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Key Points:

- This study presents a Climate Change Center as a hub for research, data, and forecasting, supporting adaptation and sustainability
- The center will develop a climate database, models, and forecasts to improve climate projections and weather predictions for the Arabian Peninsula
- It will assess extreme weather impacts and provide a climate portal for stakeholders, policymakers, and the public to access key data

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New Climate Change Center of Saudi Arabia: Advancing Understanding and Prediction for the Arabian Peninsula Climate

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Abstract The desert climate of the Arabian Peninsula (AP), marked by sparse rainfall, extreme temperatures, and frequent dust events, significantly impacts its 80-million population, environment, and economy. Rising temperatures and dust incursions exacerbate these harsh conditions, yet the AP's climate is underrepresented in global climate research. Understanding its variability is crucial for improving predictions on subseasonal-to-seasonal timescales and for developing reliable climate change projections. Existing climate models fail to capture the region's unique environment, topography, and land-use changes, leading to poor representation of key processes like local convection, aridity, and moisture transport. To address these gaps, Saudi Arabia established the Climate Change Center (CCC) in 2022, part of the Saudi Vision 2030 initiative. The CCC aims to study climate variability and project future changes using advanced Earth system models developed in collaboration with international partners. This study presents the CCC's roadmap, focusing on its relevance for global climate research and policymaking, including the Saudi and Middle East Green Initiatives. We also discuss regional uncertainties in the IPCC's climate projections for the AP and highlight the development of high-resolution regional models that account for local atmospheric, land, and oceanic processes. The CCC is developing subseasonal-to-seasonal forecasting systems and drought monitoring tools, alongside user-friendly dashboards to offer stakeholders customized climate data. These tools, set for launch in 2025, will aid informed decision-making in addressing extreme weather events and climate-related challenges in Saudi Arabia.

Plain Language Summary The Arabian Peninsula (AP) has a very dry desert climate with little rainfall, extremely high temperatures, and frequent dust storms affect the lives of over 80 million people in the region. As climate change makes things worse—like rising temperatures and more dust—it's important to understand how the climate works here and how it may change in the future. However, most global climate studies don't focus much on this region. Large-scale climate models also struggle to capture the AP's unique features, such as its deserts, mountains, and coastal areas. To address this, Saudi Arabia started the Climate Change Center (CCC) in 2022 as part of Vision 2030. In this study, we detail the CCC's goals to study the

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region's climate, improve predictions for the future using advanced climate models, develop tools for seasonal forecasting and drought monitoring, and create easy-to-use dashboards that will let people access climate data. These tools, launching in 2025, will help decision-makers in Saudi Arabia tackle problems like extreme weather, rising sea levels, and planning for greener and more sustainable cities.

1. Basis for Establishing a Climate Change Center for the Arabian Peninsula

The Arabian Peninsula (AP), 80% of which is encompassed by the Kingdom of Saudi Arabia (KSA), is among the world's most water-scarce, hot, and arid regions, making it vulnerable to environmental stress. These vulnerabilities are being further aggravated by the intensifying influences of climate change, manifesting as increasingly frequent and severe events such as heatwaves, prolonged droughts, and intense dust storms (Amin et al., 2016; Arneth et al., 2019; Dasari et al., 2021; IPCC, 2022; Luong et al., 2020; Saharwardi et al., 2023; Saharwardi, Dasari, et al., 2025, Saharwardi, Hassan, et al., 2025; Zampieri et al., 2016). For instance, the observed temperature anomaly in summer 2024, illustrated in Figure 1a, demonstrates the severity of extreme heat events across the AP, with widespread temperature deviations substantially surpassing normal levels. Projections for the end of the 21st century indicate that rising dry-bulb and wet-bulb temperatures, particularly in coastal regions adjacent to the Arabian Gulf, may approach thresholds that challenge human habitability (Pal & Eltahir, 2016; Safieddine et al., 2022). These intensifying heat stress conditions poses critical challenges, including disruptions to key religious traditions like the annual Islamic Hajj pilgrimage (S. Kang et al., 2019), while posing broader risks to public health and the well-being of millions of pilgrims. However, recent observations indicate remarkably temperature mitigation potential in regions with managed vegetation (Zampieri et al., 2023).

The above climate extremes occur in superposition to long-term climatic trends across the AP, including steadily rising temperatures and a significant decline in annual precipitation, particularly in northern regions (Almazroui et al., 2012, 2020; Almazroui, Islam, et al., 2017, Almazroui, Saeed, et al., 2017, Almazroui, Tayeb, 2017; Dasari et al., 2021; Odnoletkova & Patzek, 2021). These climate shifts have further exacerbated water scarcity issues in the KSA (Al-Zahrani, 2009; DeNicola et al., 2015), a challenge compounded by increasing water demands (Odhiambo, 2017). In addition, the region faces a rising frequency and intensity of droughts, dust storms, and extreme rainfall, amplifying its vulnerability to climate-related hazards and complicating efforts to ensure long-term sustainability (Kunchala et al., 2019; Mahmoud et al., 2023; Harikishan et al., 2022; Harikishan et al., 2023; Saharwardi et al., 2023, 2024, Saharwardi, Dasari, et al., 2025, Saharwardi, Hassan, et al., 2025). These changes are particularly noticeable in Jeddah, where the increased frequency and intensity of extreme rainfall have produced recurrent, high-impact floods (Figure 2), consistent with recent regional analyses (e.g., Ratnam et al., 2024) and earlier work on the role of Arabian Sea cyclones on the AP (Chakraborty, Mujumdar, et al., 2006). This aligns with evidence for shifting characteristics of Jeddah extreme events (Luong et al., 2020). Further, beyond these long-term shifts, the AP temperature and moisture budgets show distinct controlling processes. For temperature, near-surface variability reflects the balance of radiative heating and turbulent (sensible/latent) fluxes that set the dry-static energy budget (e.g., Smith & Dare, 1986). For precipitation, extremes depend on column-integrated moisture convergence and moisture availability over adjacent basins (e.g., Luong et al., 2024). Intraseasonal MJO phases and interannual ENSO/IOD states modulate low-level moisture transport and vertical stability over the Red Sea and Arabian Gulf, altering convective efficiency and heat stress. Regional diagnostics further show that moisture pathways into western/central KSA strengthen under favorable ENSO/IOD phases (Chakraborty, Behera, et al., 2006), consistent with observed circulation–temperature linkages over the AP (Attada et al., 2019; Dasari, Desamsetti, et al., 2022, Dasari, Viswanadhapalli et al., 2022; Harikishan et al., 2025).

The rising frequency of dust storms observed across the AP is linked to the increasing severity of droughts in the region (Saharwardi et al., 2023, 2024). As depicted in Figure 3, the long-term variability in dust storms across the AP reveals a trend of increasing intensity over time (Harikishan et al., 2022; Harikishan et al., 2023). These escalating events carry profound consequences on public health, infrastructure, and agriculture. The combined effects of dust storms, rising temperatures, and prolonged droughts highlight the urgent need for high-resolution monitoring and forecasting systems to enhance preparedness and enable effective regional planning and management strategies.

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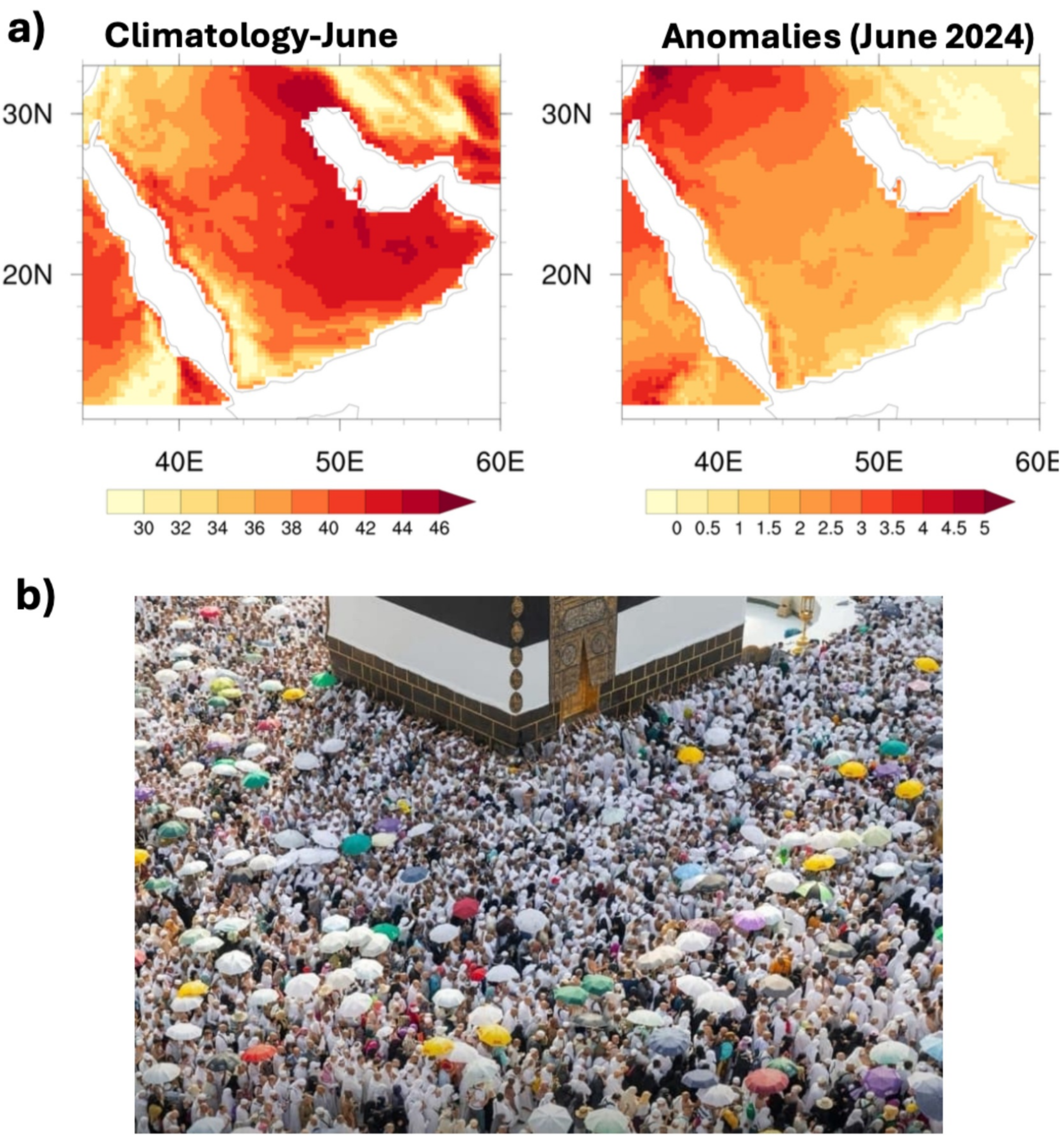

Figure 1. (a) Spatial distribution of mean summer temperatures (left) and temperatures during the 2024 temperature anomaly (right) across the Arabian Peninsula, highlighting regions experiencing extreme heat stress. (b) Photograph of a large crowd of pilgrims participating in the annual Hajj, exemplifying the vulnerability of pilgrims to extreme heat exposure during such critical religious events (https://www.yahoo.com/news/41-die-during-hajj-pilgrimage-150729603.html). To obtain the temperature climatology in (a), surface temperatures were sourced from ERA5 reanalysis data (1980–2024).

Amid the changing climatic conditions across the AP, understanding the drivers of climate variability and developing tools to monitor and predict these changes on subseasonal-to-seasonal (S2S) timescales are critical for establishing early warning systems, as advocated by United Nations Secretary-General António Guterres in 2022. Over the AP, the MJO strongly modulates wet-season rainfall and moisture transport, providing a leading source of subseasonal signal (Almazroui, 2023). QBO phases further condition sub-seasonal predictability by affecting MJO strength and teleconnections (Wang et al., 2019) with ENSO/IOD further modulating AP convection and moisture inflow (Chakraborty, Behera, et al., 2006; Hochman & Gildor, 2025), while land-surface memory underpins temperature skill at weeks 3–4 and beyond (Koster et al., 2011; Orth & Seneviratne, 2014). In ECMWF's extended-range system, MJO forecasts typically retain useful skill to weeks 3–4 (Vitart et al., 2017) and have improved with recent upgrades (Haiden et al., 2024) and reforecast initialization (Vitart et al., 2017), though some teleconnection amplitudes remain biased (Vitart & Balmaseda, 2024). Equally crucial is the development of reliable future climate projections and adaptation scenarios. Ensuring accurate monitoring and

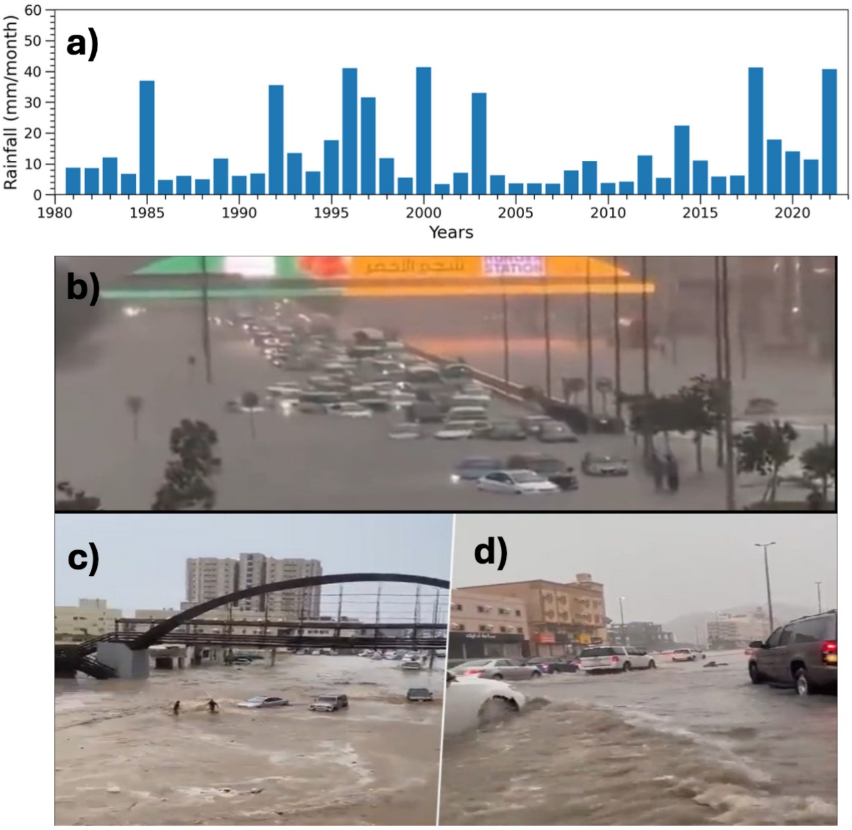

Figure 2. (a) Long-term variability of November precipitation in Jeddah, highlighting significant fluctuations and recent flood events. (b)–(d) Photographs of the Jeddah flood (online sources), depicting the impact of extreme rainfall on the city's infrastructure and residents. To obtain the temperature climatology in (a), rainfall data were sourced from ERA5 reanalysis records (1980–2024).

reliable predictions at these timescales is essential for enabling effective responses across critical sectors, such as human health protection, water resource management, ecosystem conservation, agriculture and food security, disaster preparedness, economic planning, and cultural and religious activities. These efforts also play a key role in supporting the development of sustainable adaptation strategies, such as the Saudi and Middle East Green Initiatives, aligned with the objectives of Saudi Vision 2030.

To address these challenges, the Climate Change Center (CCC) was recently established in the KSA as a collaboration between the National Center for Meteorology (NCM) and King Abdullah University of Science and Technology (KAUST). KAUST offers world-class research facilities, including the high-performance computational system Shaheen III, along with expertise in climate science and strong international collaborations (Hoteit et al., 2021). Key partners include the National Science Foundation's National Center for Atmospheric Research (NSF-NCAR, U.S.A.), Columbia Climate School's International Research Institute for Climate and Society (IRI), University of Arizona (U.S.A.), Scripps Institution of Oceanography (U.S.A.), and European Commission's Joint Research Centre (Italy). This communication highlights the CCC's primary objectives, which include studying climate variability across the AP, developing S2S prediction capabilities, and projecting future climate changes by developing comprehensive regional climate model data sets. In addition, the CCC aims to develop advanced interactive climate information dashboards in collaborations with international partners to grant stakeholders, policymakers, and the public easy access to climate data sets. These initiatives will provide valuable insights to various stakeholders, including local and national governments, industries, policymakers, and academics, enabling effective climate planning and decision-making.

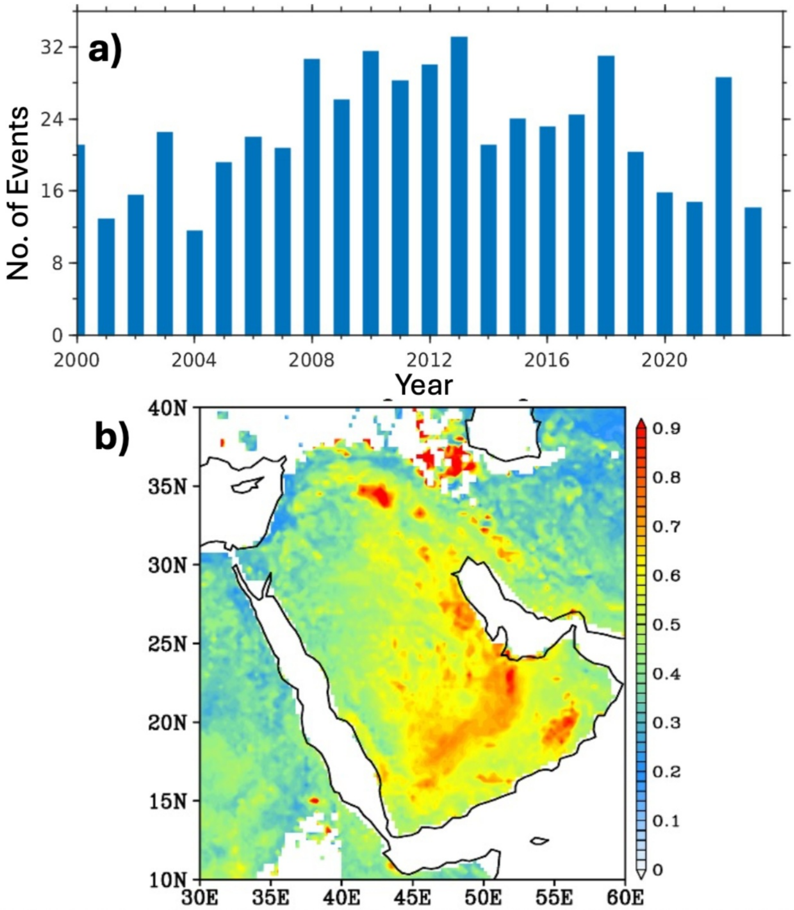

Figure 3. (a) Long-term variability in dust storm events across the Arabian Peninsula based on MODIS data, highlighting a significant increase in frequency and severity, particularly between 2003 and 2012. (b) Dust distribution captured from MODIS imagery, depicting the intensity and widespread extent of dust storm events. Panel (a) further exhibits a decadal modulation, with a pronounced mid-2000s maximum, which is coherent with AP-wide drought variability linked to the AMO (Schlesinger & Ramankutty, 1994) and with the documented 2002–2012 dust amplification over the region.

2. CCC's Mission, Objectives, and Plans

The CCC is spearheading the establishment of seamless climate information services for the KSA and the broader AP region (Figure 4). These services are designed to support ongoing efforts to mitigate the impacts of climate variability and change while aligning with the KSA's sustainable development goals. Additionally, the CCC is advancing climate science by investigating regional climate processes and their global teleconnections. This study aims to uncover the processes driving climate variability and change across the AP.

Aligned with this mission, the CCC's initiatives extend beyond studying and predicting climate variability at subseasonal, seasonal, and multidecadal timescales in the AP region (Figure 4). Its efforts focus on strengthening the understanding of both local-scale processes and large-scale climate drivers while enhancing human and technical capabilities for monitoring and predicting extreme events. The CCC is also examining the future evolution of weather and climate extremes, including droughts, extreme rainfall events, heatwaves, dust storms, and sea-level rise. Furthermore, it is striving to establish itself as a leading regional hub for climate variability and change research by fostering strong global partnerships. The CCC's activities are structured around the following six pillars:

- Establishing a regional climate database, including the development of a high-resolution regional atmospheric reanalysis scheme and a gridded meteorological baseline.

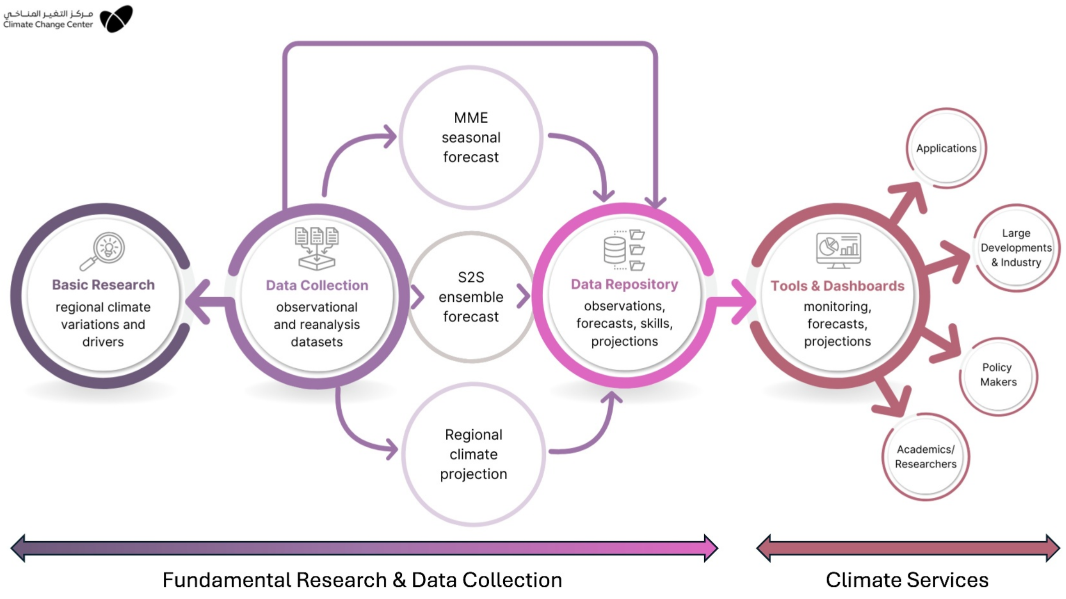

Figure 4. Scope of CCC's activities and stakeholder engagement.

- Developing state-of-the-art regional climate modeling tools to generate future regional climate change projections.
- Developing operational ensemble subseasonal and seasonal forecasting systems for the AP.
- Assessing the effects of regional climate change on extreme weather events, with a focus on heatwaves, dust storms, extreme rainfall events, droughts, and sea-level rise.
- Supporting the KSA's sustainable development goals, including the Saudi and Middle East Green Initiatives.
- Creating a climate service portal for the AP region that is easily accessible to stakeholders, policymakers, and the public.

The CCC's mandate is primarily research-focused, aiming to advance understanding and prediction of the AP's climate while supporting domestic and regional stakeholders. However, the CCC is expected to progressively evolve toward operational functionality within the framework of the National Center for Meteorology (NCM), the Kingdom's WMO-designated authority, to ensure long-term sustainability and interoperability with WMO systems such as the S2S Prediction Project and the Global Producing Centers for S2S Predictions (GPC-SSP).

2.1. Development of a Regional Climate Database

Several studies (Almazroui et al., 2020; Attada et al., 2019; Dasari et al., 2017, 2021; Dasari, Desamsetti, et al., 2022, Dasari, Viswanadhapalli et al., 2022; I. S. Kang et al., 2015; Luong et al., 2020, 2024) have reported that the climate of the AP exhibits variability across subseasonal, interannual, and multidecadal timescales. Enhancing the predictive capabilities for climate variability and extreme weather events requires a thorough understanding of the spatiotemporal interactions between climate drivers and their influence on local climate patterns. A major challenge, however, is the limited availability of long-term, continuous observational data across the AP (IPCC, 2022), which is compounded by a sparse network of monitoring stations. Our recent findings highlight the uncertainties arising from the inferior quality and limited coverage of observational data sets, particularly in the southern AP, where data gaps and discontinuities are more prevalent (Saharwardi et al., 2023, 2024). To address these issues, we are compiling a diverse range of climate data sets from various sources to develop a comprehensive regional climate database. This effort integrates in situ and remotely sensed observations, including surface, upper-air, and marine data, along with the global climate projections and reanalysis data sets. Notably, we have developed the Red Sea Regional Reanalysis, a regional reanalysis product covering the period from 1980 to 2024 (Dasari et al., 2017, 2021; Dasari, Desamsetti, et al., 2022, Dasari, Viswanadhapalli et al., 2022; Viswanadhapalli, et al., 2017, 2020). These data sets are being evaluated to examine climate variability in the AP across subseasonal to multidecadal timescales, while also assessing the roles of

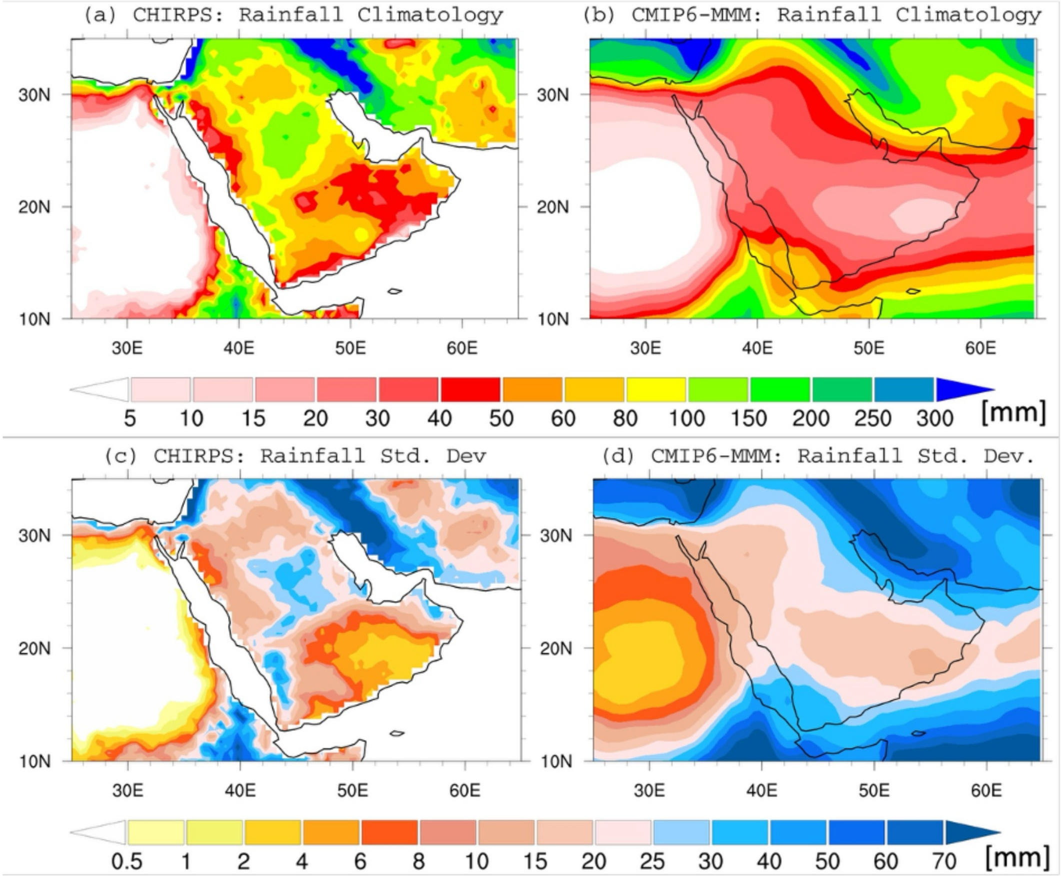

Figure 5. Spatial variations of climatological wet season (November–April) precipitation (mm) based on (a) CHIRPS observations, and (b) the multimodel mean (CMIP6-MMM) from 15 models with the highest fidelity for global and MENA climate (Pathak et al., 2023) for the period 1980 to 2014. Standard deviation of the wet season rainfall in (c) CHIRPS and (d) CMIP6-MMM.

natural variability and anthropogenic factors, such as greenhouse gas emissions, aerosols, and land-use changes (Harikishan et al., 2023; Saharwardi et al., 2023; Zampieri et al., 2023).

To address the sparse and uneven instrumental coverage across parts of the AP, CCC is assembling a unified regional climate database that integrates surface, upper-air and marine observations with satellite retrievals and global/regional reanalyzes. CCC is also compiling available in-situ and satellite measurements of temperature, salinity and sea level for the Red Sea and Arabian Gulf, and integrating these records into its modeling framework to produce high-resolution regional reanalyzes for the AP atmosphere and adjacent seas.

In parallel, CCC is implementing near-real-time monitoring for drought, heat stress and extreme rainfall driven by ERA5/GPM/GEFS forcings and satellite vegetation indices (e.g., MODIS NDVI), with routine products delivered through the climate service portal. Looking further back in time, CCC has initiated a proxy-data effort to extend the baseline prior to the satellite/reanalysis era by compiling and harmonizing marine and terrestrial archives (e.g., Red Sea coral cores, regional speleothems, lake and wadi sediments, and historical documentary records). These proxy compilations will be quality-controlled and reconciled with instrumental and reanalysis data sets to characterize multi-decadal variability (e.g., AMO influence) and to benchmark recent trends.

2.2. Generation of High-Resolution Regional Climate Projections

Our analysis of Coupled Model Intercomparison Project Phase 6 (CMIP6) projections from global climate models (GCMs) suggests a projected temperature rise of approximately 5°C and significant changes in rainfall patterns across the AP by the end of the 21st century. Although the most reliable models capture key global climate statistics, including those for the Middle East–North Africa (MENA) region (Pathak et al., 2023), they fail to accurately reproduce the observed spatial; distribution of mean annual rainfall over the historical period from 1980 to 2014 (Figures 5a and 5b). The biases in rainfall and temperature for the AP from CMIP6-GCMs is also highlighted in our recent study (Saharwardi, Dasari, et al., 2025; Saharwardi, Hassan, et al., 2025). These GCMs also exhibit limitations in simulating extreme rainfall events, recent changes in area-averaged winter rainfall, and the interannual variability of rainfall across the AP (Figures 5c and 5d). Overall, the fidelity of climate simulations —particularly for local rainfall dynamics—remains inadequate for the AP (IPCC, 2022; Saharwardi et al., 2023; Soraisam et al., 2018). These shortcomings are primarily attributed to uncertainties inherent to coarse-resolution models, unresolved physical processes, and their inaccurate parameterizations (Brunner et al., 2020; Pathak et al., 2023). For instance, the inability of these models to resolve localized phenomena such as intense convection, aridity, or moisture transport from surrounding marginal seas results in a significant underestimation of mean climate conditions and variability in the AP.

Several studies have demonstrated that downscaling coarse global model outputs using high-resolution regional models greatly enhances the representation of local meteorological processes in the region by incorporating advanced physics, explicit convection, and realistic topography (Castro et al., 2005; Dickinson et al., 1989; Giorgi & Bates, 1989; Giorgi & Mearns, 1999). However, downscaling the outputs from multiple CMIP6 models presents significant challenges due to the extensive computational resources and storage requirement involved. To address this challenge, we comprehensively analyzed 67 CMIP6 model outputs over the historical period and selected 15 models that effectively simulated global climate statistics and the regional climate dynamics of the AP (Pathak et al., 2023). The model selection process involved rigorous validation, including comparative assessments of regional dynamics during the historical period, evaluations of their intermodel dependencies, and consideration of intermodel and observational uncertainties (Pathak et al., 2023), in line with established protocols (Di Virgilio et al., 2022; Jourdain et al., 2013; Knutti et al., 2013). From this subset of 15 models, we prioritized the top 4–5 models for dynamical downscaling of historical simulations and future climate scenarios, covering SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, at convective-permitting resolution over the AP to explicitly simulate critical convective rainfall processes. This approach focuses on model selection and scenario-based uncertainties using a limited subset of CMIP6 GCMs. To enhance our understanding of internal variability at the regional scale, incorporating large ensembles of regional simulations would be highly beneficial (Deser et al., 2012). As a next step, we intend to explore ensemble simulations using either perturbed initial conditions or multiple realizations of the same GCM, subject to the available computational resources.

For dynamical downscaling, we implemented two regional models—the Weather Research and Forecasting (WRF v4.5) model and the Regional Climate Model (RegCM5)—using high-performance computing facilities at KAUST and the NCM. The downscaling framework comprises an outer domain with a 12 km resolution, covering the MENA region as defined by the Coordinated Regional Climate Downscaling Experiment, and an inner domain with a 4 km resolution specifically over the AP (Figure 6). Preliminary results from the downscaling MPI-ESM1-HR model outputs using a one-way nesting approach with the WRF and RegCM models reveal that this approach effectively mitigates systematic biases observed in current GCMs, particularly in capturing the climate dynamics of the AP (Figure 6).

To further expand the portfolio of downscaled climate products, we have implemented an eddy-resolving MIT Ocean General Circulation model (MITgcm) model to downscale ocean projections from selected CMIP6 models (Figure 7). Adopting this approach, we are evaluating projected future changes in the physical properties, general circulation trends, and sea-level rise of the Red Sea and Arabian Gulf. The Arabian Seas MITgcm model is configured on a high-resolution 2 km grid, with its domain encompassing the Red Sea, Arabian Gulf, and the northern part of the Indian Ocean. To capture fine-scale processes, ocean variables are stored on a daily basis.

2.3. Development of S2S Forecasting Systems

Previous regional efforts for S2S predictions in the AP involved implementing GCMs with modified parameterizations at a 50 km resolution (Abid et al., 2018; Almazroui, Tayeb, et al., 2017; Ehsan et al., 2019; Vigaud et al., 2019). However, the predictive skill of these models for the AP climate is yet to be fully demonstrated. As highlighted previously, high-resolution models at convective-permitting scales are essential for accurately capturing rainfall statistics in the AP (Dasari et al., 2017; Luong et al., 2020). To address this, the CCC is developing regional convection-permitting forecasting systems for subseasonal (2–6 weeks lead) and seasonal

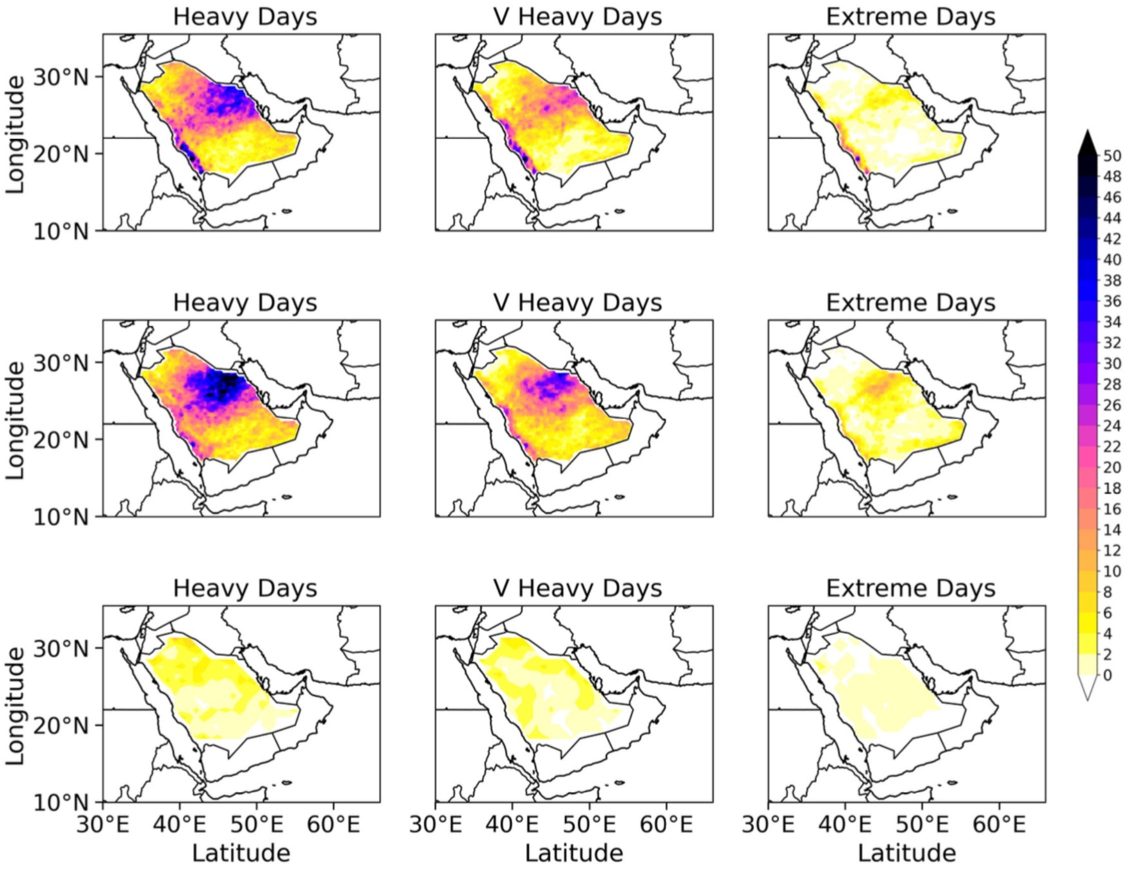

Figure 6. The total number of heavy (Heavy Days), very heavy (V Heavy Days), and extreme (Extreme Days) rainfall days during the historical period (1980–2014). The top panel represents ERA5 data, second panel shows WRF model outputs obtained from the dynamical downscaling of MPI-ESM1-2-HR global climate model (GCM) outputs, and bottom panel displays the original MPI-ESM1-2-HR GCM outputs. The daily precipitation amounts between the 10–19 mm/day, 19–34 mm/day, and >34 mm/day were used to define heavy-rainfall days, very-heavy-rainfall days, and extreme-rainfall days, respectively.

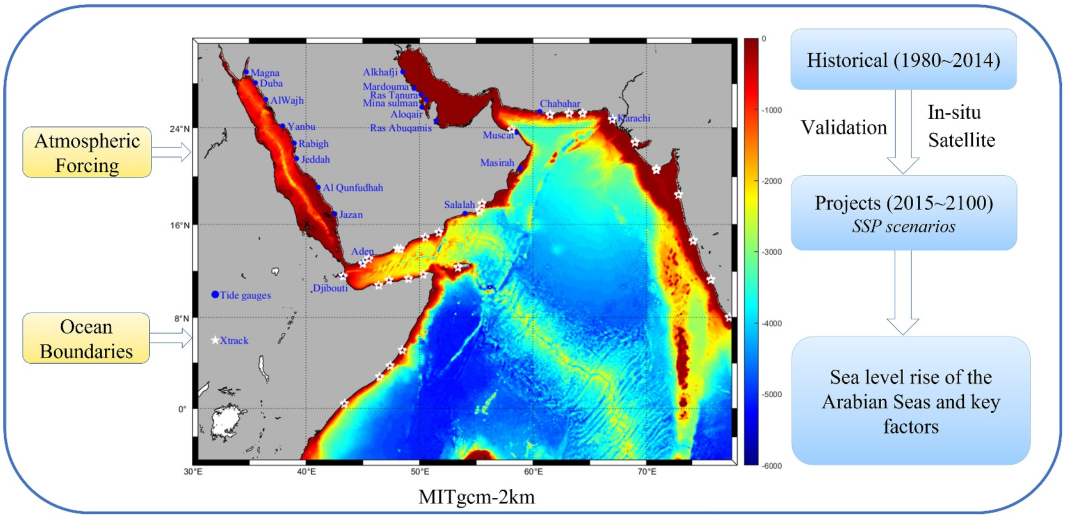

Figure 7. Proposed domain and workflow for generating historical and future climate projections of the marginal seas (Red Sea and Arabian Gulf) surrounding the Arabian Peninsula using the MIT Ocean General Circulation model (MITgcm). The blue dots on the topographic map indicate available tide gauges, while the white stars represent X-track virtual altimetry stations.

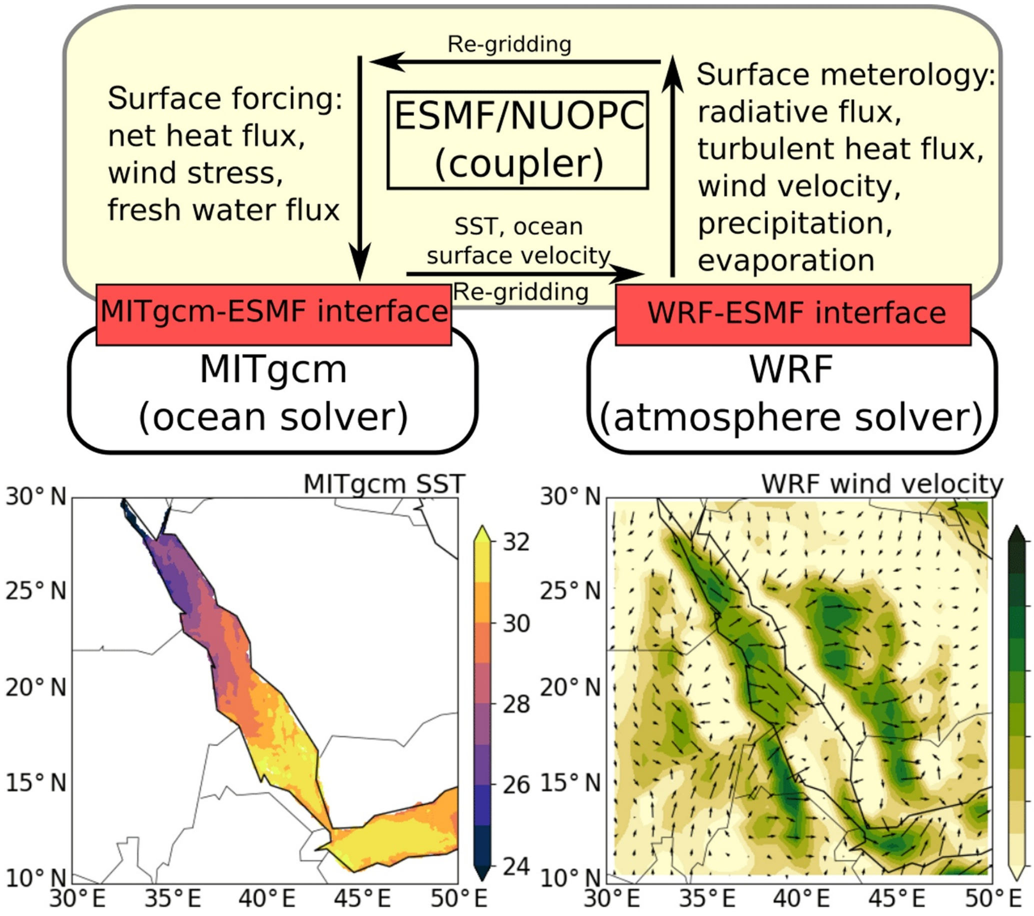

Figure 8. Schematic representation of the coupled ocean–atmosphere model. The yellow block represents the ESMF/NUOPC coupler, while the red blocks indicate the implemented MITgcm–ESMF and WRF–ESMF interfaces. The white blocks correspond to the oceanic and atmospheric components. The coupler collects atmospheric surface variables from the WRF model (i.e., radiative flux, turbulent heat flux, wind velocity, precipitation, and evaporation) and updates the surface forcing for MIT Ocean General Circulation model (i.e., net surface heat flux, wind stress, and freshwater flux).

(1–6 months lead) timescales in the AP. These systems incorporate large and multimodel ensembles. For instance, the current subseasonal operational system downscales the six-week lead, 51-member ensemble subseasonal forecasts of the European Center for Medium-Range Weather Forecasts (ECMWF) using the WRF model at a 4 km resolution.

This high-resolution, unique regional subseasonal operational system provides significantly improved predictions up to a lead time of 4 weeks, outperforming the predictions of the ECMWF model that serve as input for our regional model (Luong et al., 2025; Risanto et al., 2022). By leveraging this system, probabilistic forecasts of mean climate conditions and extreme events, such as heavy precipitation and heatwaves, will be produced. Simultaneously, while assessing the predictive capabilities of this WRF-based system for downscaling global seasonal forecasts, we are also developing and validating an operational seasonal forecasting system. This system is based on the IRI statistical downscaling framework and integrates seasonal forecasts from the North American Multi-Model Ensemble and the European Copernicus Climate Change Service.

The regional WRF forecasts presented here (Figure 8) are driven at the lateral boundaries by the ECMWF 51-member S2S ensemble. In future, we plan to evaluate a multi-model ensemble strategy, which may provide additional robustness by capturing inter-model spread and complementary strengths across different global prediction systems. However, prescribing only interpolated sea-surface temperatures from coarse-resolution models omits mesoscale air–sea interactions and can introduce imbalances in surface energy and moisture fluxes. To address this, we are coupling WRF with MITgcm using the ESMF/NUOPC coupler so that SST,

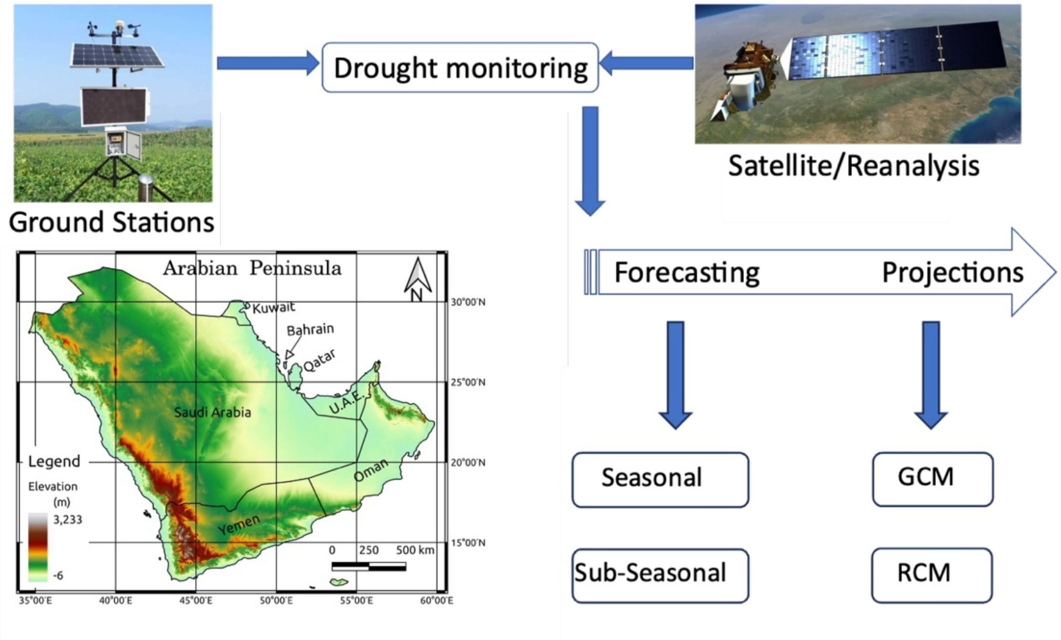

Figure 9. Illustration of drought monitoring and forecasting systems, along with future projection frameworks for the Arabian Peninsula (AP). Near real-time rainfall data sets (e.g., ERA5, GPM) and temperature data sets (e.g., GEFS, ERA5), along with various satellite-based NDVI products (e.g., MODIS), will be utilized to monitor drought conditions at 3-, 6-, and 12-month timescales. Outputs from downscaled projections and subseasonal-to-seasonal (S2S) predictions using will be used to generate monthly to seasonal drought forecasts and scenario-based drought projections for the AP. Global climate model (GCM) referred to GCM, and RCM is for Regional Climate Model.

surface fluxes, and near-surface winds evolve interactively during the forecast (Sun et al., 2019). This coupled configuration is currently being tested for downscaling ECMWF seasonal reforecasts and is expected to improve the realism of atmosphere–ocean feedbacks over the Red Sea and the Arabian Gulf. By integrating this new regional ocean–atmosphere coupled system with the IRI ensemble framework, we expect to achieve substantial improvements in seasonal forecasting capabilities for the AP region. Furthermore, a seasonal drought forecasting system will be introduced to complement the existing drought monitoring framework (Figure 9).

2.4. Assessment of the Regional Impacts of Climate Change

Evaluating the effects of climate change on the mean climate, extreme weather events, and environmental conditions in the AP is a central objective of the CCC. The center's efforts focus on examining shifts in climate patterns related to droughts, land and marine heatwaves, extreme rainfall events, and dust storms, as well as assessing trends in sea-level rise in the marginal seas of the AP. Preliminary research by Almazroui and Islam (2019) evaluated the performance of various CMIP6 models in capturing observed drought patterns across the AP, highlighting the potential of GCMs in describing drought patterns. Building on this, Saharwardi et al. (2023) conducted a spatiotemporal analysis of drought variability in the AP from 1951 to 2020, highlighting a notable increase in drought frequency and severity over the past two decades. This increasing trend was primarily attributed to rising temperatures rather than reductions in precipitation. More recently, Saharwardi et al. (2024) identified distinct homogeneous drought regions within the AP and investigated the role of seasonal circulation changes and underlying physical mechanisms contributing to these patterns.

The CCC is also investigating long-term trends and variability in heatwaves across the AP from 1940 to 2022 (Saharwardi et al., 2024). The findings reveal a significant increase in the frequency and spatial extent of large-scale heatwaves, with abrupt shifts identified in the late 1970s and 1990s, consistently with previous studies (Zampieri et al., 2016). Additionally, the frequency and duration of compound marine and atmospheric heatwaves in the AP have risen significantly over the study period (Saharwardi, Hassan, et al., 2025).

To enhance understanding of dust storm dynamics in the AP, Harikishan et al. (2022) developed a regionally tuned high-resolution dust optical depth data set using MODIS aerosol measurements. This data set facilitated the identification of key dust sources and highlighted two primary dust regions: the KSA and Iraq's Tigris–Euphrates River Basin (TERB), both heavily influenced by geomorphological factors (Harikishan et al., 2023). In addition, the study emphasized the crucial role of the Shamal winds—driven by high-pressure systems—in transporting dust from the TERB to the AP, thereby intensifying dust storms throughout the region.

These findings highlight the complex interactions of regional climate processes and the increasing intensity and frequency of extreme weather events, emphasizing the urgent need for robust climate change adaptation and mitigation strategies. The CCC's approach extends beyond analyzing regional drivers of extreme events by advancing capabilities for monitoring and forecasting climate extremes across different timescales. The center is also committed to producing high-resolution data products for various climate extremes, incorporating relevant uncertainties to improve preparedness for such events. Furthermore, the CCC is investigating the influence of dust activity on the regional climate through sensitivity experiments conducted using a high-resolution WRF-Chem regional model, assessing how dust variations influence local radiative forcing (Ramakrishna et al., 2021, 2024). However, existing climate models lack the capability to adequately capture the land–atmosphere coupling mechanisms that drive dust generation. Therefore, developing specialized modules to represent localized physical processes is essential for improving our understanding and projections of climate change effects, land cover changes, and their interactive feedback mechanisms.

2.5. Support for the KSA's Sustainable Development Goals

The CCC's primary objective is to develop scientific strategies that align with the KSA's sustainable development initiatives. Under Vision 2030, the KSA has launched a comprehensive plan to diversify its economy and establish itself as a global hub for innovation, tourism, and sustainability. Major projects such as NEOM, the Red Sea Project, AMALA, and OXAGON are at the forefront of this transformation, driving economic growth, generating employment opportunities, and advancing technology and environmental stewardship. Additionally, by hosting international events such as FIFA, the World Expo, and the COP Summit, the KSA aims to strengthen its global presence, attract top-tier talent, and promote sustainability on an international scale.

To support this vision, the CCC is developing scientific strategies and equipping governmental administrations with tools to enhance planning and mitigate the impacts of climate change. Furthermore, monitoring systems for droughts, dust storms, and heatwaves, currently under development at the CCC, will play a vital role in enabling policymakers to implement necessary precautions for sustainable development. The CCC's operational S2S forecasting systems will also be critical in strategic planning for agriculture, water resource management, and the Hajj season.

The Saudi Green Initiative and Middle East Green Initiative are key components of the KSA's strategy to combat climate change. The CCC is actively contributing to these efforts by conducting targeted observational studies (Zampieri et al., 2023) and developing climate sensitivity scenarios to guide decision-making. This includes experiments designed to inform irrigation expansion projects and optimize reforestation and afforestation plans (Zampieri et al., 2024). Currently, the CCC is performing sensitivity experiments using the WRF model coupled with the Noah-MP land surface scheme to assess the potential climatic impacts of afforestation. These experiments will support the Saudi Green Initiative by identifying optimal land-use strategies, such as reducing overgrazing and expanding irrigation.

The above findings and strategies will be integrated into an accessible database with interactive tools designed for a diverse range of stakeholders, including local and national governments, industries, policymakers, and academic institutions.

2.6. Development of Online Interactive Visualization Dashboards

The CCC is committed to providing seamless access to its diverse data sets and products, serving a broad spectrum of stakeholders. To accomplish this, the center is developing visual-analytics-based dashboards that feature web-based interactive visualizations, enabling users to explore large, multidimensional spatiotemporal climate data sets. These dashboards are designed on a custom multitiered architecture comprising: (a) a high-performance computing module that processes raw simulation data sets end-to-end; (b) a data querying and

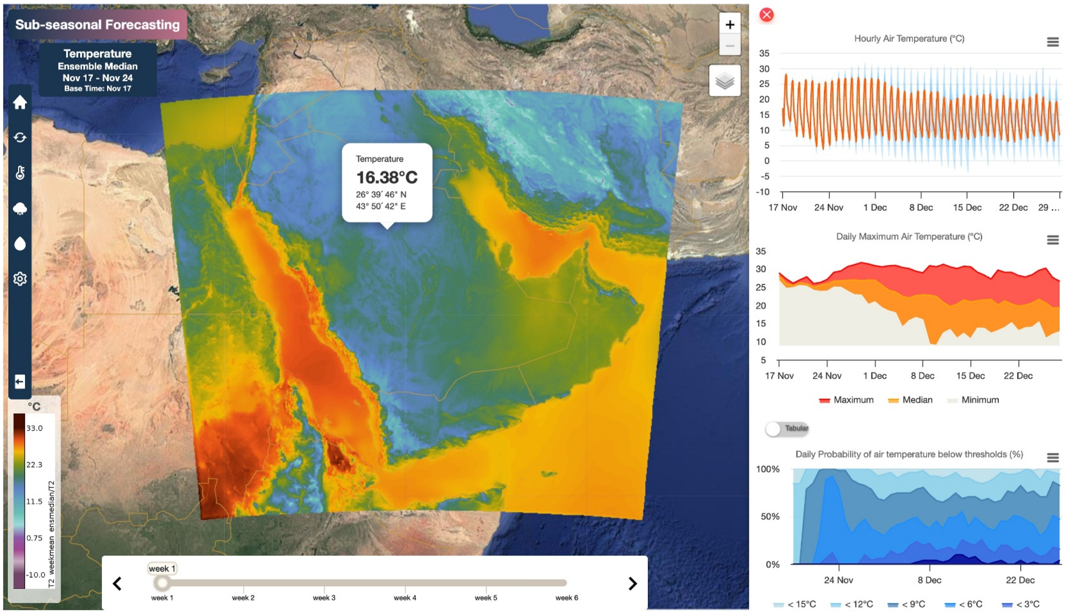

Figure 10. Overview of the visualization dashboard developed for subseasonal forecasting.

indexing module that supports efficient data storage and retrieval at interactive speeds using RESTful APIs; and (c) a comprehensive suite of visualization tools that supports diverse climate research applications. Figure 10 presents an example of the subseasonal forecasting system, which provides detailed exploration and analysis of S2S forecasts for temperature and rainfall across the AP. This system provides decision-makers and researchers with timely, accurate information to support planning and mitigation strategies.

While developed under the KSA–NCM framework, the dashboards and APIs can be made accessible to stakeholders across the MENA and AP regions. Practical benefits to neighboring countries include: (a) region-wide S2S probabilistic outlooks of temperature, rainfall, heatwaves, and heavy-precipitation risk to support water and agriculture planning; (b) a drought monitoring and forecasting system; (c) access to high-resolution climate data sets generated through dynamical downscaling based on WRF and RegCM simulations for historical and future scenarios, (d) high-resolution MITgcm ocean projections for the Red Sea and Arabian Gulf; (e) compute on-the-fly statistics (e.g., exceedance frequencies, return levels) and to interactively visualize geospatial maps and associated time series; and (f) coastal risk information (circulation, extremes, and sea-level trends) in the Red Sea and Arabian Gulf from the high-resolution ocean projections. These AP-wide services are delivered through the same web-based dashboard interface to ensure consistent, comparable information across borders.

Data compression plays a crucial role in climate research, as GCMs and RCMs generate petabytes of data over extended temporal scales and at high spatial resolutions. Efficient compression techniques, including lossless and lossy algorithms, are essential for reducing storage requirements while maintaining scientific accuracy. The CCC is actively harnessing artificial intelligence (AI) algorithms to develop advanced data compression tools that enable drastic reductions in storage requirements, improve data transfer speeds, and enhance the efficiency of processing climate data (Hoteit et al., 2021).

3. Concluding Remarks

The unique arid climate of the desert-dominated AP remains underrepresented by GCMs, posing significant challenges for developing scientifically grounded strategies to address extreme weather events and mitigate regional influences of climate change. This study outlines the rationale behind establishing the CCC, which seeks to overcome the limitations in existing climate data sets for the AP and drive strategic developments tailored to the region's needs. Once validated and documented, the CCC's products will be integrated into the NCM's operational framework. Additionally, data sets and analysis results provided by the CCC will be made accessible through the NCM portal, providing critical support to various government ministries in the KSA for formulating actionable strategies in response to worsening climate challenges. These tools will also play a key role in supporting large-scale initiatives such as the Saudi Green Initiative.

To handle the vast data sets generated by the CCC, multipurpose visualization dashboards are being developed to provide on-demand, user-friendly access to regional climate products. These dashboards will allow stakeholders to generate customized statistical insights and graphical outputs. Additionally, national and international researchers will have regulated access to these data sets in compliance with NCM guidelines.

Despite these advancements, the CCC faces several key challenges, including (a) securing adequate computational and human resources to manage its vast and complex climate data sets, (b) ensuring data quality and seamless data integration into NCM operations, (c) providing user-friendly access to data sets for various government ministries and stakeholders, and (d) developing and maintaining multipurpose visualization dashboards and customized outputs to meet the diverse user needs.

AI is emerging as a transformative tool for addressing these challenges, particularly in downscaling climate model outputs, with potential to drastically reduce the computational resources required for generating high-resolution regional climate data sets. Advanced AI techniques, such as deep learning (DL) and generative adversarial networks, can effectively model complex, nonlinear relationships between large-scale atmospheric patterns and localized extreme events. We recently showcased this capability in a simplified geophysical fluid dynamics study (Hammoud et al., 2024). Building on this foundation, we are exploring the application of DL models for downscaling CMIP6 GCM outputs. If successful, this approach could dramatically improve the efficiency of high-resolution regional climate data generation while alleviating storage constraints by enabling on-the-fly data processing. Moreover, AI offers promising applications in the identification and prediction of extreme weather events, which we are investigating to develop more efficient S2S forecasting systems.

In the future, the CCC plans to expand its applications into agriculture, hydrology, energy and support to policymaking, while further augmenting its modeling capabilities. In fact, the center has initiated efforts to enhance its modeling capabilities by developing a unique high-resolution GCM tailored to the unique physical characteristics of the AP. This model will incorporate interactive dust processes and an unstructured grid to better capture regional atmospheric circulation and the oceanic dynamics of the AP marginal seas in a self-consistent framework.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The data on which this article is based are available in Saharwardi and Dasari (2025).

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