, and +6.17 °C for the near-term, mid-century, and late-century periods, respectively, yielding a full-period mean of +3.76 °C. Qaisumah and Hail follow closely, reaching late-century anomalies of approximately +6.06 °C and +6.02 °C, with full-period means of +3.71 °C and +3.68 °C. Rafha and Al-Jouf are slightly lower but still substantial, with late-century anomalies near +5.98 °C and +5.83 °C, and full-period means of +3.66 °C and +3.57 °C, respectively.

The inter-station spread is relatively small in the near-term (about 0.06 °C) but widens gradually to approximately 0.34 °C by late century, indicating a strengthening yet regionally uniform warming signal with limited modulation from local physiographic and continental influences.

These anomaly-based results align closely with the steep linear Tmin trends of approximately 0.80–0.84 °C decade^{-1}. They further indicate that warm nights intensify rapidly after mid-century, with late-century Tmin anomalies near +6 °C at most stations. Notably, Tmin anomalies exceed corresponding Tmax anomalies under SSP5-8.5 at all stations, particularly at Hail and Qaisumah,

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where differences approach +0.9 to +1.0 °C. This confirms a progressive narrowing of the diurnal temperature range, with nights warming faster than days.

Overall, the results demonstrate a robust and spatially consistent escalation in annual minimum temperature across Al-Jouf, Gassim, Rafha, Hail, and Qaisumah under SSP5-8.5, increasing from about +1.3 °C in the near-term to +3.2 °C by mid-century and approximately +6.0 °C by late century relative to 1985–2014. These findings highlight severe future nighttime heat stress risks under continued high-emission forcing.

3.9 Projected Changes in Annual Precipitation under SSP2-4.5

Figure 11 illustrates projected annual precipitation during 2015–2100 under the SSP2-4.5 scenario for five stations within the Imam Turki bin Abdullah Royal Reserve. The results indicate no statistically significant long-term trends in annual precipitation at any of the stations. Although the annual precipitation time series exhibit pronounced interannual variability, the fitted linear trend lines remain weak and nearly flat, indicating that long-term trends explain only a small fraction of total rainfall variance. This confirms the dominant role of internal climate variability in controlling year-to-year precipitation fluctuations across this arid region.

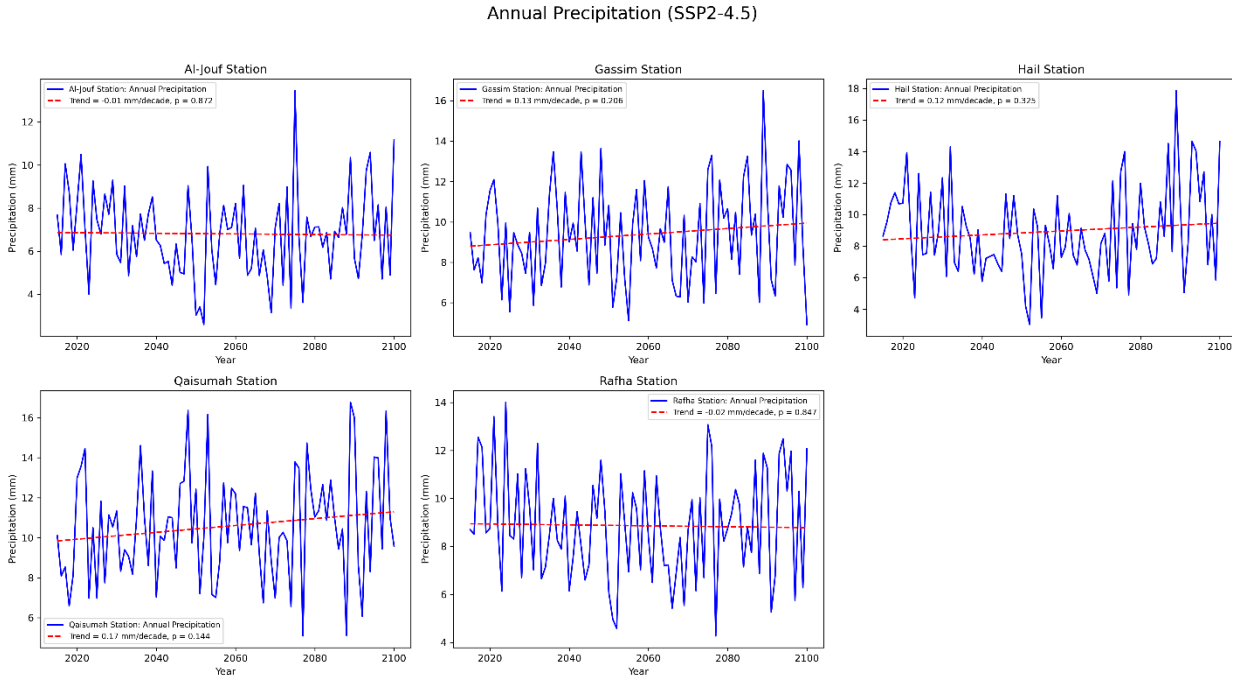

Figure 11. Projected Annual Precipitation (2015–2100) under SSP2-4.5 for **(a)** Al-Jouf, **(b)** Gassim, **(c)** Rafha, **(d)** Hail, and **(e)** Qaisumah based on CMIP6 GCMs. The blue line shows the annual precipitation variability, while the red dashed line indicates the linear trend.

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Station-specific trend estimates are small and statistically insignificant. Al-Jouf shows a slight negative trend of approximately −0.01 mm decade^{-1} ($p = 0.872$), while Rafha records a similarly weak decline of about −0.02 mm decade^{-1} ($p = 0.847$). In contrast, Gassim, Hail, and Qaisumah display weak positive tendencies of about +0.13, +0.12, and +0.17 mm decade^{-1}, respectively, but none are statistically significant ($p = 0.206$, 0.325, and 0.144). These very small slopes are negligible compared with the magnitude of annual rainfall variability observed in the time series.

Among the stations, Qaisumah exhibits the largest positive tendency, whereas Rafha and Al-Jouf remain nearly unchanged. However, the absence of statistical significance across all stations indicates that these differences should be interpreted cautiously and cannot be considered robust climate signals.

The lack of a clear long-term precipitation trend does not contradict the pronounced warming projected for the region. Rather, it reflects limited model agreement regarding monotonic changes in annual rainfall under intermediate forcing. Stable annual rainfall totals do not necessarily imply hydroclimatic stability. With projected increases in Tmax and Tmin across the reserve, potential evapotranspiration is expected to rise, thereby increasing aridity, soil-moisture stress, and drought risk even without substantial reductions in annual precipitation.

In addition, annual precipitation totals may conceal important shifts in rainfall seasonality, wet-day frequency, precipitation intensity, and dry-spell duration, all of which are highly relevant for groundwater recharge, flash-flood risk, rangeland productivity, and ecosystem resilience.

Overall, the CMIP6 multi-model ensemble under SSP2-4.5 suggests that annual precipitation totals across the reserve are likely to remain broadly stable through the 21st century, although rising temperatures may substantially worsen effective moisture deficits and water-resource stress.

3.10 Future Period Changes in Annual Precipitation Relative to 1985–2014 Baseline

Figure 12 summarizes projected annual precipitation anomalies under SSP2-4.5 relative to the historical baseline period (1985–2014). The heatmap reveals small and spatially mixed changes across stations and future periods, with no coherent regional tendency toward wetter or drier conditions. Averaged across all stations, anomalies are approximately −0.21 mm in the near-term period (2015–2039), −1.04 mm by mid-century (2040–2069), +0.13 mm in late century (2070–2100), and −0.38 mm for the full projection period (2015–2100).

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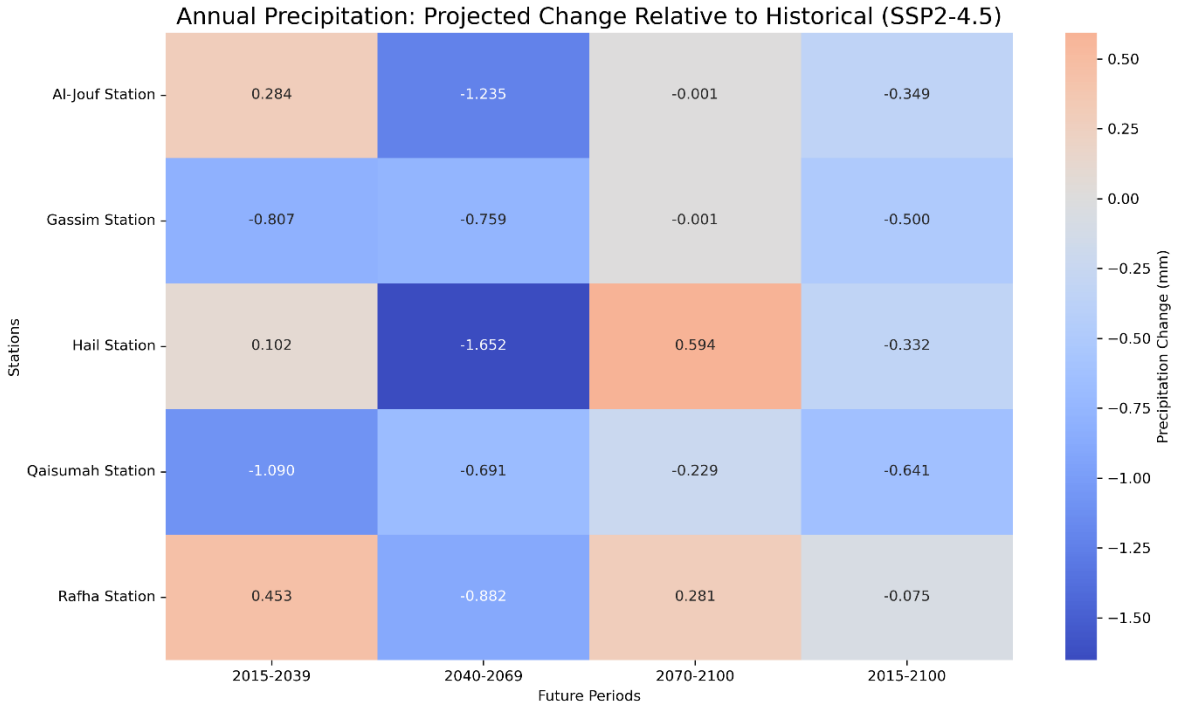

Figure 12. Heatmap of projected changes in Annual Precipitation (ΔPRCP, °C) under SSP2-4.5 relative to the 1985–2014 baseline across four future periods near-term (2015–2039), mid-century (2040–2069), late-century (2070–2100), and the full period (2015–2100) for the five stations (Al-Jouf, Gassim, Rafha, Hail, and Qaisumah).

This pattern indicates a modest drying tendency through mid-century followed by partial recovery toward late century. However, the magnitude of these anomalies remains very small relative to the pronounced year-to-year variability shown in Figure 11, confirming a low-signal and high-uncertainty precipitation response under SSP2-4.5.

At the station scale, Al-Jouf shows slightly wetter near-term conditions (+0.284 mm), followed by stronger mid-century drying (−1.235 mm), and near-neutral late-century conditions (−0.001 mm), resulting in a full-period anomaly of −0.349 mm. Gassim remains drier than the baseline in most periods, with anomalies of −0.807 mm, −0.759 mm, and −0.001 mm, yielding an overall anomaly of −0.500 mm.

Hail exhibits a mixed pattern, with near-neutral near-term conditions (+0.102 mm), pronounced mid-century drying (−1.652 mm), followed by the strongest late-century wetting signal among all stations (+0.594 mm), although its full-period anomaly remains negative (−0.332 mm). Qaisumah records persistent negative anomalies throughout all periods (−1.090 mm, −0.691 mm, and −0.229 mm), producing the largest long-term drying signal (−0.641 mm). Rafha shows slight wetting in the near-term (+0.453 mm) and late century (+0.281 mm), interrupted by mid-century drying (−0.882 mm), resulting in a near-neutral long-term anomaly (−0.075 mm).

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Collectively, these findings indicate that precipitation changes under SSP2-4.5 are modest, spatially heterogeneous, and dominated more by temporal variability than by a strong externally forced signal. Most stations experience drier conditions during mid-century, while some recovery or weak wetting appears by late century. Nevertheless, there is no robust evidence of sustained long-term wetting or drying across the reserve.

Consequently, future water-resource challenges are likely to arise less from major shifts in mean annual precipitation totals and more from increasing evaporative demand, recurrent drought stress, and rainfall variability under continued warming.

3.11 Projected Changes in Annual Precipitation under SSP5-8.5

Under the high-emission scenario SSP5-8.5, the CMIP6 multi-model ensemble (MME) indicates no statistically significant long-term change in annual precipitation across the five study stations within the Imam Turki bin Abdullah Royal Reserve during 2015–2100 (Figure 13). Annual precipitation time series exhibit substantial interannual variability, while the fitted linear trend lines remain weak and only slightly positive. This indicates that long-term linear trends explain only a very small fraction of total rainfall variance, with natural variability remaining the dominant control on annual precipitation.

Although all stations show positive tendencies, their magnitudes are small and mostly statistically insignificant. Al-Jouf records a weak increase of approximately +0.04 mm decade^{-1} ($p = 0.670$). Gassim and Qaisumah exhibit comparatively larger positive slopes of about +0.21 and +0.22 mm decade^{-1}, respectively, with marginal statistical significance ($p = 0.079$ and 0.098). Hail shows the strongest increase (+0.24 mm decade^{-1}), although it remains statistically insignificant at the 95% confidence level ($p = 0.110$). Rafha displays a moderate positive trend of +0.14 mm decade^{-1} ($p = 0.260$). Even when extrapolated over the projection period, these increases remain modest relative to the large year-to-year rainfall fluctuations shown in the figure 13.

Among the five stations, Hail, Qaisumah, and Gassim show the strongest upward tendencies, suggesting a slightly wetter signal compared with Al-Jouf and Rafha. However, because statistical significance is weak or absent, these differences should be interpreted cautiously and do not represent robust regional precipitation changes.

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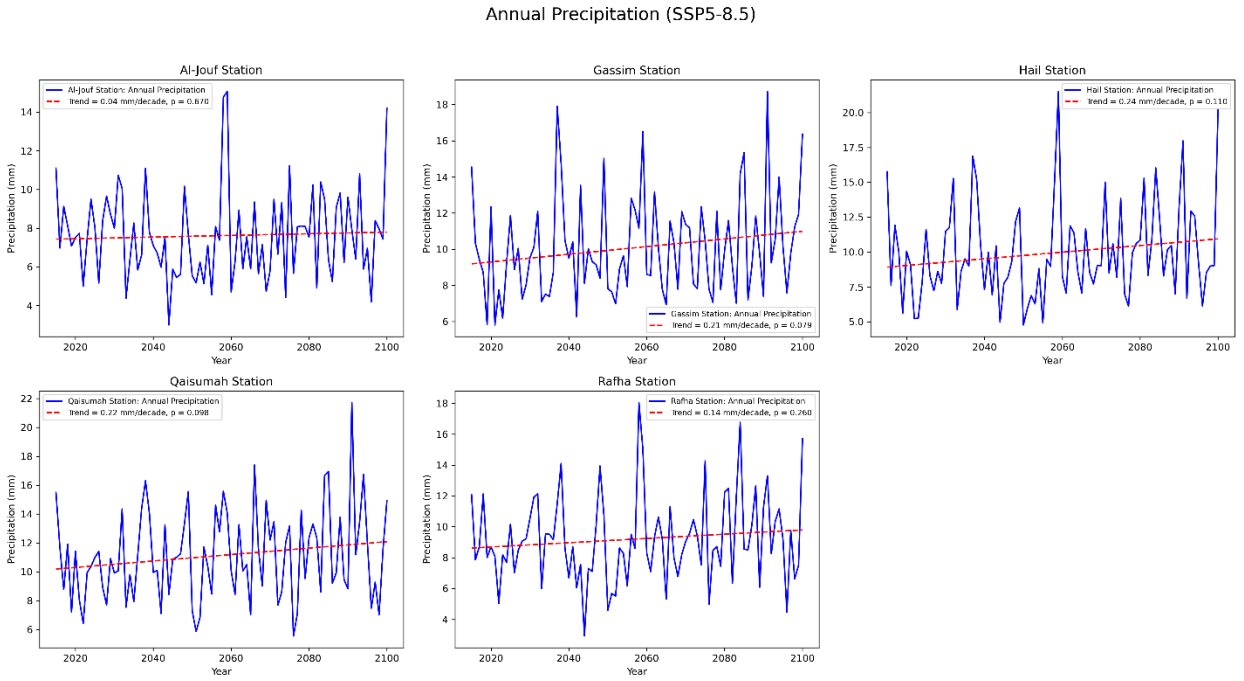

Figure 13. Projected Annual Precipitation (2015–2100) under SSP5-8.5 for **(a)** Al-Jouf, **(b)** Gassim, **(c)** Rafha, **(d)** Hail, and **(e)** Qaisumah based on CMIP6 GCMs. The blue line shows the annual precipitation variability, while the red dashed line indicates the linear trend.

The absence of a strong precipitation trend should not be interpreted as hydroclimatic stability. Under SSP5-8.5, substantial warming in Tmax and Tmin is projected across the reserve, which is likely to increase potential evapotranspiration and intensify climatic aridity even if annual rainfall remains near current levels. Furthermore, annual precipitation totals may mask shifts in seasonality, wet-day frequency, rainfall intensity, and dry-spell duration, all of which are highly relevant for groundwater recharge, water availability, rangeland productivity, and flash-flood risk.

Overall, the CMIP6 MME suggests that mean annual precipitation under SSP5-8.5 remains broadly stable, but rising temperatures are expected to substantially worsen effective moisture deficits and hydrological stress across the region.

3.12 Future Period Changes in Annual Precipitation Relative to Baseline (1985–2014)

Figure 14 presents projected anomalies in annual precipitation under SSP5-8.5 relative to the historical baseline period (1985–2014). The heatmap shows small and mixed-sign changes across stations and future periods, reinforcing the conclusion from the annual time series that no robust long-term precipitation trend emerges under high forcing. Averaged across all stations, anomalies

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are approximately +0.21 mm in the near-term period (2015–2039), −0.16 mm by mid-century (2040–2069), +0.85 mm in the late-century period (2070–2100), and +0.31 mm for the full projection period (2015–2100).

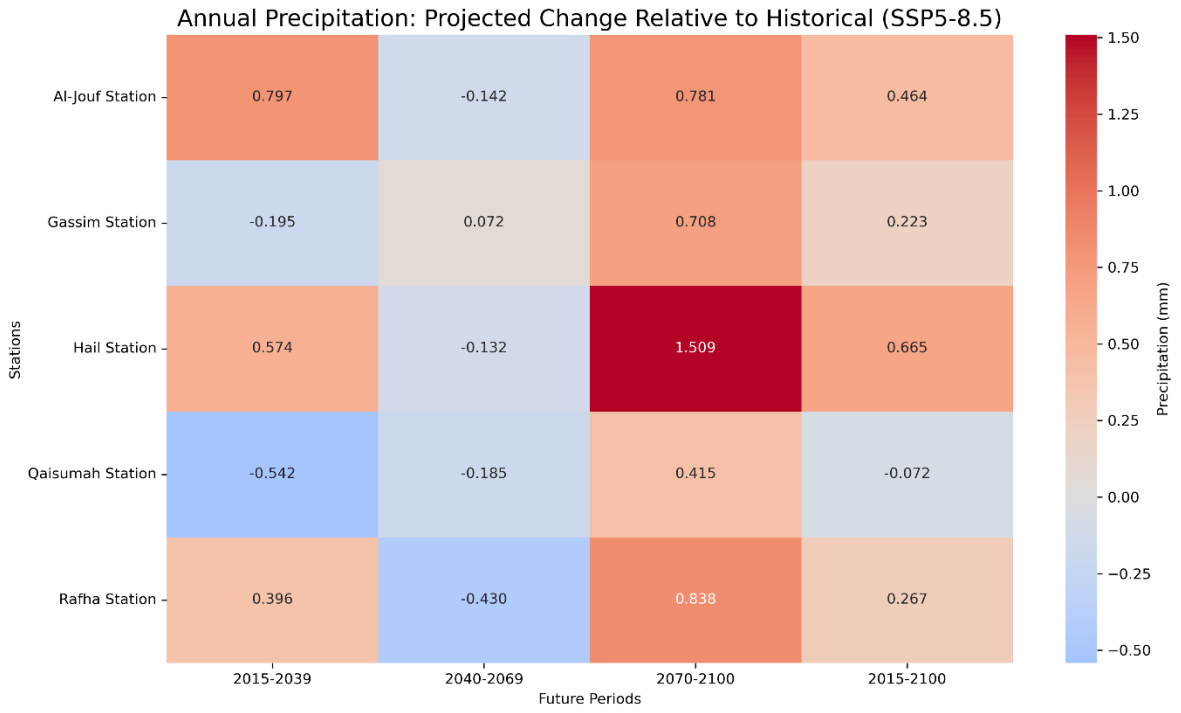

Figure 14. Heatmap of projected changes in Annual Precipitation (ΔPRCP, °C) under SSP5-8.5 relative to the 1985–2014 baseline across four future periods near-term (2015–2039), mid-century (2040–2069), late-century (2070–2100), and the full period (2015–2100) for the five stations (Al-Jouf, Gassim, Rafha, Hail, and Qaisumah)

These results indicate a weak but somewhat more positive precipitation response than under SSP2-4.5, particularly in late century. However, the signal remains small relative to strong natural interannual variability, and no consistent transition toward substantially wetter regional conditions is evident.

At the station level, Al-Jouf shows wetter near-term conditions (+0.797 mm), slight mid-century drying (−0.142 mm), and renewed wetting by late century (+0.781 mm), yielding a positive full-period anomaly of +0.464 mm. Gassim begins slightly drier (−0.195 mm), shifts weakly wetter in

mid-century (+0.072 mm), and records stronger late-century wetting (+0.708 mm), producing an overall anomaly of +0.223 mm.

Hail exhibits the strongest wetting signal among all stations, with anomalies of +0.574 mm in the near term, −0.132 mm in mid-century, and +1.509 mm in late century, resulting in the largest full-period increase (+0.665 mm). Qaisumah remains the driest station overall, with anomalies of −0.542 mm, −0.185 mm, and +0.415 mm, producing a near-neutral full-period anomaly (−0.072 mm). Rafha records +0.396 mm in the near term, −0.430 mm in mid-century, and +0.838 mm in late century, yielding an overall anomaly of +0.267 mm.

Inter-station differences increase slightly by late century, with Hail and Rafha showing stronger wetting responses than Qaisumah and Gassim. Nevertheless, the overall spread remains modest, indicating that projected precipitation changes are still considerably smaller than the temperature-driven hydroclimatic signal.

When considered alongside the pronounced warming projected under SSP5-8.5, these modest precipitation increases are unlikely to offset the substantial rise in evaporative demand caused by higher temperatures. Consequently, climatic aridity and drought risk may intensify despite small increases in annual rainfall totals. In addition, any increase in annual precipitation could arise through fewer but more intense rainfall events, altered seasonality, or longer dry periods interrupted by heavy storms, thereby increasing flash-flood risk while continuing to stress water resources and ecosystems.

4. Conclusion

This study evaluated future climate projections for the Imam Turki bin Abdullah (ITBA) Royal Reserve using the CMIP6 multi-model ensemble under the intermediate-emission scenario SSP2-4.5 and the high-emission scenario SSP5-8.5. Climate projections were derived from CMIP6 multi-model ensembles (MMEs), with model selection tailored to each station based on performance (Al-Shahrani et al., 2026). The results consistently indicate that temperature change will be the dominant climate signal across the reserve during the 21st century, whereas projected changes in annual precipitation remain comparatively weak, uncertain, and highly variable.

Both maximum temperature (Tmax) and minimum temperature (Tmin) show statistically significant warming trends at all five representative stations under both scenarios. Under SSP2-4.5, annual Tmax is projected to increase by approximately +2.4 to +2.6 °C by 2100 relative to historical baseperiod, while Tmin rises by about +2.8 to +2.9 °C. Under SSP5-8.5, warming intensifies substantially, with Tmax increasing by about +5.7 to +6.4 °C and Tmin by approximately +6.8 to +7.2 °C by the end of the century. These findings demonstrate that nighttime

temperatures are projected to rise faster than daytime temperatures, particularly under the high-emission pathway.

The faster increase in Tmin relative to Tmax implies a progressive narrowing of the diurnal temperature range (DTR), especially under SSP5-8.5. Reduced nocturnal cooling may intensify heat stress, increase cooling-energy demand, and negatively affect ecosystem recovery, livestock productivity, and crop performance. Warm nights are particularly critical in arid environments where nighttime cooling provides essential thermal relief.

Temporal analysis of future periods further shows progressive warming from the near-term to late century. Under SSP2-4.5, temperature increases continue through mid-century and then rise more gradually thereafter, reflecting partial stabilization under moderate forcing. In contrast, SSP5-8.5 exhibits accelerated warming after mid-century, with the largest increases occurring during 2070–2100. This divergence between scenarios highlights the strong influence of future greenhouse gas emissions on regional climate outcomes.

In contrast to temperature, annual precipitation projections remain much less certain. Under SSP2-4.5, no statistically significant long-term wetting or drying trend is detected, and anomalies remain small, mixed in sign, and inconsistent across stations and future periods. A modest drying tendency appears during mid-century, followed by partial recovery in late century. Under SSP5-8.5, annual precipitation also shows no robust statistically significant long-term trend, although several stations exhibit weak positive tendencies and slightly wetter late-century conditions, particularly Hail, Rafha, and Al-Jouf. Nevertheless, these projected changes remain small compared with the magnitude of natural interannual rainfall variability.

Therefore, relatively stable annual precipitation totals should not be interpreted as hydroclimatic stability. Rising temperatures are expected to substantially increase potential evapotranspiration, intensify soil-moisture deficits, and increase drought risk under both scenarios. Moreover, annual precipitation totals may mask important shifts in rainfall characteristics, including changes in seasonality, wet-day frequency, storm intensity, and dry-spell duration. Such changes may increase flash-flood risk while simultaneously reducing effective groundwater recharge and stressing rangeland ecosystems.

Overall, the findings indicate that the ITBA Royal Reserve is highly vulnerable to future warming, particularly under SSP5-8.5. The most significant climate risks are likely to arise from increasing heat extremes, warmer nights, enhanced evaporative demand, and greater hydrological stress rather than large shifts in mean annual rainfall totals. These results highlight the urgent need for climate adaptation strategies focused on heat-risk management, sustainable water-resource planning, rangeland and biodiversity resilience, ecosystem conservation, and climate-resilient infrastructure. Finally, the substantial contrast between SSP2-4.5 and SSP5-8.5 demonstrates that

emissions mitigation can significantly reduce long-term climate risks across the reserve and surrounding dryland regions of northern Saudi Arabia.

Author Contributions: All the authors contributed to the main idea and design of the study. Material preparation, data collection, and analyses were performed by A.A.H.A.-S. H.A. supervised the research work, interpreted the results and helped in writing the first draft of the manuscript. A.A.A.-D. assisted in data collection, literature review, visualization, and final proofreading of the manuscript.

Data availability: Observed climate data were obtained from the National Center of Meteorology (NCM), Saudi Arabia, and are not publicly available but may be accessed upon reasonable request and with permission from NCM. CMIP6 model data are publicly available through the Earth System Grid Federation (ESGF) data repository (https://esgf.llnl.gov/).

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