Climate Futures Report

SAUDI ARABIA IN A 3-DEGREES WARMER WORLD

KAUST
AEON COLLECTIVE
KAPSARC

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KING ABDULLAH UNIVERSITY OF SCIENCE AND TECHNOLOGY (KAUST)
AEON COLLECTIVE
KING ABDULLAH PETROLEUM STUDIES AND RESEARCH CENTER (KAPSARC)

"The world has a narrow window to alter the current climate trajectory and navigate towards a more sustainable future. To miss this opportunity risks delivering a future that is less safe and prosperous than our past."

Prof. Matthew F. McCabe
Climate and Livability Initiative, Biological and Environmental Sciences and Engineering (BESE), King Abdullah University of Science and Technology (KAUST), Saudi Arabia

A 3-Degrees Warmer World

Saudi Arabia, a country characterized by its vast deserts, unique geographical features, and rich cultural heritage, stands at the precipice of a transformative challenge: adapting to the impacts of a rapidly changing climate. As global temperatures continue to rise due to the accumulation of greenhouse gasses in the atmosphere, Saudi Arabia is projected to experience more rapid changes in its climate patterns compared to other regions. This will not only intensify climate-related risks across the country, but also profoundly impact biodiversity, freshwater resources, agricultural productivity, industry and economy, and the health and wellbeing of its people.

What future might we face in a 3°C warmer world?

While expectations of rising temperatures and sea levels are a certain outcome of increasing greenhouse gas emissions, other aspects come with less certainty. What is well accepted is that for each degree of global warming, the corresponding increase in regional temperatures is significantly more pronounced for the Arabian Peninsula, which has already warmed at a rate 50% higher than other landmasses in the northern hemisphere. In short, Saudi Arabia can expect to see an amplification in climate response across many factors, relative to other parts of the world. Similarly, while greenhouse gas emissions continue to rise unabated, climate change will deliver an associated cost.

National security dictates that every country seeks to map out the unique risks and challenges that climate change will impose on their society and economy. As such, the case for planning and preparation is strong. In the context of Vision 2030 and the many ambitious giga-project initiatives that span tourism, entertainment, ecosystem restoration and urban redevelopment and renewal, there is an underlying climate fingerprint that has the potential to influence the viability and success of these nation-building efforts. An unstated feature of the Kingdom's ambitious efforts towards delivering sustainable growth, driven by substantial investments in these giga-projects, is that they will depend to a large degree on the preservation, protection and restoration of its vital and unique natural ecosystems.

As will be discussed in the following Chapters, Saudi Arabia is already witnessing the impacts of climate change within its local and regional environments. The Kingdom's marine systems, hosting some of the most diverse and rich aquatic ecosystems seen around the world, are straining under the compound effects of climate change and anthropogenic pressures. While coral bleaching and die-off, together with a rise in species under threat due to overfishing are obvious indicators, the effects ripple across diverse habitats and species. Similar responses can be seen across terrestrial ecosystems, with increasingly degraded environments suffering the burden of pollution and overexploitation of resources. Periods of extreme temperatures, along with shifts in rainfall patterns, are driving desertification trends here and elsewhere. The consequent effects on vegetation and wildlife, which already struggle under a harsh arid climate, may prove to be irreversible.

Humanity relies on Earth's natural ecosystems to provide essential services that ensure our survival: the provision of freshwater and stable food supplies foremost amongst these. Yet their viability is increasingly threatened by climate change and anthropogenic factors. Extreme heat directly affects crop yields, while variable rainfall patterns disrupt the security of water resources. With groundwater resources being rapidly depleted due to local food production, and overuse degrading the quality of our soils, Saudi Arabia increasingly relies on the importation of food, which brings its own climate and geopolitical risks. Even the Kingdom's position as the world's largest producer of desalinated water does not insulate against the challenge of water availability. While desalination capacity is sufficient to supply potable water needs, it brings a significant economic, energy and environmental burden.

While the natural system is obviously and evidently struggling, our man-made environments are similarly imperiled. As one of the most urbanized regions in the world, the basic operation and function of human cities and settlements is increasingly at risk. Existing vulnerabilities to sea level rise, together with increased storm frequency and floods, pose significant and escalating threats to coastal cities and infrastructure. Rising temperatures, combined with the energy intensive processes we rely upon to survive the inhospitable conditions of the region, have created a positive feedback cycle, where the insatiable energy appetite of modern cities drives further pollution and greenhouse gas emissions: amplifying the very conditions we seek to safeguard against. It is a cycle that will only be broken through a deliberate shift to a more sustainable lifestyle, and driven by an aggressive decarbonization strategy.

With the health of both our natural and urban ecosystems under threat, we are also seeing the direct and indirect impacts of climate change on human health. Heat waves and periods of high humidity are projected to increase in frequency, straining the fundamental biological functions that regulate the human body. A concerning increase in heat-related stress and death has been observed in recent heat-wave events around the world, while the health risks associated with extreme temperatures are well documented, exacerbating existing conditions including cardiovascular and respiratory diseases, diabetes, kidney issues, and mental health concerns. The health risks associated with poor air quality driven by both climate and anthropogenic factors, are similarly concerning, as are the challenges associated with vector-borne and other diseases that risk being enhanced under future climate scenarios.

Ongoing climate change is global in nature, and will therefore require a global solution. In the modern world, no country operates in isolation from another. Climate-driven events occurring outside the borders of Saudi Arabia have consequences that are felt within. Put simply, local climate-related events will not respect national borders, and have the potential to spill over into larger regional and global crises.

Yet there is still an inherent local and regional context to expected impacts. Importantly, not all countries will experience the same climate outcomes, either in degree, magnitude or extent. And while a nation's ability to respond to the climate challenge may be measured in their level of preparedness, there is also an undeniable economic lever that may drive further inequality: especially to those that cannot afford to adapt.

In this report we forecast some of the potential consequences arising from a climate trajectory that might deliver a 3°C warmer world by the end of the century. By exploring the likely impacts and outcomes of such a climate scenario, we seek to encourage informed decision-making processes, drive the adoption of adaptive and climate resilient strategies, and facilitate needed efforts in sustainable development—all of which can be used to help avert the looming climate-related challenges described herein.

Another goal of the report is to provoke discussion around how to avoid some of the potential climate outcomes that such a future might impose. The emphasis on potential is important. While certain changes are expected and likely “locked-in”, the degree and magnitude of these depends strongly on the actions and decisions made today. Choosing a path of no action, or relying solely on a capacity to adapt or mitigate the climate challenge away, is not an effective strategy. In many ways, Saudi Arabia’s environmental parameters are already at the verge of livability. An emergent and unmitigated climate crisis will have profound implications on the future viability of a sustainable and healthy society, and will likely manifest an existential crisis to Saudi Arabia.

Forecasting the future is inherently uncertain, and uncertainty will always exist. However, that does not preclude the need for direct and targeted action, particularly when the risks and costs of inaction can have such major consequences. The world has a narrow window to alter the current climate trajectory and navigate towards a more sustainable future. To miss this opportunity risks delivering a future that is less safe and prosperous than our past.

Photo by NEOM on Unsplash

“Characterizing the cross-sectoral impacts of climate change provides a scientific basis to guide policy, support decision-making, inform the development of adaptation pathways, enhance climate resilience, and facilitate sustainable development in the face of climate change challenges.”

Princess Mashael AlShalan
AEON Collective, Saudi Arabia

Dr. Mohamad Hejazi
Climate and Sustainability Program, King Abdullah Petroleum Studies and Research Center (KAPSARC), Saudi Arabia

A Global and Local Context

Over the last decade, average annual global greenhouse gas emissions were at their highest levels in human history[1]. While the growth rate has slowed, the global emission trajectory is nowhere near the deep and rapid emission reductions that are necessary to keep the 2015 Paris Agreement alive. The sobering reality is that the world's greenhouse emissions are still on the rise, and even after decades of climate diplomacy and mitigation efforts, including 27 Conference of the Parties (COP) annual meetings, global greenhouse gas emissions are yet to take the meaningful downturn needed to achieve carbon neutrality and the goals of the Paris Agreement.

International Targets

The Paris Agreement aims to keep global temperature increases well below 2°C and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels. Individual country climate ambitions, as expressed through their nationally determined contributions (NDCs), vary in their alignment with a 2°C world. While many countries have set targets in line with the agreement's goals, the overall level of ambition falls well short of what is required to meet a 2°C target.

For example, the United Nations Framework Convention on Climate Change (UNFCCC) estimates that current commitments will increase emissions by 10.6% by 2030 compared to 2010 levels, and that current NDCs may only limit global temperature rise to around 2.7 to 3.2 degrees by the end of the century[2]. However, there are other estimates that show that if all countries achieve their stated climate ambition, whether under their NDCs or through stated Net-Zero ambitions, the sub-2°C target can be achieved[3, 4, 5].

FIGURE 1 →

Warming projections for 2071-2100 relative to 1850-1900. Refer to Chapter 2 for details.

Here, it is important to acknowledge and distinguish between climate policies that are enacted and enshrined into law, versus publicly announced pledges and targets: especially since many of the latter lack sufficient details to support the chance of achieving them. When excluding such announcements, the warming level rises significantly and the likelihood of exceeding the 2°C threshold increases, making a 3°C world a plausible outcome.

Another important consideration is the recognition that there will be differences between what is experienced on average at the global scale, compared to what might be realized at the local and regional scale. That is, even under a 2°C warmer world, there will be variations around the average response, with the Middle East expecting to see amplified warming relative to other regions.

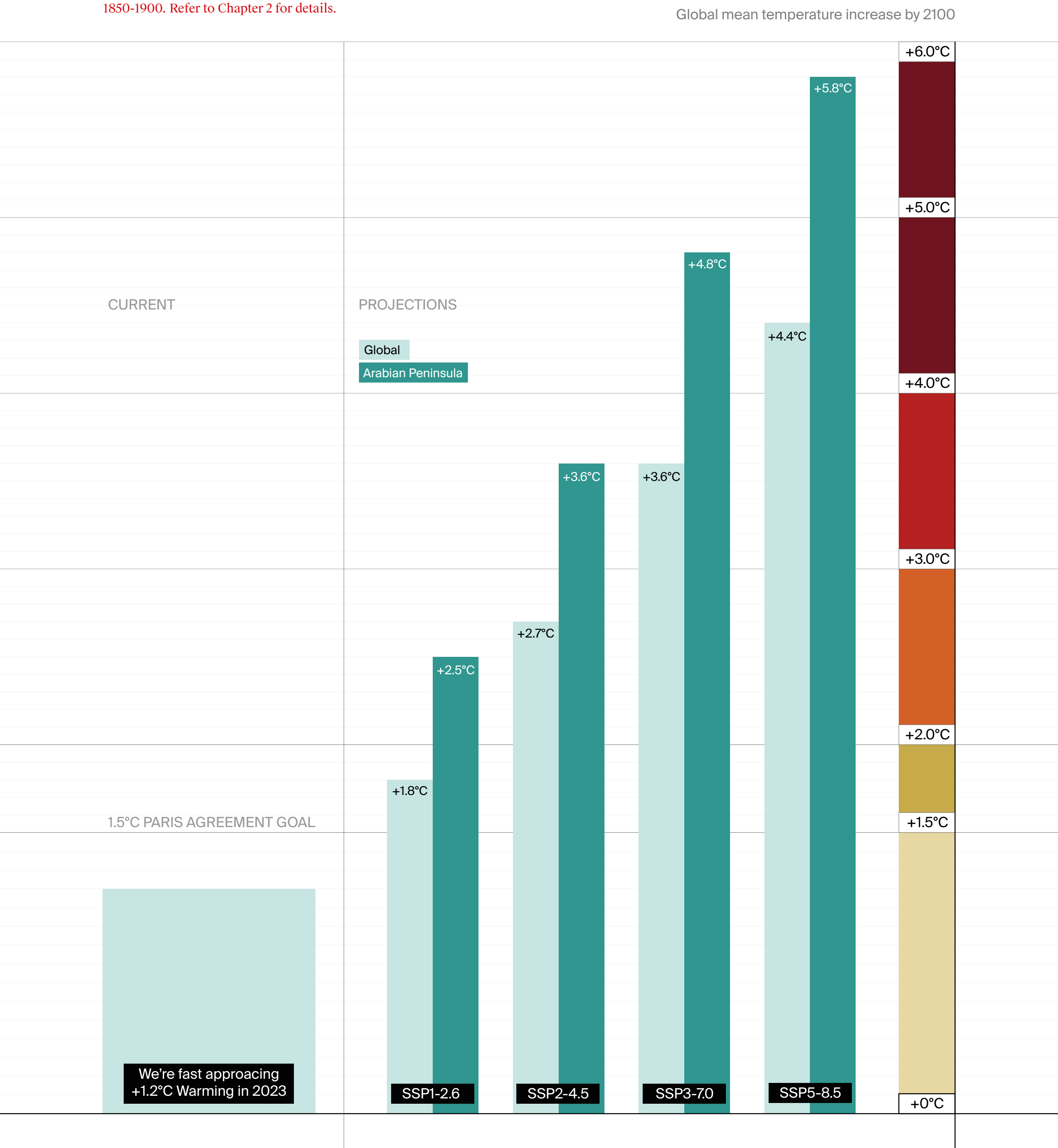
Given this context, this report will present a broad perspective on the implications of a 3°C warmer world, highlighting how this scenario may challenge different aspects of the natural, social, and economic landscapes over the Kingdom of Saudi Arabia.

Anticipated Climate Impacts

The 6th Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) states the world has already warmed by an average of 1.1 degrees Celsius since the pre-industrial era (1850-1900), leading to widespread impacts on ecosystems and human societies[6]. Saudi Arabia has also experienced an increase in average temperatures, which has led to higher summer temperatures and more frequent and intense heat waves over the past four decades (see Chapter 2).

FIGURE 1

Warming projections for 2071-2100 relative to 1850-1900. Refer to Chapter 2 for details.



With global temperatures on the rise, the frequency of severe heat waves, heavy rainfall events, droughts and floods, combined with increases in ocean warming, acidification, and sea-level rise, are all expected to impact Earth's terrestrial and marine systems. The fingerprints of climate change have already been implicated in catastrophic climate extreme events around the globe. Of particular concern is that the Middle East has been identified as a hotspot for future temperature changes due to its arid environmental conditions[7, 8].

As with many regions around the world, climate change is projected to have cross-sectoral impacts throughout Saudi Arabia that will be manifested through a variety of ways:

Increased temperatures

Saudi Arabia experiences hotter than average temperatures, and climate change is expected to exacerbate this. Rising temperatures could lead to heat-related health issues, reduced agricultural productivity, and increased electricity demand for cooling, with many other cross-sectoral implications.

Water scarcity

Saudi Arabia is a water-scarce country, and climate change is predicted to put further strain on water availability. When combined with expected increases in evaporative demand, any decrease in rainfall (or even changes in its distribution), could lead to reduced water resources,

Farms in Al-Hofuf, Saudi Arabia
Image via Google Erath

affecting agricultural production and domestic supply, as well as increased competition for water amongst different sectors.

Sea-level rise

Saudi Arabia has a long coastline along the Red Sea and the Arabian Gulf. Rising sea levels due to climate change could increase the risk of coastal flooding, shoreline erosion, infrastructure damage via storm surges, and saltwater intrusion into coastal aquifers.

Coral bleaching

The Red Sea, integral to Saudi Arabia's marine ecosystem, is susceptible to coral bleaching, a direct impact of warming ocean temperatures resulting from climate change. Notably, the 3rd global coral bleaching event that occurred between 2014-2017 affected numerous reefs, including those in the Red Sea. High temperatures led to significant bleaching, particularly to inshore reefs. Such events can lead to decreased species richness, crucial for a healthy coral reef. The long-term effects remain uncertain, with 2023's El Niño expected to deliver further damage.

Impact on ecosystems

Climate change may affect Saudi Arabia's unique marine and terrestrial ecosystems. Changes in temperature and rainfall patterns can lead to shifts in vegetation, disruption of migratory patterns of wildlife, and increased risk of desertification.

Impact on energy demand

Saudi Arabia is a major producer, consumer, and exporter of oil. Combined with projected population growth, climate change will affect energy demand patterns globally, impacting Saudi Arabia's exports, internal energy usage, and economy.

To address these and many other climate related impacts, Saudi Arabia is taking steps to mitigate climate change by diversifying its economy, investing in renewable energy sources, promoting water conservation, and participating in international climate dialogs and agreements. A key motivation for this report is to understand how climate change under a 3-degrees warming world will deliver multi-dimensional impacts with cross-sectoral repercussions throughout the nation.

Cascading Risks

Characterizing the cross-sectoral impacts of climate change provides a scientific basis to guide policy, support decision-making, inform the development of adaptation pathways, enhance climate resilience, and facilitate sustainable development in the face of climate challenges. However, climate impacts do not exist in isolation from each other, nor from other non-climatic

Coral Bleaching,
September 2021–September 2023,
Photos by Morgan Bennett-Smith

forces and stressors. As such, it is important to understand the interplay and interdependencies that exist across sectors and even geographic boundaries (i.e. impacts that happen outside the borders of Saudi Arabia, but have consequences that are felt within), and the importance of human and natural systems to adapt and be resilient to both internal and external disruptions.

Several examples illustrate the cascading risks in the context of Saudi Arabia:

Climate Impacts on Hajj and Disease Spread

The Hajj pilgrimage, a cornerstone of Islamic faith, faces potential challenges due to climate change. These challenges are not only limited to projected temperature increases in Makkah, the focal point of Hajj, but also include the risk of climate-induced diseases. The likelihood of significant humid heatwaves poses a particular risk to both the young and elderly. Moreover, the geographical range of disease vectors, such as Aedes aegypti, may expand due to global climate change, increasing the risk of communicable diseases. This could have a cascading effect on public health and safety during Hajj.

Coral Bleaching and Impact on Fisheries

FIGURE 2 →

Cascading effect in the context of Saudi Arabia.

The Red Sea, home to vibrant coral reefs and diverse marine life, is not immune to the devastating impacts of coral bleaching, one of the most immediate impacts of climate change on marine ecosystems. The "3rd global coral bleaching event" between 2014-2017 impacted reefs in every major ocean, including the Red Sea. The potential long-term changes in these coral reef communities remain to be seen, but the loss of biodiversity could have significant implications for marine life and the communities that rely upon these ecosystems.

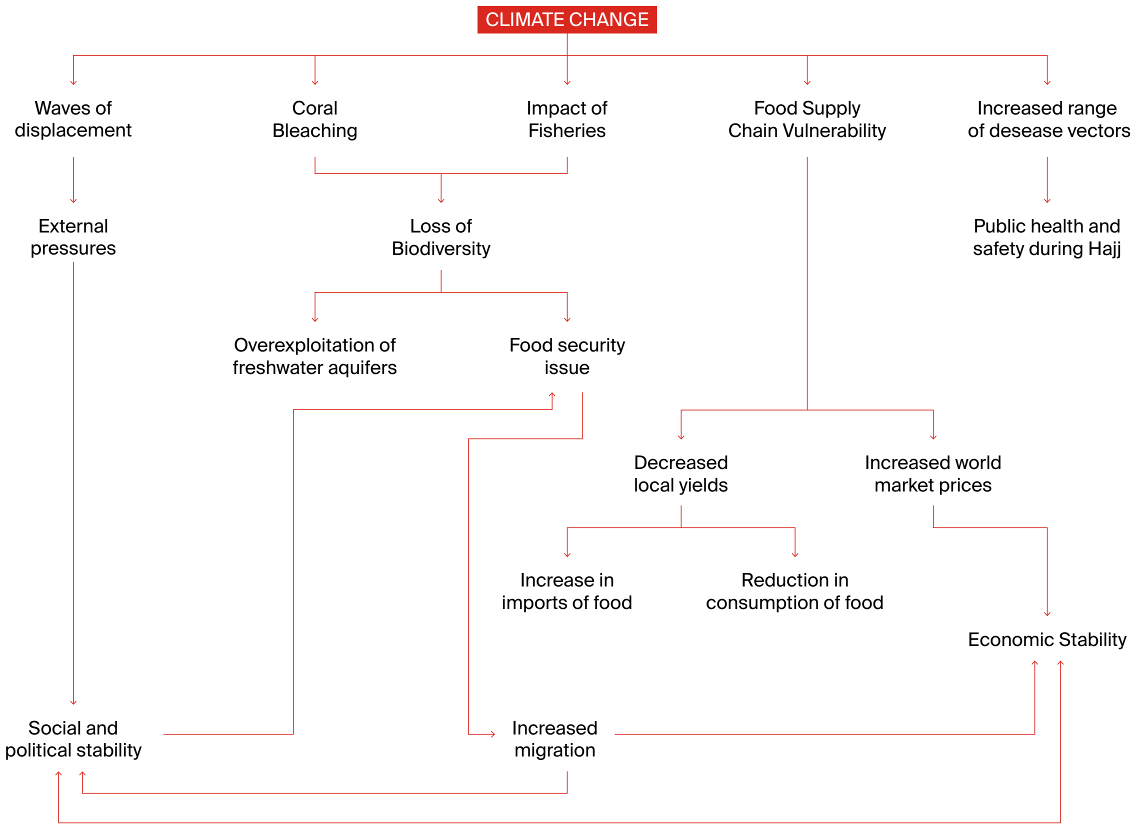
Terrestrial and Marine Ecosystems

Global warming is causing a cascading effect on both terrestrial and marine ecosystems, disrupting the balance of life on the land and in our oceans, and threatening the livelihoods of communities dependent upon these ecosystems. The loss of these ecosystems, some of which are globally unique, could have cascading effects on biodiversity, impacting fisheries and other marine life that rely on these ecosystems, as well as the flora and fauna inhabiting niches extending from the shoreline into the deep desert. Such changes are particularly concerning in the context of global overfishing and ocean pollution, which further stress marine ecosystems and could lead to food security issues[9], as does the overexploitation of freshwater aquifers that drive international food production[10].

Food Supply Chain Vulnerability and Economic Stability

The GCC, including Saudi Arabia, relies heavily on food imports. Future climate and demographic changes could affect world food supply from traditional trading partners, potentially leading to decreased local yields and increased world market prices. This could result in moderate re-

FIGURE 2
Cascading effect in the context of Saudi Arabia.



ductions in per capita consumption of all food commodities and a significant increase in imports of cereals, fruits, vegetables, oilseeds, and meat. Such changes could threaten food security and social stability. Global climate change is causing a cascading effect on food security and agricultural production, potentially leading to social unrest and increased migration. These challenges could further impact the economy and social stability[11, 12].

Displacement and Regional Stability

Climate change, conflicts, and displacement are intricately linked. The state of "uncertainty" when exploring the direct relationship between these factors underscores the need to monitor and examine the complicated links between them. Climate changes in both the Arab world and neighboring regions could lead to waves of displacement and migration to wealthier Gulf countries, creating external pressures. This cascading effect of global climate change on human migration could increase social and political tensions, potentially leading to resource strain, social unrest, and political instability. These effects could further impact trade, security, and regional cohesion[13].

Mineral Supply Chain Shock and Energy Transition

The shift to clean energy necessitates a range of critical minerals, but future supply is uncertain. Risks such as schedule delays, cost overruns, and the need for clean, responsibly sourced supplies pose significant challenges. The global nature of these challenges is highlighted by China's dependence on imported raw materials and its efforts to diversify its supply portfolio[14]. Saudi Arabia, with its abundant mineral resources, could play a pivotal role in addressing these challenges. The global demand for clean energy is causing a ripple effect on mineral supply chains, potentially leading to supply shocks and geopolitical tensions. These challenges could disrupt the global energy transition, impacting fossil fuel-dependent economies like Saudi Arabia, and have cascading effects on energy prices, economic stability, and progress towards climate goals.

Climate Cooperation

Addressing the cascading effects of a 3-degrees warmer world calls for a comprehensive approach that transcends individual sectors and borders. This includes robust mitigation strategies, adaptive measures, and international cooperation to manage shared risks and challenges. The interconnected nature of these impacts, spanning public health to food security, and energy supply to economic stability, underscores the need for integrated solutions.

Coalition building is crucial in this global endeavor. It is an opportunity for a respectful exchange of ideas and perspectives that can foster innovation and transcend the bounds of current understanding. However, navigating the complexities of climate change also involves grappling with uncertainties: the known unknowns and the unknown unknowns!

This report aims to shed light on these dynamics, providing a detailed exploration of potential impacts and implications for Saudi Arabia in a 3-degrees warmer world. It also seeks to offer actionable recommendations for policymakers, emphasizing risk management, resilience building, and international collaboration.

Furthermore, addressing environmental challenges extends beyond technology and policy. It involves creating a culture of sustainability, where every individual and organization understands their role in protecting the environment and is motivated to make sustainable choices. This work contributes to the global dialogue on climate change and aims to inspire action towards a more sustainable future.

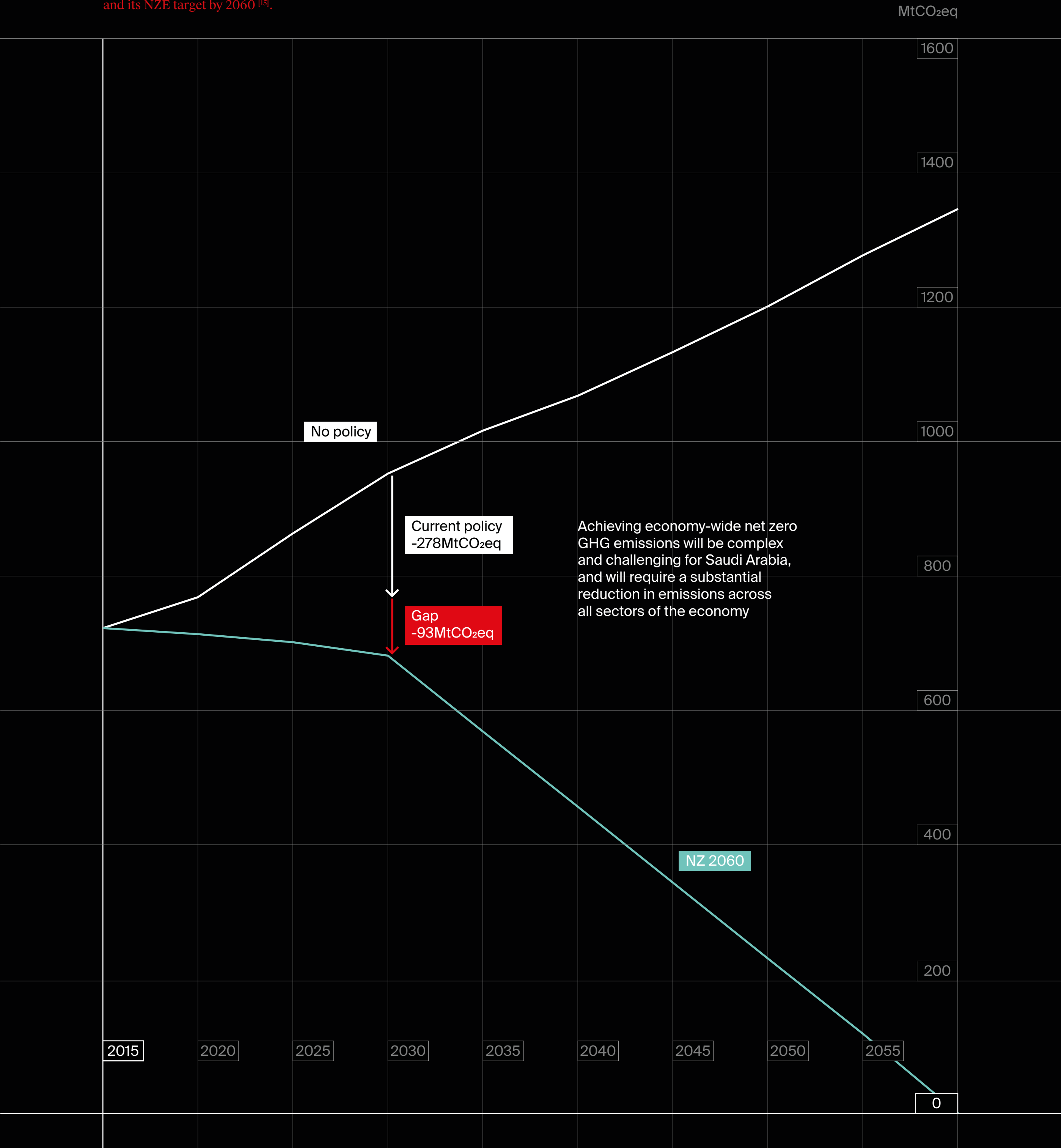
Photo by Usef Ateyah on Unsplash

Saudi Arabia has recently been taking steps to address climate change and reduce its greenhouse gas emissions. The country's current climate policy is primarily guided by its Vision 2030, a comprehensive economic and social reform plan aimed at diversifying its economy and reducing its dependence on oil. In 2021, Saudi Arabia has committed under its updated nationally determined contributions (NDC) to reducing, avoiding, and removing its GHG emissions by 278 million tons of CO_2eq annually by 2030. Also, in the same year, the Kingdom announced its pledge to achieve GHG net-zero emissions (NZE) by the year 2060. To achieve its climate ambition, the country has implemented various initiatives and measures. One significant step is the expansion of renewable energy sources, particularly solar power. The country aims to increase its renewable energy capacity to 50% of the electricity mix, which will help decrease its reliance on fossil fuels. Additionally, Saudi Arabia is implementing energy efficiency programs to ensure more sustainable energy consumption across sectors such as industry, transportation, and buildings.

To understand the contributions of current climate policies and additional ones that are needed for the Kingdom to deliver on its short- (NDC) and long-term (NZE) targets, it is important to explore different decarbonization pathways for Saudi Arabia to guide its future efforts. Kamboj et al.[15] establishes a scenario where the Kingdom achieves its updated NDC target by 2030, and its NZE target by 2060. The results suggest that achieving economy-wide net zero GHG emissions will be complex and challenging for Saudi Arabia, and will require a substantial reduction in emissions across all sectors of the economy. The results also show that price reforms, energy efficiency measures, and the 50% renewable target, are insufficient to achieve the 278 mt CO_2 by 2030 target and will yield an abatement of 185 mt CO_2eq. The results also show that Saudi Arabia will have to increase its ambition of reducing emissions in the next round of updating the NDCs to better align with its long-term target of achieving net zero GHG emissions by 2060. Furthermore, each sector will follow a separate decarbonization pathway and not necessarily achieve sectoral zero emissions. Finally, understanding how these sectors will evolve into the future and their vulnerability and adaptive capacity to climate change is vital to chart a pathway that is more climate-adaptive and resilient naturally, socially, and economically.

FIGURE 3

Scenario where the Kingdom achieves its updated NDC target by 2030, and its NZE target by 2060 [15].



[1] Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Gregor, L., et al. Global Carbon Budget 2022, Earth Syst. Sci. Data, 14, 4811–4900, https://doi.org/10.5194/essd-14-4811-2022, 2022.

[2] UNFCCC, 2022. Nationally determined contributions under the Paris Agreement. Synthesis report by the secretariat. https://unfccc.int/documents/619180

[3] Birol, F. (2021). COP26 climate pledges could help limit global warming to 1.8 C, but implementing them will be the key. https://www.iea.org/commentaries/cop26-climate-pledges-could-help-limit-globalwarming-to-1-8-c-but-implementing-themwill-be-the-key.

[4] Ou, Y., Iyer, G., Clarke, L., Edmonds, J., Fawcett, A.A., Hultman, N., McFarland, J.R., Binsted, M., Cui, R., Fyson, C., et al. (2021). Can updated climate pledges limit warming well below 2C? Science 374, 693–695.

[5] Sognnaes, I., Gambhir, A., van de Ven, D.-J., Nikas, A., Anger-Kraavi, A., Bui, H., Campagnolo, L., Delpiazzo, E., Doukas, H., Giarola, S., et al. (2021). A multi-model analysis of long-termemissions and warming implications of current mitigation efforts. Nat. Clim. Chang. 11, 1055–1062. https://doi.org/10.1038/s41558-021-01206-3.

[6] IPCC, 2022: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844.

[7] Lelieveld, J., Proestos, Y., Hadjinicolaou, P. et al. Strongly increasing heat extremes in the Middle East and North Africa (MENA) in the 21st century. Climatic Change 137, 245–260 (2016). https://doi.org/10.1007/s10584-016-1665-6

[8] Planton, Serge ; et al. Sub-chapter 1.2.2. The climate of the Mediterranean regions in the future climate projections In: The Mediterranean region under climate change: A scientific update [online]. Marseille: IRD Éditions, 2016 (generated 02 août 2023). Available on the Internet: <http://books.openedition.org/irdeditions/23085>. ISBN: 9782709922203. DOI: https://doi.org/10.4000/books.irdeditions.23085.

[9] Monroe AA, Ziegler M, Roik A, Röthig T, Hardenstine RS, Emms MA, et al. (2018) In situ observations of coral bleaching in the central Saudi Arabian Red Sea during the 2015/2016 global coral bleaching event. PLoS ONE 13(4): e0195814. https://doi.org/10.1371/journal.pone.0195814

[10] Famiglietti, J. The global groundwater crisis. Nature Clim Change 4, 945–948 (2014). https://doi.org/10.1038/nclimate2425

[11] Josef Schmidhuber and Francesco N. Tubiello. 2007. Global food security under climate change. Proceedings of the National Academy of Sciences, 19703-19708, 104, 50, 10.1073/pnas.0701976104, https://www.pnas.org/doi/full/10.1073/pnas.0701976104

[12] H. Charles J. Godfray et al. ,Food Security: The Challenge of Feeding 9 Billion People.Science327,812-818(2010). DOI:10.1126/science.1185383

[13] Ibrahim Abubakar, Robert W Aldridge, Delan Devakumar, Miriam Orcutt, Rachel Burns, et al. 2018. The UCL–Lancet Commission on Migration and Health: the health of a world on the move. https://doi.org/10.1016/S0140-6736(18)32114-7

[14] IEA (2023), Critical Minerals Market Review 2023, IEA, Paris https://www.iea.org/reports/critical-minerals-market-review-2023, License: CC BY 4.0

[15] Kamboj, Puneet, Mohamad Hejazi, Yang Qiu, Page Kyle, Gokul Iyer (in review). Long-term decarbonization pathway for Saudi Arabia to reach net-zero GHG emissions by 2060. KAPSARC Discussion Paper.


Red Sea Rainforests, March 28, 2021, NASA

“If the global average temperature increases by 3°C, as projected under a middle-of-the-road scenario, it will likely translate to a 4°C change in Saudi Arabia.”

Prof. Hylke Beck
Climate and Livability Initiative, Physical Sciences and Engineering (PSE), King Abdullah University of Science and Technology (KAUST), Saudi Arabia

Climate Changes: Past, Present and Future

Climate change is already impacting Saudi Arabia and will impose significant challenges for the future. Warming in the Arabian Peninsula has already surpassed 1.5°C above pre-industrial levels (1850–1900) and is on the verge of exceeding 2°C. Depending on the future socio-economic scenario, climate models project that average temperatures could increase anywhere between 2.5°C to 5.8°C by the end of the century (relative to 1850–1900). Simultaneously, precipitation may become more erratic, with extremes increasing by 7% to 33% depending on the level of global warming, resulting in more severe flash floods. Rising sea levels are a threat to the country's densely populated coastal cities. With a projected population growth of 32% by 2050, more people will be at risk from climate-related hazards. The variation in climate outcomes projected from different climate models and scenarios underscores the importance of our decisions and actions today in shaping Saudi Arabia's climate future.

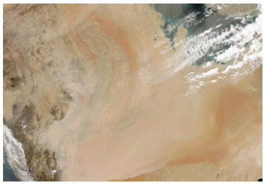
The Recent Past

Saudi Arabia's climate is predominantly hyper-arid, with summer temperatures frequently exceeding 40°C in the country's center. According to the Köppen climate classification, the country is classified as having a "hot desert climate" (type BWh). Precipitation is sporadic and sometimes heavy, averaging less than 100 mm/yr, with the majority falling between November and May. The Asir Mountains, located in the southwest, are a notable exception. Here, the topography induces cooler temperatures, even dropping below 0°C in winter, and the region experiences more frequent precipitation, producing a more semi-arid climate.

Saudi Arabia's arid climate is due to its position in the subtropical high-pressure zone, where the downward movement of warm, dry air hinders the formation of clouds. Weather patterns in the country are governed by variations in the strength and position of this pressure system, as well as others such as the Siberian high, the Icelandic low, the Sudanese low, and Mediterranean depressions[1]. The Arabian Gulf and the Red Sea are the primary sources of atmospheric moisture, delivering the characteristic humidity and moderating temperatures along the coast. Mediterranean Sea disturbances provide additional moisture to the north during winter periods, while the Indian Ocean monsoon system draws in moisture to the southwest in summer. Global phenomena such as the El Niño Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Indian Ocean Dipole (IOD) further modulate the country's weather patterns.

Jeddah Flood 2009, King Abdullah Street. Photo by Rami Awad

[A]



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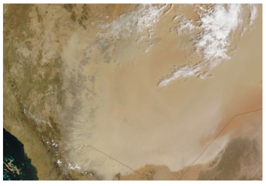


[C]

Like nearly all regions worldwide, Saudi Arabia has seen a rise in average temperatures over the past century: a trend that is attributed to the increase in atmospheric greenhouse gasses, primarily in response to the burning of fossil fuels for electricity, heating/cooling, and transportation. Of some concern is the fact that the warming trend has accelerated in recent years, with Saudi Arabia's temperature rise outpacing the global average. Indeed, recent research indicates that the temperature rise over the Arabian Peninsula over the last four decades is double the global average[2,3]. This has been attributed to the land-sea warming contrast: land masses, with their limited heat capacity and limited water supply for evaporation, tend to heat up more quickly. Such rapid regional warming has already exceeded 1.5°C and is on the verge of surpassing 2°C above pre-industrial times, which are typically defined as the period between 1850–1900 (when human impact on the climate was less pronounced). However, it is worth noting that this rate of double the global average is not expected to persist indefinitely, as will be discussed in the "Future Climate Projections" subsection of this chapter.

Reconstructing historical precipitation trends tend to be more uncertain than for temperature, due to the inherent difficulties in accurately measuring and modeling the sporadic, high-intensity precipitation that is typical of the region. Additionally, trends in precipitation have been much less uniform across Saudi Arabia than trends in temperature. Over the past few decades, there has been a general decrease in annual and wet season precipitation, particularly in the central and southwestern regions[4]. However, some areas in the eastern, northwestern, and southern extents have experienced a slight increase in precipitation. Extreme precipitation events, which can trigger destructive flash floods, have shown an increasing trend. While these trends cannot be unequivocally linked to climate change, the increase in extremes aligns with the expectation that climate change enhances the atmosphere's ability to hold moisture[5].

Similar to global trends, sea levels in the Red Sea and the Arabian Gulf are also on the rise. This increase is primarily due to the melting of ice sheets and glaciers and the expansion of oceans as they heat up. The average rate of sea level rise in the Red Sea was 5.7 mm/yr during 2006–2018 and 4.1 mm/yr during 1993–2022, while the Arabian Gulf experienced a sea level rise rate of 3.4 mm/yr during 2006–2018 and 3.9 mm/yr during 1993–2022[6]. The rate of sea level rise in the Arabian Gulf aligns closely with the global rate, while the rise in the Red Sea surpasses the global average.

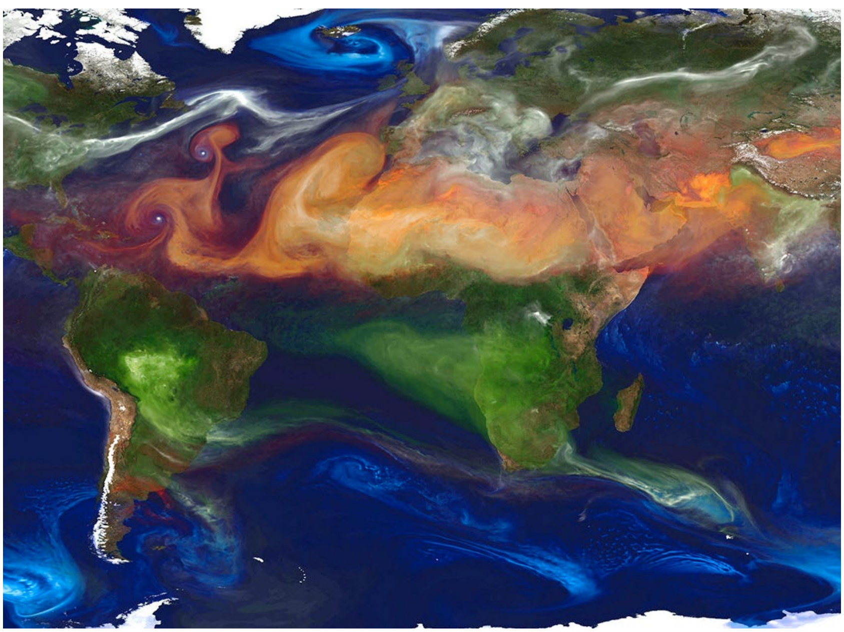
[A] Dust storm across the Persian Gulf and Saudi Arabia, March 27, 2003, Jacques Descloitres, MODIS Rapid Response Team, NASA/GSFC
[B] Dust storm in Saudi Arabia and Yemen, March 27, 2015, Images by the LANCE/EOSDIS Rapid Response team
[C] Dust storm in Iraq and Saudi Arabia, October 29, 2017,Images by the LANCE/EOSDIS Rapid Response team

Climate Models and Future Scenarios

Climate projections provide our best estimates of future climate conditions. These are primarily based on climate models, such as those forming part of the Coupled Model Intercomparison Project Phase 6 (CMIP6)[7]. These models harness our best understanding of the complex physical processes occurring within the Earth system and simulate how the global climate responds to changes in external forcings, such as atmospheric greenhouse gas concentrations, solar radiation, volcanic eruptions, and changes in land use. Current climate models reflect the pinnacle of our knowledge and technical capacity. They are rooted in well-established physical principles, validated by a wealth of observations, and capable of reproducing both current and past climate changes.

However, these models do have limitations, and as a result, their projections are subject to a degree of uncertainty. The primary source of most of this uncertainty is that many critical small-scale processes cannot be explicitly represented in models and must therefore be approximated — often referred to as “parameterisation”. Other factors contributing to this uncertainty include our limited understanding of clouds and aerosols, and the unpredictability of some natural climate variations, such as the previously mentioned IOD and ENSO. Regardless, climate models are crucial tools for providing us with the best possible predictions of future climate change and its potential impacts, allowing policymakers and stakeholders to develop informed climate change adaptation and mitigation strategies.

When modeling the future, it is important to understand that future trajectories of economic development, population growth, and the rate of greenhouse gas emissions are inherently uncertain, as they are shaped by decisions and actions yet to be taken. To account for this uncertainty, so-called Shared Socio-economic Pathways (SSPs) have been developed[8]. These



View of aerosol movement created by NASA’s models and supercomputers, NASA/Goddard Space Flight Center pathways encompass a range of potential future scenarios and serve as drivers for the climate models used to generate climate projections.

The main SSPs are as follows:

- SSP1-2.6: represents a sustainable future, where the world rapidly reduces greenhouse gas emissions and achieves a relatively low level of global warming;
- SSP2-4.5: a “middle of the road” scenario reflecting a world in which trends broadly follow their historical patterns, with moderate levels of warming;
- SSP3-7.0: represents a fragmented world with high levels of greenhouse gas emissions and significant global warming;
- SSP5-8.5: depicts a world with strong economic growth and high energy demand that is met mainly by fossil fuels, leading to very high levels of greenhouse gas emissions and global warming.

Throughout this report, we refer most often to changes anticipated within climate projections based upon SSP2-4.5. Many climate scientists currently view this scenario as the most likely trajectory for our future.

FIGURE 1 ↓

[A] Simulated mean annual temperature change relative to 1850-1900.
[B] Simulated mean annual precipitation change relative to 1850-1900.

Air temperature changes in °C (a) and precipitation changes in % (b) relative to 1850–1900 for the Arabian Peninsula. These changes were obtained using a subset of 22 CMIP6 models with realistic CO_2-induced warming rates[16]. The dashed vertical lines mark January 1, 2015. For air temperature, changes relative to 1850–1900 are calculated by adding 1.086°C (the observed temperature increase for the Arabian Peninsula from 1850–1900 to 1991–2020) to simulated changes relative to 1991–2020. For precipitation, changes relative to 1850–1900 are calculated by adding 3% (the mean simulated precipitation increase for the Arabian Peninsula from 1850–1900 to 1991–2020) to simulated changes relative to 1991–2020. To smooth out yearly fluctuations, a 10-year moving average is applied. The shaded regions around each line depict the 68% confidence interval, which is calculated based on the spread among the models.

Future Climate Projections

A rise in air temperature is a certain outcome of increases in atmospheric greenhouse gas concentrations. According to CMIP6 models, the projected global warming for the range of future scenarios expressed within SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 by 2081–2100 (relative to the pre-industrial period 1850–1900) is estimated at 1.8°C, 2.7°C, 3.6°C, and 4.4°C, respectively[9]. The timeframe for reaching 3°C of global warming also varies depending on the SSP. Under the high-emission scenarios of SSP3-7.0 and SSP5-8.5, this warming threshold will likely be reached in 2077 and 2065, respectively. Under the low-emission scenario of SSP1-2.6, we can entirely avoid this level of warming, while under the moderate-emission scenario of SSP2-4.5, we may only reach this level in the 22nd century, if at all.

However, it is important to note that the projected temperature increases reflect global averages. Local and regional variation will exist amongst these projections. Indeed, the projected average temperature increase for the Arabian Peninsula for the period 2071 to 2100 under scenarios SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 is 2.5°C, 3.6°C, 4.8°C, and 5.8°C, respectively (relative to 1850–1900; FIGURE 1) reflecting the regional tendency to warmer than average responses. A rise in global average temperature of 3°C above the pre-industrial level is projected to result in an approximate 4.4°C increase in the average temperature for the Arabian Peninsula by the end of this century[2]. For global warming levels of 1.5°C, 2°C, and 4°C, the projected average temperature increases across the Arabian Peninsula are approximately 2.2°C, 2.9°C,

FIGURE 1 [A]

Simulated mean annual temperature change relative to 1850-1900.

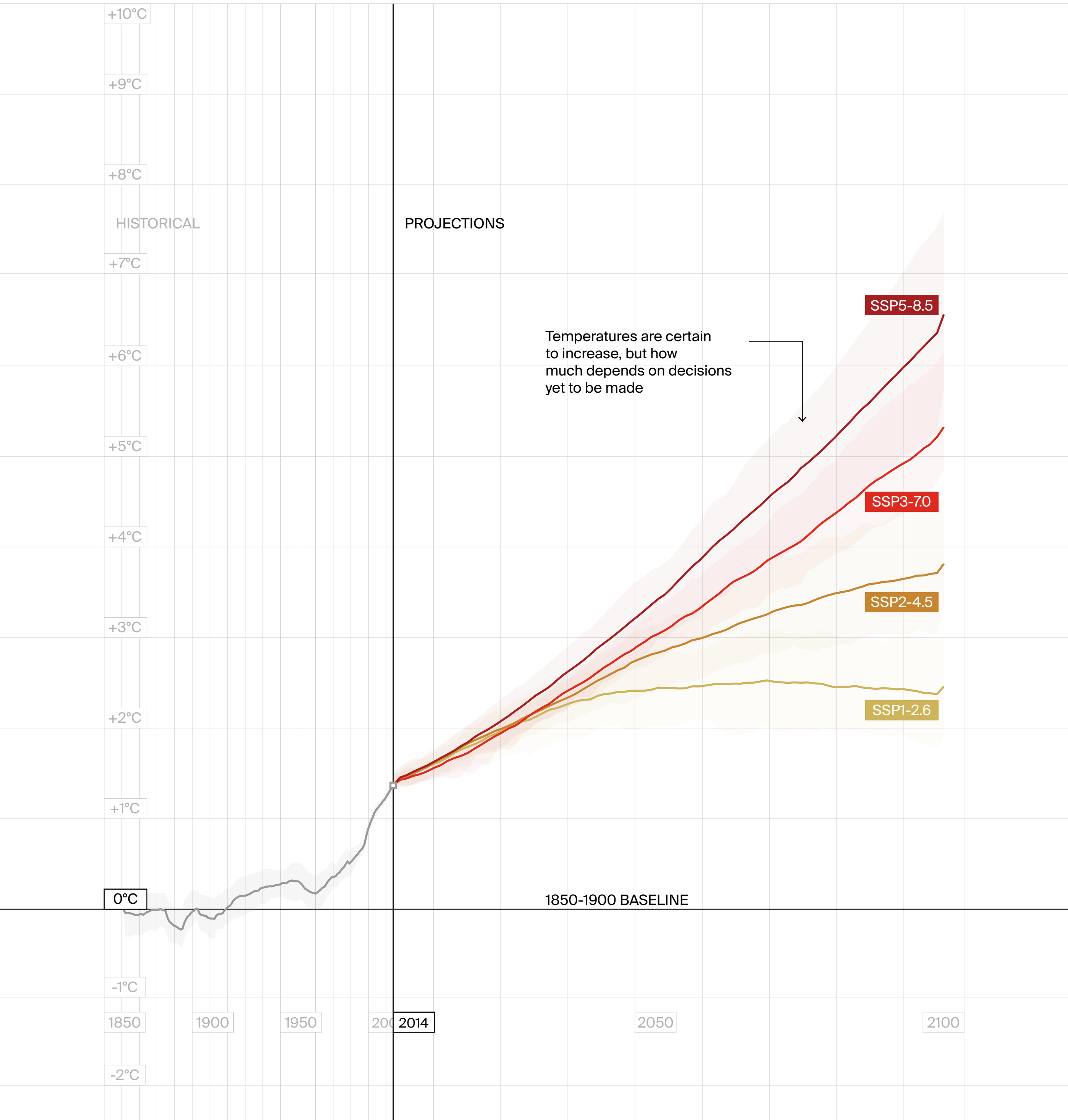
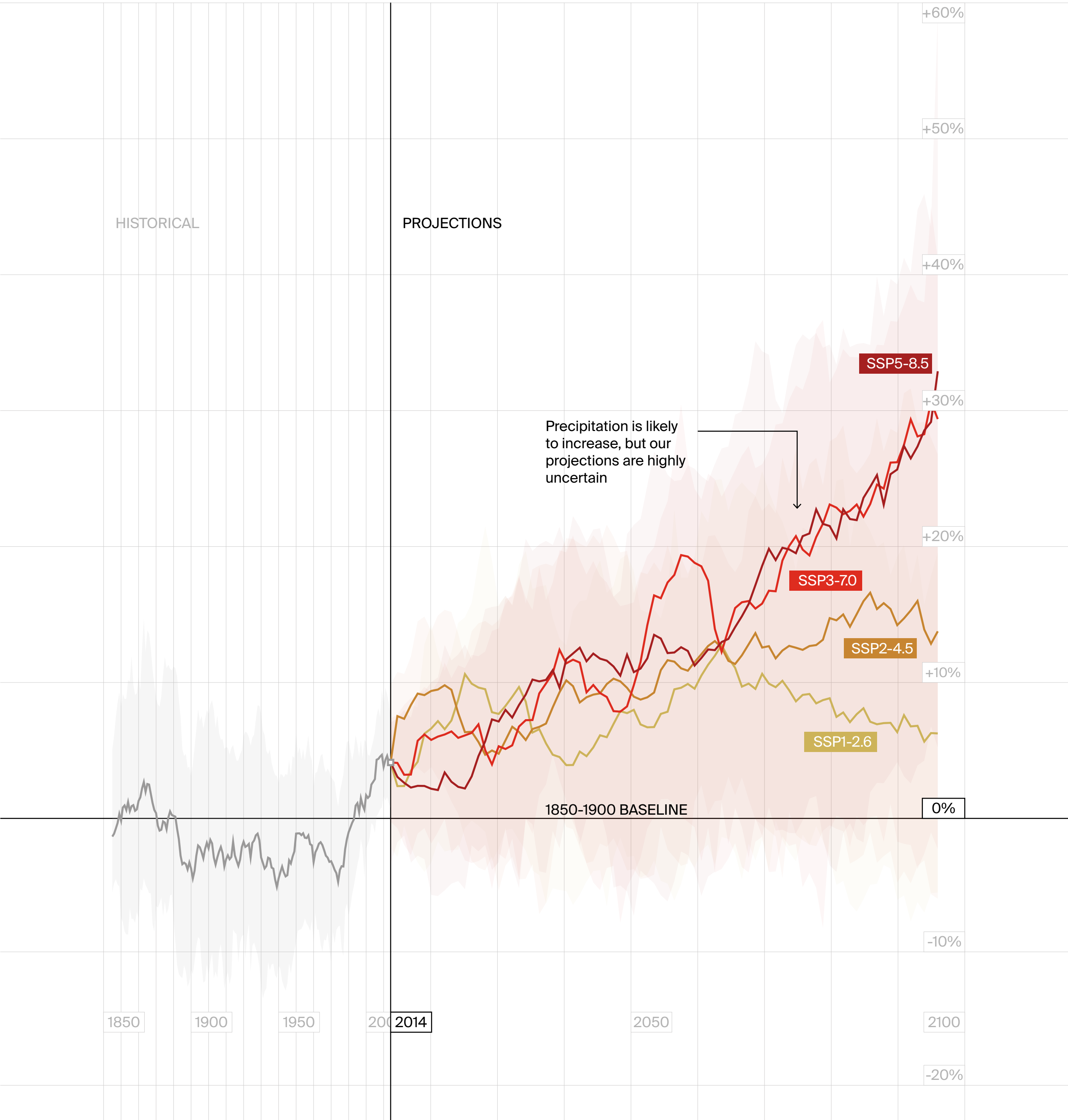
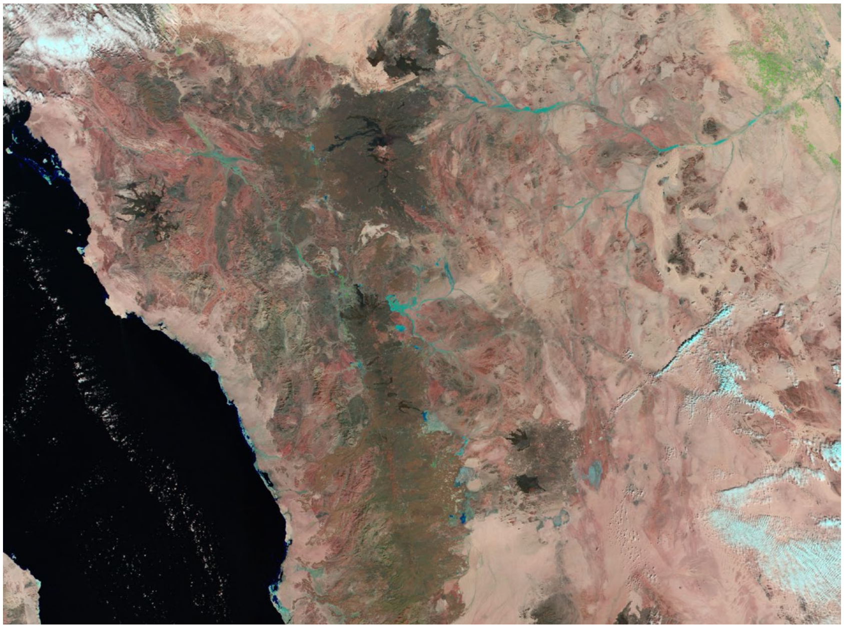


FIGURE 1 [B]

Simulated mean annual precipitation change relative to 1850-1900.





Floods in Saudi Arabia, January 24, 2005, NASA image created by Jesse Allen, Earth Observatory, using data obtained from the MODIS Rapid Response team.

and 5.6°C, respectively. Consequently, with each degree of global warming, the corresponding increase in temperature is significantly more pronounced for the Arabian Peninsula, due to the aforementioned land-sea warming contrast.

In agricultural areas, higher temperatures, along with changes in other meteorological variables, may increase the demand for water. In the Al Qassim region, one of Saudi Arabia's most important agricultural areas, the crop water demand is projected to rise by 6.0% and 12.0% respectively by the end of the 21st century under scenarios SSP2-4.5 and SSP5-8.5[10]. This increase will certainly place additional pressure on the region's already stressed water resources, particularly the finite and over-exploited groundwater reserves (Chapter 5).

In cities, the increase in temperature may be even greater, due to the anticipated urbanization associated with projected population growth of 32% by 2050 (UN, 2022). This urbanization will exacerbate the urban heat island effect, the phenomenon of city infrastructure absorbing and retaining heat[11]. Climate models generally do not account for this effect due to their coarse 50 to 100 km spatial resolution. Higher temperatures will also increase the need for cooling, which can lead to increased energy use and potentially higher greenhouse gas emissions (Chapter 7).

The projected average precipitation increase for the Arabian Peninsula for the period 2071 to 2100 under scenarios SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 is 3%, 8%, 15%, and 16% respectively, compared to 1991–2020 (see FIGURE 1). The shaded areas around each line indicate the uncertainty in these projections, arising from the limitations inherent in the climate models.

Notably, the shaded areas are much broader for precipitation than for temperature, highlighting the significant uncertainty surrounding precipitation projections. Accurately simulating precipitation is particularly challenging because of its considerable spatial and temporal variability and the multitude of factors affecting precipitation generation. This uncertainty emphasizes the need for effective water management strategies (Chapter 5), especially since projections also suggest that annual precipitation variability in the region will increase[12], enhancing the risk of both floods and droughts.

It is important to recognize that a small-to-moderate percentage change in precipitation will not dramatically alter the water supply outlook for Saudi Arabia. Given the low total volumes of annual precipitation, Saudi Arabia will remain an environment dominated by semi- and hyper-arid conditions, even under the most optimistic precipitation projections.

Similar to the rise in temperature, the rise in sea level is a certain outcome of climate change. For SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 the global mean sea level is expected to rise by 0.58 m, 0.70 m, 0.81 m, and 0.91 m, respectively, by the end of the 21st century (relative to the year 1900[9]). It is important to note that these estimates are subject to considerable uncertainty, due to our limited understanding of the future response of the ice sheets. Furthermore, regional sea level rise projections can significantly deviate from global projections due to changes in gravity fields, wind patterns, and land subsidence or uplift. Regardless, these rising sea levels pose a substantial risk to the many densely populated cities located along Saudi Arabia's coasts, as they could lead to increased storm surges (Chapter 6).

FIGURE 2 ↓

[A] Simulated annual maximum temperature change relative to 1981-2010.
[B] Simulated annual maximum precipitation change relative to 1981-2010.

Projected changes in annual maximum temperature (a) and 1-day maximum precipitation (b) for the Arabian Peninsula relative to 1981–2010 at 1.5°C, 2°C, 3°C, and 4°C of global warming (with respect to 1850–1900). These changes were obtained by averaging simulations from 27 CMIP6 models using the SSP5-8.5 scenario.

Changes in Extremes

The effects of climate change are not solely reflected in shifts in average temperatures and precipitation patterns. Generally, changes in extreme weather events are more pronounced than changes in the average climate. This is because climate change does not merely "shift" averages, but often "stretches" the entire statistical distribution of climate variables such as temperature and precipitation. The tail ends of these distributions, representing extreme weather events (i.e., those least likely to occur), are thus affected in a non-linear and often more dramatic fashion compared to the averages.

The most common natural hazards in Saudi Arabia are heat waves, flash floods, and dust storms. To illustrate the impact of climate change on heat waves, FIGURE 2 shows the projected change in annual maximum temperature by 2081–2100 (relative to 1981–2010). Here, we have chosen to focus on potential global warming levels, rather than choosing an individual SSP, to illustrate a range of possible climate outcomes. For global warming levels of 1.5°C, 2°C, 3°C, and 4°C above pre-industrial levels, the annual maximum temperature for the Arabian Peninsula increases by 1.6°C, 2.3°C, 3.9°C, and

FIGURE 2 [A]

Simulated annual maximum temperature change relativeto 1981-2010.

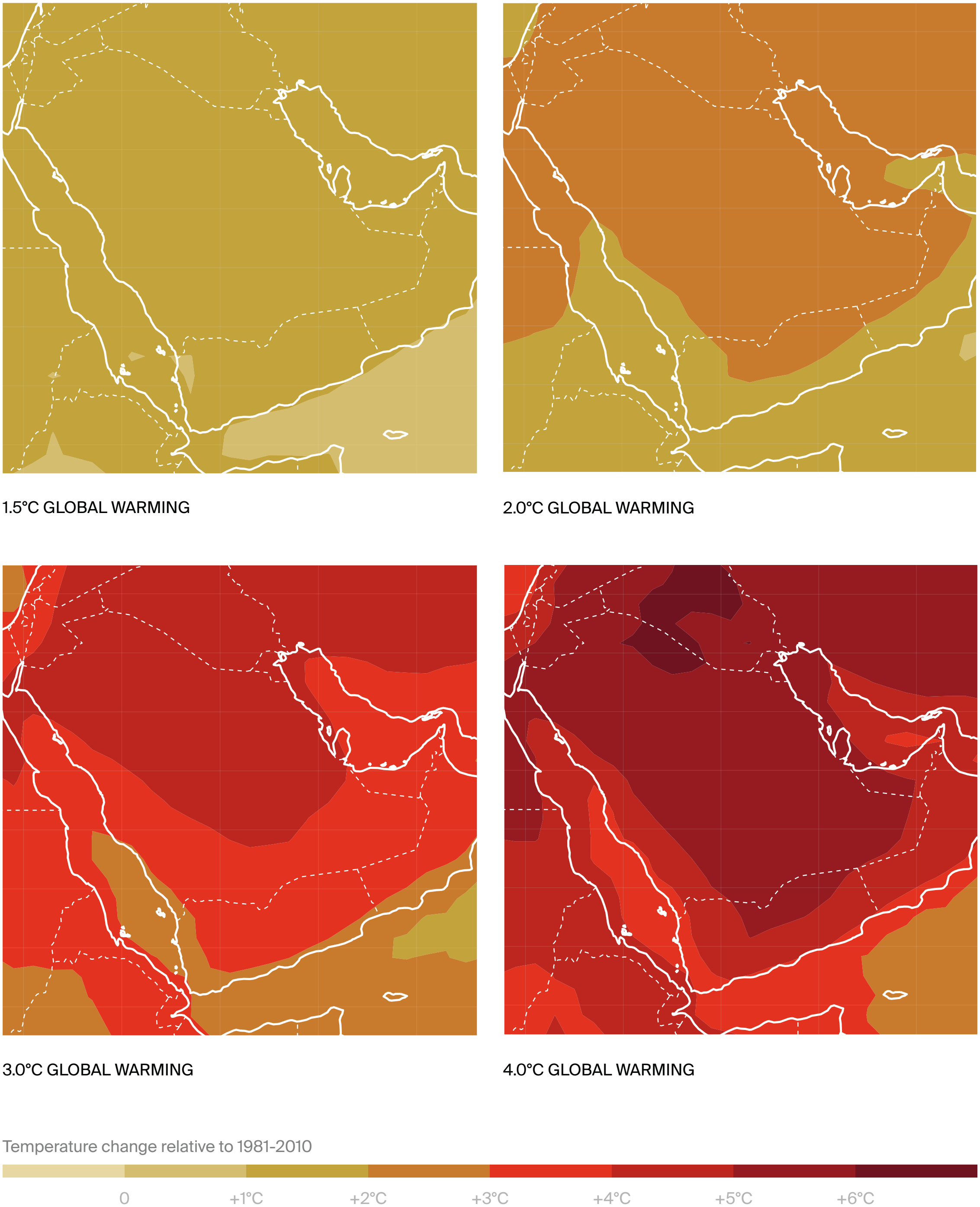
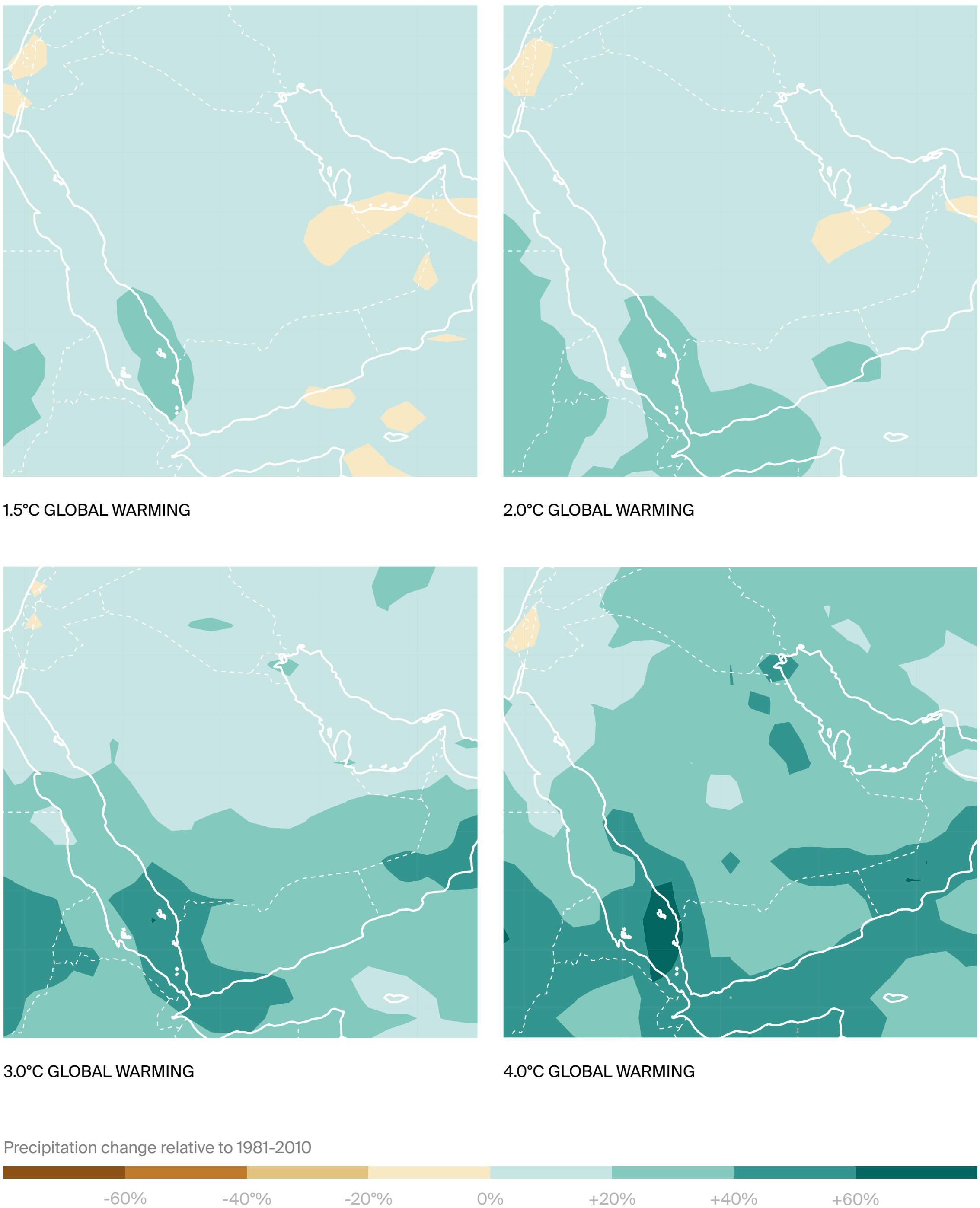


FIGURE 2 [B]

Simulated annual maximum precipitation change relative to 1981-2010.



5.2°C, respectively, with the greatest warming expected to occur in central northern Saudi Arabia.

Concerningly, under a high-emission scenario such as SSP5-8.5, outdoor conditions during heat waves in certain cities along the Arabian Gulf could exceed the survivability threshold towards the end of the century[13]. Notably, the referenced study did not take into account the previously mentioned urban heat island effect, which further exacerbates the heating.

Despite the low annual volumes of rainfall, Saudi Arabia frequently experiences sudden and intense precipitation events, resulting in flash floods that have claimed lives and inflicted significant damage to infrastructure and property. Many cities in Saudi Arabia are vulnerable to these flash floods, due to a lack of adequate storm drainage infrastructure.

As temperatures rise due to climate change, so does the capacity of our atmosphere to hold moisture. Specifically, for every degree Celsius of warming, the air's ability to hold moisture increases by roughly 7%: a relationship described by the Clausius-Clapeyron equation. Increases in humidity can lead to more extreme precipitation events, as the moisture-laden air has the capacity to carry, and subsequently release, more water[5].

To illustrate the impact of climate change on extreme precipitation events in Saudi Arabia, FIGURE 2 also depicts the projected change in annual 1-day maximum precipitation by 2081–2100 (relative to 1981–2010). For global warming of 1.5°C, 2°C, 3°C, and 4°C (above pre-industrial levels), the 1-day maximum precipitation for the Arabian Peninsula increases by 7%, 10%, 23%, and 33%, respectively, with the greatest increases expected to occur in the southwest.

While there is uncertainty regarding the magnitude of these increases, mainly due to the relatively simplistic way precipitation processes are "parameterized" in global climate models (rather than physically simulated), any substantial increase in precipitation extremes would likely result in more frequent and severe flash floods. Such an outcome is particularly worrisome given the projected population growth of 32% by 2050[14], which will expand the number of people exposed to the risks of flooding.

The Middle East is a hot spot for dust storms, which degrade air quality and visibility. These storms not only pose threats to human health (Chapter 8), but also impact crucial sectors such as aviation and energy. CMIP6 projections indicate that while surface dust concentrations might decrease in the southeast, they could rise in the northwest under all scenarios[15].

However, dust projections are perhaps even more uncertain than those for precipitation, due to the complex interplay of factors affecting dust concentration, transport and dispersal. Higher temperatures can exacerbate soil dryness, making it more susceptible to wind erosion and dust emission.

Precipitation, on the other hand, can mitigate dust events by wetting the soil, reducing its vulnerability to wind-driven erosion. Winds not only lift and transport dust particles from the source regions, but also influence the distance and direction these particles travel.

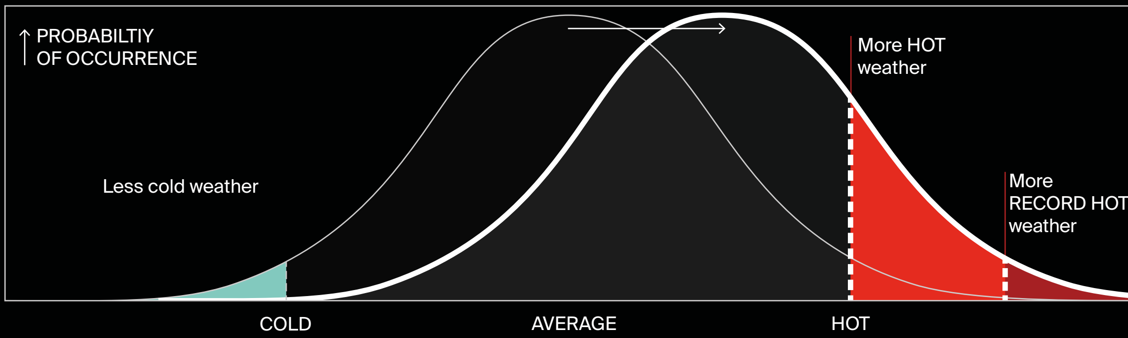
Dealing with Uncertainty

While the implications of climate change are clear in some areas, such as the undeniable rise in temperatures and sea levels, other aspects remain less certain, including changes in precipitation and dust concentrations. However, the presence of uncertainties should not deter the implementation of climate change adaptation and mitigation measures. On the contrary, such uncertainties underscore the need for decisions that strengthen infrastructure and enhance community preparedness, even in the absence of precise forecasts. Indeed, the differences that exist in projections of the various socio-economic scenarios emphasizes the profound impact that today's decisions and actions can have on the future climate trajectory of Saudi Arabia.

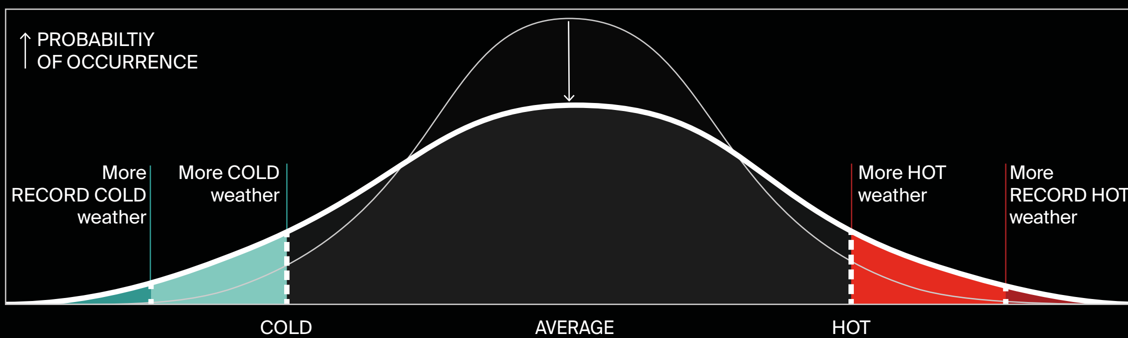
Recent years have witnessed a remarkable willingness and commitment to undertake transformational change, with the protection, preservation and restoration of natural capital a primary focus. Although innovative solutions like afforestation, carbon capture, and nature based solutions show promise, it is important to understand their limitations. Relying solely on these techniques without a parallel decarbonization strategy will not provide a comprehensive solution to the climate related challenges of the future. Given its vast solar potential, commitment to economic diversification under Saudi Vision 2030, and its strategic importance in the global energy market, Saudi Arabia is strongly positioned to become a global leader in climate change mitigation and adaptation.

Myths	Facts
“How can we confidently forecast climate trends when we can’t predict the weather accurately for the next week?”	Climate represents an average of weather patterns over decades in a specific region, and it evolves more gradually than weather. As a result, predicting long-term climate trends can be more feasible than short-term weather forecasting.
“The climate has changed before.”	While the climate has indeed changed in the past, it’s essential to note that humans are now the leading force driving these changes.
“The sun is causing global warming.”	Over the last few decades, during the phase of global warming, the sun’s activity and the Earth’s climate have been on divergent paths.
“Global warming isn’t so bad.”	The adverse impacts of global warming on agriculture, health, and the environment significantly outweigh any potential benefits.
“There is no consensus on climate change.”	An overwhelming majority, 97% of climate experts, agree that human activities are the primary cause of global warming.
“Climate models are unreliable.”	Climate models have successfully replicated global temperatures since 1900 across various domains—land, air, and oceans.
“The temperature record is unreliable.”	The observed warming trend remains consistent in both rural and urban areas, as confirmed by measurements from thermometers and satellites.

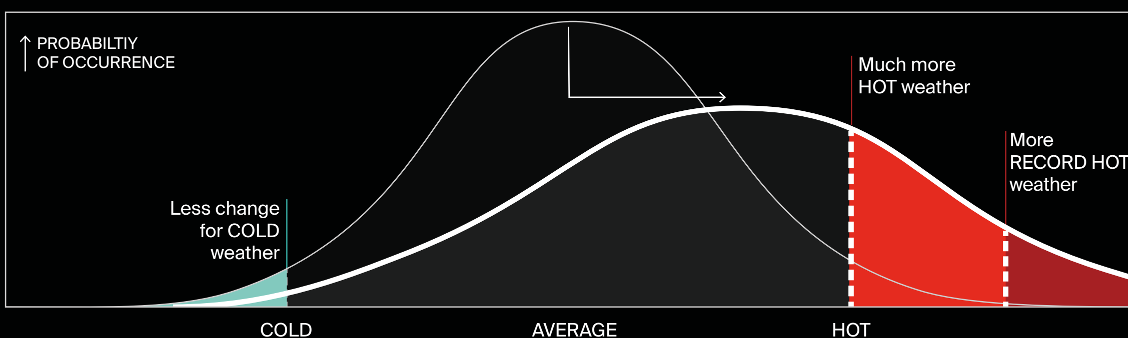
Increase in mean



Increase in variance



Increase in mean and variance



Previous climate
New climate

[1] Hasanean, H., Almazroui, M. (2015). Rainfall: Features and Variations over Saudi Arabia, A Review. Climate 3, 578–626.

[2] Malik, A., G. Stenchikov, S. Mostamandi, et al. Accelerated Historical and Future Warming over the Middle East and North Africa in Response to the Global Temperature Change. ESS Open Archive, 2023.

[3] Zittis, G., Almazroui, M., Alpert, P., Ciais, P., Cramer, W., Dahdal, Y., et al. (2022). Climate change and weather extremes in the Eastern Mediterranean and Middle East. Reviews of Geophysics, 60, e2021RG000762. https://doi.org/10.1029/2021RG000762

[4] Almazroui, M. Rainfall Trends and Extremes in Saudi Arabia in Recent Decades. Atmosphere 2020, 11, 964. https://doi.org/10.3390/atmos11090964.

[5] Fowler, H.J., Lenderink, G., Prein, A.F. et al. Anthropogenic intensification of short-duration rainfall extremes. Nat Rev Earth Environ 2, 107–122 (2021).

[6] Guérou, A., Meyssignac, B., Prandi, P., Ablain, M., Ribes, A., and Bignalet-Cazalet, F. (2023): Current observed global mean sea level rise and acceleration estimated from satellite altimetry and the associated measurement uncertainty, Ocean Sci., 19, 431–451.

[7] Eyring, V., Bony, S., Meehl, G.A., Senior, C.A., Stevens, B., Stouffer, R.J. and Taylor, K.E., 2016. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geoscientific Model Development, 9(5), pp.1937–1958.

[8] Riahi, K., Van Vuuren, D.P., Kriegler, E., Edmonds, J., O'neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O. and Lutz, W., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global environmental change, 42, 153–168.

[9] IPCC. Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge University Press, Cambridge, UK, and New York, NY, 379 USA, 2021).

[10] El-Rawy, M., Batelaan, O., Al-Arifi, N., Alotaibi, A., Abdalla, F., and Gabr, M. (2023). Climate Change Impacts on Water Resources in Arid and Semi-Arid Regions: A Case Study in Saudi Arabia. Water, 15(3), 606.

[11] Addas, A. (2023). Machine Learning Techniques to Map the Impact of Urban Heat Island: Investigating the City of Jeddah. Land, 12(6), 1159.

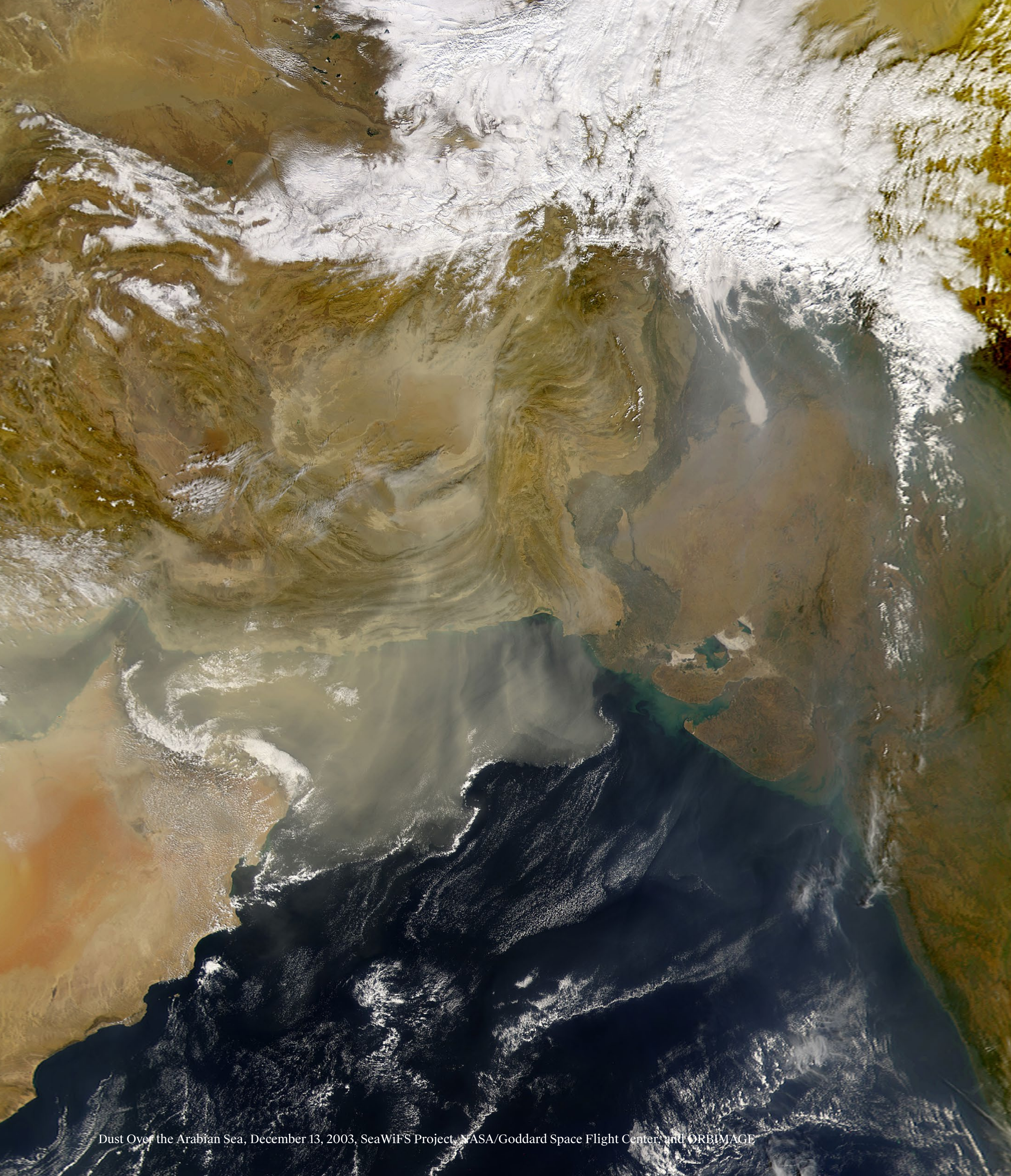
[12] Chen, H., & Wang, S. (2022). Accelerated transition between dry and wet periods in a warming climate. Geophysical Research Letters, 49(19), e2022GL099766.

[13] Pal, J., Eltahir, E. Future temperature in southwest Asia projected to exceed a threshold for human adaptability. Nature Clim Change 6, 197–200 (2016).

[14] UN (2022). World population prospects 2022. Technical report, United Nations, Department of Economic and Social Affairs, Population Division, Paris, France. https://population.un.org/wpp/.

[15] Zhao, Y., Yue, X., Cao, Y., Zhu, J., Tian, C., Zhou, H., Chen, Y., Hu, Y., Fu, W., and Zhao, X.: Multi-model ensemble projection of the global dust cycle by the end of 21st century using the Coupled Model Intercomparison Project version 6 data, Atmos. Chem. Phys., 23, 7823–7838, https://doi.org/10.5194/acp-23-7823-2023, 2023.

[16] Beck, H. E., T. R. McVicar, N. Vergopolan, A. Berg, N. J. Lutsko, A. Dufour, Z. Zeng, X. Jiang, A. I. J. M. van Dijk, and D. G. Miralles (2023). High-resolution (1 km) Köppen-Geiger maps for 1901–2099 based on constrained CMIP6 projections, Scientific Data, in press.



Dust Over the Arabian Sea, December 13, 2003, SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE

“The key factors that promote land degradation and desertification, including wind and water erosion, aquifer depletion, overgrazing, and increases in aridity, will all be exacerbated by the climatic conditions projected in a 3°C warmer world.”

Prof. Fernando T. Maestre, Dr. Emilio Guirado
Department of Ecology & Multidisciplinary Institute for Environment Studies "Ramón Margalef", University of Alicante, Spain

Terrestrial Ecosystems

Over the past four decades, Saudi Arabia has warmed at a rate 50% higher than landmasses in the Northern Hemisphere[1]. Such an amplified degree of terrestrial warming, together with changes in aridity conditions and rainfall patterns, is already having noticeable impacts on ecosystems within the Kingdom and their associated biodiversity. Ongoing climate change is also exacerbating the ecological impacts of other human activities, such as unsustainable groundwater use, overgrazing, urbanization, poaching, and land use change, as well as accelerating major environmental problems like land degradation and desertification. The capacity of Saudi Arabia's terrestrial ecosystems to deliver essential services for human wellbeing and development is under threat, requiring action to protect and preserve these unique environments.

Land Degradation and Desertification

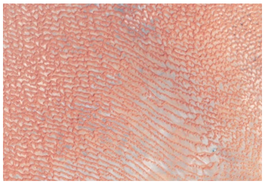
Desertification is formally defined as “land degradation in arid, semi-arid and dry sub-humid areas due to various factors, including climate change and human activities”[2], Desertification impairs the capacity of the land to provide essential ecosystem services and to support life, and represents a major environmental challenge for Saudi Arabia. Although drylands are considered by many as inhospitable to life, they provide a wide range of ecosystem services, including rangelands that provide grazing for nomadic communities[3] and biocrusts that sequester carbon and reduce runoff[4]. Along Saudi’s coastlines, mangrove forests and salt-marshes serve as nursery grounds for marine life and support human populations by protecting shorelines against erosion and providing commercial species for food and nutrition[5].

Large regions of Saudi Arabia are composed of drylands in which land degradation processes have been documented, including the Eastern Province[6] as well as between Jeddah and Haql[7]. Of considerable concern is that the key factors that promote land degradation and desertification, including wind and water erosion, aquifer depletion, overgrazing, and increases in aridity, will all be exacerbated by the climatic conditions projected in a 3°C warmer world.

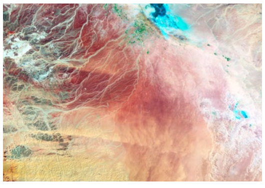
Expectations of increased aridity, drought length and intensity, sporadic and heavy rainfall events and enhanced atmospheric evaporative demand, will all act to reduce water availability throughout Saudi Arabia. Indeed, estimates predict a loss of up to 26 liters per square meter per year by the end of the

Salam Park, Riyadh, Saudi Arabia, Google Earth Studio century[8]. Such reductions will impact the amount of water available to natural vegetation, which is unlikely to be offset by any increases in water use efficiency (promoted by higher concentrations of CO_2 in the atmosphere). The consequence is a likely reduction in vegetation cover and diversity, aggravating the effects of overgrazing and wind and water erosion and amplifying the risks of further degradation and desertification[9].

[A]



[B]



Global drylands are expected to be among the environments most affected by ongoing climate changes[10]. Saudi Arabia will be no exception. While not formally included in the definition of desertification in the UN Convention to Combat Desertification (UNCCD) (because they are assumed incapable of supporting economic activity), hyper-arid areas can also be desertified by human activities. Overexploitation of water resources in hyper-arid lands fits within the UNCCD concept of desertification, in which human activities are recognized as drivers of irreversible degradation[2]. The mining of fossil groundwater in Saudi Arabia to irrigate agriculture exceeds 20 billion cubic meters per year, representing an order of magnitude difference to the annual recharge[11]. Climatic changes associated with a 3°C warming are expected to reduce the annual groundwater recharge by 5% for the period 2045-2055 compared to the timeframe 2015-2025[11], further exacerbating the land degradation and desertification associated with unsustainable water use.

Terrestrial Biodiversity

Currently, Saudi Arabia protects more than 66,000 km^2 of its land and sea, representing around 17% of the total surface area. Driven by recent conservation efforts, these numbers are expected to increase to a total of 30% by 2030. However, climate change, coupled with anthropogenic influences, is already driving the loss of natural habitats, including unique ecosystems such as sabkhas, karst systems, oases, and wadis, which are highly dependent on above- and below-ground water resources[12]. The loss of these ecosystems is affecting unique native species, as well as migratory birds that rely on them as a waypoint for breeding, resting, and feeding grounds during their migratory routes[13].

Terrestrial warming and changes in rainfall patterns that can be expected under a 3°C warming scenario will act to increase water scarcity and exacerbate these negative impacts. Furthermore, agriculture and other human activities, including urban expansion, will continue to compete with natural systems for available water, reducing the volumes available to maintain water-dependent ecosystems and placing further stress on an already water constrained environment.

Expected temperature changes are a major threat to animals currently living in the region, as many are non-migratory, and thus need to cope with temperature increases. Rapid adaptation may not be possible for many animals under a 3°C warming scenario. Ambient temperature across many parts of Saudi Arabia already reach 45 °C during the summer, stressing endangered

[A] Empty Quarter, Image created by Robert Simmon, using Landsat data provided by the United States Geological Survey. Caption by Michon Scott
[B] Arabian Desert, NASA

FIGURE 1 [A]

The threatened species of Saudi Arabia: endangered animals and the reserves where they are found.

RUPPELL'S FOX

Class: Least concern
NoMA: Unkwown
Binomial: Vulpes rueppellii

ASIAN HOUBARA

Class: Vulnerable
NoMA: 33,000-67,000
Binomial: Chlamydotis macqueenii

STRIPED HYENA

Class: Near threatened
NoMA: 10,000
Binomial: Hyaena hyaena

LAPPET-FACED VULTURE

Class: Endangered
NoMA: 5,700
Binomial: Torgos tracheliotos

DUGONG

Class: Vulnerable
NoMA: Unkwown
Binomial: Dugong dugon

NUBI

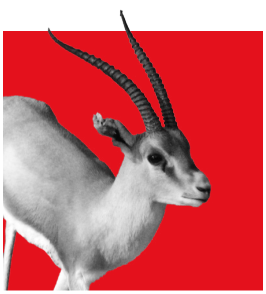
Class: Vulnerable
NoMA: 2,500
Binomial: Capra nubiana

RED-NECKED OSTRICH

Class: Critically endangered
NoMA: 125-150 (KSA)
Binomial: Hyaena hyaena

SAND CAT

Class: Least concern
NoMA: Unknown
Binomial: Felis margarita



RHIM GAZZELLE

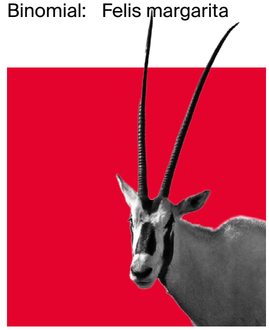
Class: Endangered
NoMA: 300-600
Binomial: Gazella leptoceros

ARABIAN GAZZELLE

Class: Vulnerable (protected)
NoMA: 5,000-7,000
Binomial: Gazella arabica

ARABIAN LEOPARD

Class: Critically endangered
NoMA: 100-250
Binomial: Hyaena hyaena



ARABIAN ORYX

Class: Endangered
NoMA: 1,000
Binomial: Oryx leucoryx

Red List, categories of the IUCN

- Critically endangered
- Endangered
- Vulnerable
- Near threatened
- Least concern

Threatened categories

Class: Classification
NoMA: Number of Mature Animals

and iconic Saudi fauna (FIGURE 1). According to the International Union for Conservation (IUCN)'s red list of threatened species, Saudi Arabia hosts several threatened species, ranging from vulnerable (e.g., the Arabian gazelle, Gazella arabica; and the lappet-faced vulture, Torgos tracheliotos) to critically endangered (e.g., the red-necked ostrich, Struthio camelus camelus; and the Arabian leopard, Panthera pardus nimr). In many cases, the number of mature animals for some of these unique species is currently uncertain or unknown. For example, the red-necked ostrich and the Arabian leopard are suspected to have populations of mature individuals ranging from 125-150 and 100-250, respectively. The number of individuals in populations of dugong (Dugong dugon) and ruppell's fox (Vulpes rueppellii), classified as vulnerable and least concern, respectively, is unknown.

Projections under the SSP2-4.5 scenario will shift temperature distributions, with extremes likely to exceed 47°C during summer, representing an upper lethal limit for many endangered species, and threatening others such as the Arabian spiny-tailed lizard (Uromastyx spp.) or the hoopoe lark (Alaemon alaudipes)[14]. Changes in the diurnal temperature range may also negatively impact reptiles, as their current distribution is significantly impacted by this climatic feature[13]. The influence of increasing temperatures on important pollinators such as bees remains a serious concern in Saudi Arabia, with registered losses of up to 92% in communities of Apis mellifera carnica in summer months, when temperatures are at their maximum[15].

Saudi Arabia's vegetation, which is already adapted to extremely dry condi-

Villages of Fifa Mountains, Jazan Province. Photo via Saudi Green Initiative

FIGURE 1 [B] ↓

The threatened species of Saudi Arabia: endangered animals and the reserves where they are found.

tions, will almost certainly be negatively affected, as warmer temperatures and altered precipitation patterns will increase evaporation and reduce soil water availability. However, evidence of potential changes is scarce, and will likely differ depending on the species and habitat being considered. For example, field surveys in the Khulais region have reported that ongoing increases in aridity between 2011 and 2020 have reduced the frequency of 50 out of 251 plant species found, with the largest declines observed in agricultural weeds and valley plants, while species of rocky and mountain habitats were less affected[16].

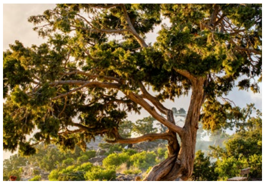
Source IUCN red list of threatneded species Saudi wildlife authority (SWA).

Any scenario reflecting an increase in global temperatures approaching 3°C of warming will undoubtedly exacerbate impacts on the flora and fauna of Saudi Arabia. While there is limited analyses regarding climate change impacts on natural habitats within the Kingdom, it remains unlikely that any warming approaching 3°C will produce positive outcomes for terrestrial biodiversity. One exception might relate to anticipated sea level rises, which could act to increase the distribution range of mangroves along the Arabian coastlines.

Ecosystem Services

[A]

[B]



Ecosystem services encompass the ecological attributes, operations, or mechanisms that play a role, either directly or indirectly, in enhancing human wellbeing. In essence, they represent the advantages that individuals obtain from the proper functioning of ecosystems. Such services include sediment retention, the provision of water, food production, the maintenance of soil fertility or climate regulation, to name a few. As such, ecosystem conservation is not only critical for biodiversity, but also for human wellbeing, as human populations in the Kingdom and elsewhere rely on the services they provide for our survival and development.

The provision of ecosystem services relies upon the maintenance of healthy ecosystems, so any factor negatively impacting them will have detrimental effects. As an example, declining vegetation cover and loss of biodiversity negatively impact the ability of ecosystems to retain water and prevent soil erosion, increasing the risk of flooding and water quality degradation. Similar to the forecasts on future biodiversity, there are few specific studies addressing how a 3°C warming will impact the provision of ecosystem services in the region. However, like elsewhere around the world, and particularly in arid and semi-arid environments[17], the burden of evidence suggests major impacts on essential ecosystem services.

Global studies based on previous IPCC scenarios indicate that a 2.8°C warming will substantially decline carbon storage (up to 2000 Mg/km^2) in the region, which exerts a major control on climate regulation and is a key action to mitigate climate change[18]. As noted previously, the detrimental effects of such warming on populations of bees and other wild pollinators will directly impact the cultivation of fresh fruits, especially considering that approximately 75% of flowering plants and 35% of the world's food crops depend on animal pollination. Other important services, such as sediment retention and the maintenance of soil fertility, will also be negatively affected as increased temperatures, droughts, and reduced soil water availability, acting in combination with urbanization and other land use changes, reduces natural vegetation and increases wind and water erosion.

[A] Photo by NEOM on Unsplash
[B] Photo by Dr Muhammad Amer on Unsplash

Ecosystem Restoration and Enhancement

To protect and preserve Saudi Arabia's terrestrial ecosystems into the future it is crucial to take measures to mitigate climate change and adapt to its effects as soon as possible. This includes reducing greenhouse gas emissions, conserving and restoring natural habitats, managing water sustainably, and developing novel ecosystem restoration strategies.

Major national and regional initiatives aiming to protect biodiversity, restore degraded ecosystems and mitigate climate change include the Saudi and Middle East Green Initiatives[19]. Tree planting is at the cornerstone of both initiatives, with aims to plant 10 and 40 billion trees throughout Saudi Arabia and the Middle East, respectively. These measures are complemented by important actions such as the establishment of protected areas covering more than 30% of the Saudi territory (including marine and coastal ecosystems), a transition to green energy, and the establishment of waste reduction and improved management measures, to name a few.

FIGURE 2 →

The preservation and restoration of dryland ecosystems, together with its monitoring, is needed to ensure resilience and the manteinance of Saudi Arabia's unique natural environment.

Saudi Arabia's unique natural environment will face additional pressures under projected climate changes. Restoration strategies will need to consider the interlinked elements that make up a healthy and functioning ecosystem, from microbial and insect communities, to soil biocrusts, grasslands and shrubs. Relieving anthropogenic pressures such as unsustainable water extraction and land degradation will be critical.

Such initiatives will be fundamental to improve the provision of ecosystem services by increasing vegetation cover and associated organisms, reducing soil erosion and dust production, improving air and soil quality and mitigating desertification and climate change. If implemented successfully, it has been estimated that these activities will help to offset 2.5% of the global greenhouse gas emissions, including the reduction and removal of 670 million tons of carbon dioxide equivalent. Such an outcome would represent the entirety of nationally determined contributions of all countries in the Middle East region.

However, any such estimates should be treated with considerable caution, as the carbon sequestration potential of vegetation in arid- and hyper-arid environments is poorly studied, and there is considerable uncertainty associated with such numbers. Indeed, a 3°C warmer world delivering a drier and more arid climate will impose serious challenges to the success of any restoration initiative. To ensure that positive outcomes are maximized, the selection of species must consider both their habitat requirements under future climatic conditions as well as the ecosystem services that they will provide. Given these constraints, a key performance metric should focus on the delivery of improved ecosystem resilience and biodiversity outcomes, as opposed to using carbon sequestration as a primary criteria to guide success.

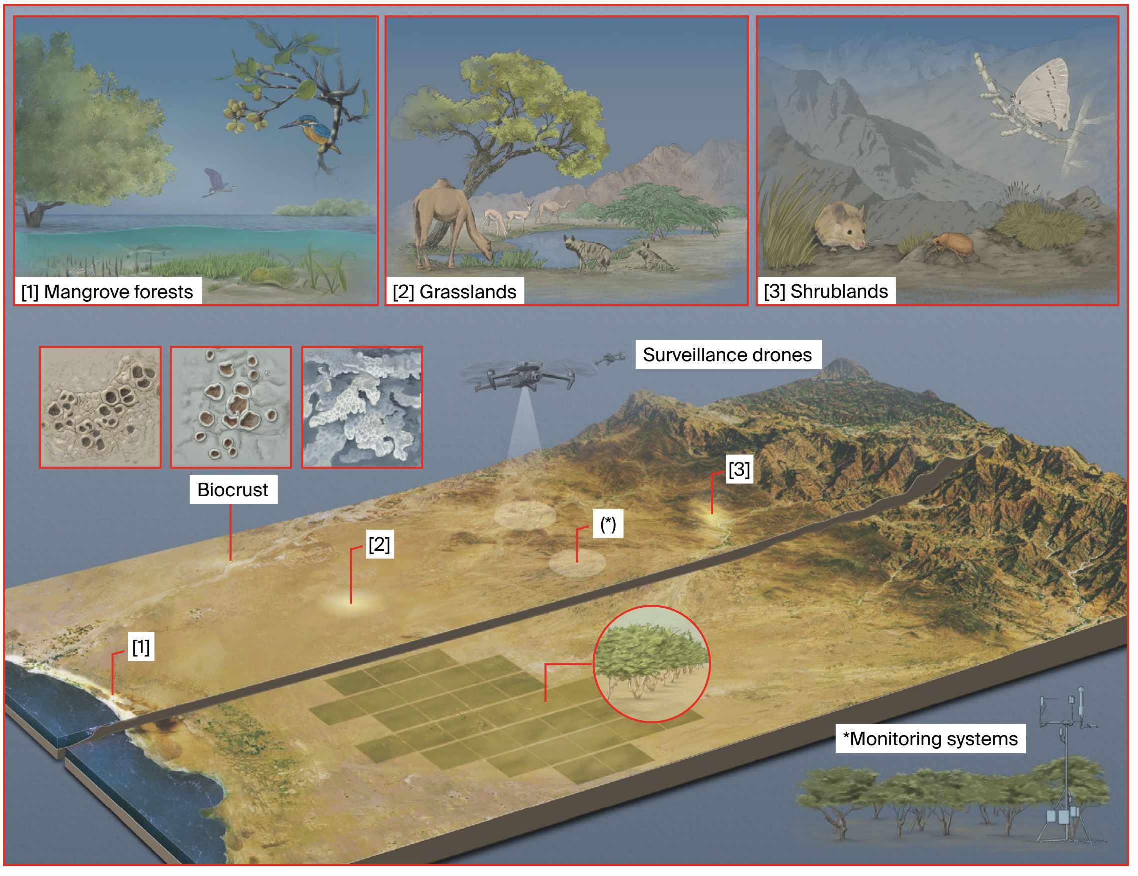
Urban landscapes can also benefit from vegetation enhancement efforts. Proposed urban tree planting schemes should be scaled up and deployed throughout Saudi Arabia and beyond large cities, as this will be a major lever to adapt urban systems to a warmer world, while improving the health and livelihoods of their inhabitants. Given increasing constraints on water availability, these actions should be accompanied by the deployment of appropriate infrastructure to augment the irrigation of planted trees with water not appropriate for human use, including treated wastewater and water harvested from storms[20].

Ecosystem restoration actions in Saudi Arabia will need to consider the use of organisms other than vascular plants. Biocrusts, communities formed by photoautotrophic (algae, lichens, cyanobacteria, liverworts, and bryophytes) and heterotrophic (bacteria, fungi, protozoa, and nematodes) soil organisms, hold considerable potential for the restoration of desert environments, as they have very low water requirements (compared to vascular plants) and prevent soil erosion and aeolian dust production[21]. These top-soil communities can also increase soil carbon stocks and affect nitrogen cycling at large scales[22], and serve as habitats for a myriad of soil organisms. Despite their potential importance in the region, there is a lack of detailed knowledge of the organisms forming biocrust communities, their distribution and potential to restore degraded habitats and mitigate climate change in the region[23].

One of the key mechanisms towards protecting Saudi Arabia's terrestrial ecosystems is the control of livestock grazing. Livestock grazing, and overgrazing in particular, is a major source of land degradation. Under a warmer

FIGURE 2 ↓

The preservation and restoration of dryland ecosystems, together with its monitoring, is needed to ensure resilience and the manteinance of Saudi Arabia's unique natural environment.



climate, the negative effects of increasing grazing pressure are expected to be exacerbated[24]. Livestock exclusion areas can significantly enhance the cover, diversity, and richness of species[25], and their strategic use can be an important biodiversity conservation tool. To improve their effectiveness, the implementation of these areas must consider local environmental knowledge and traditional ways of managing the land. The use of traditional approaches when establishing protected and grazing-exclusion areas can have far-reaching implications for the preservation of biodiversity and the sustainable use of natural resources under a changing climate[26].

Repairing Natural Systems

Ecosystems across Saudi Arabia will be impacted by climate changes, particularly those where projections indicate increased temperatures and decreased rainfall. Natural systems are interlinked entities, with complex feedbacks and interdependencies, so any disturbance to one element is likely to propagate throughout. As such, any measures directed towards protection, restoration or enhancement must be implemented in an integrated manner and tailored to the specific characteristics of Saudi Arabia's unique ecosystems. Cooperation between stakeholders, including government, non-governmental organizations, the private sector, and the local community is paramount when deploying targeted actions. In parallel, the development of educational programs and awareness campaigns on climate change impacts and the importance to maintain and restore terrestrial ecosystems will be key. Underlying these actions is the implicit message that the faster a nation can adopt a low-carbon lifestyle, the less likely the impacts of climate change will cascade to become unmanageable.

Photos by NEOM on Unsplash

[1] Odnoletkova, N., Patzek, T.W., 2021. Data-Driven Analysis of Climate Change in Saudi Arabia: Trends in Temperature Extremes and Human Comfort Indicators. Journal of Applied Meteorology and Climatology 60: 1055–1070.

[2] United Nations, 1994. United Nations Convention to Combat Desertification in Countries Experiencing Serious Drought and/or Desertification, Particularly in Africa Document A/AC. 241/27, 12. 09. with Annexe.

[3] Johnson, D. L. (1993). Nomadism and desertification in Africa and the Middle East. GeoJournal, 31, 51-66.

[4] Kidron, G. J., Posmanik, R., Brunner, T., & Nejidat, A. (2015). Spatial abundance of microbial nitrogen-transforming genes and inorganic nitrogen in biocrusts along a transect of an arid sand dune in the Negev Desert. Soil Biology and Biochemistry, 83, 150-159.

[5] El-Regal, M. A. A., & Ibrahim, N. K. (2014). Role of mangroves as a nursery ground for juvenile reef fishes in the southern Egyptian Red Sea. The Egyptian Journal of Aquatic Research, 40(1), 71-78.

[6] Barth, H. J. (1999). Desertification in the eastern province of Saudi Arabia. Journal of Arid Environments, 43(4), 399-410.

[7] Alharthi, A., El-Sheikh, M.A., Elhag, M., Alatar, A.A., Abbadi, G.A., Abdel-Salam, E.M., Arif, I.A., Baeshen, A.A., Eid, E.M., 2020. Remote sensing of 10 years changes in the vegetation cover of the northwestern coastal land of Red Sea, Saudi Arabia. Saudi Journal of Biological Sciences 27, 3169–3179.

[8] Ajjur, S.B., Al-Ghamdi, S.G., 2021. Evapotranspiration and water availability response to climate change in the Middle East and North Africa. Climatic Change 166, 28.

[9] Sen, Z. (2013). Desertification and climate change: Saudi Arabian case. International Journal of Global Warming 5: 270-281.

[10] Huang, J., Yu, H., Dai, A., Wei, Y., Kang, L., 2017. Drylands face potential threat under 2 °C global warming target. Nature Clim Change 7, 417–422. https://doi.org/10.1038/nclimate3275

[11] Spano D., Armiento M., Aslam M.F., Bacciu V., Bigano A., Bosello F., Breil M., Butenschön M., Cadau M., Cogo E., Colelli F. P., Costa Saura J.M., Dasgupta S., De Cian E., Debolini M., Didevarasl A., Ellena M., Galluccio G., Harris R., Johnson K., Libert A., Lo Cascio M., Lovato T., Marras S., Masina S., Mercogliano P., Mereu V., Mysiak J., Noce S., Papa C., Phelan A.S., Pregagnoli C., Reder A., Ribotta C., Sano M., Santini A., Santini M., Sartori N., Sini E., Sirca C., Tharmananthan R., Torresan S., Trabucco A., "G20 Climate Risk Atlas. Impacts, policy and economics in the G20", 2021, DOI: 10.25424/cmcc/g20_climaterisk

[12] Al-Obaid, S., Samraoui, B., Thomas, J., El-Serehy, H. A., Alfarhan, A. H., Schneider, W., & O'connell, M. (2017). An overview of wetlands of Saudi Arabia: Values, threats, and perspectives. Ambio, 46, 98-108.

[13] Alatawi, A.S., 2022. Conservation action in Saudi Arabia: Challenges and opportunities. Saudi Journal of Biological Sciences 29, 3466–3472.

[14] Williams, J.B., Shobrak, M., Wilms, T.M., Arif, I.A., Khan, H.A., 2012. Climate change and animals in Saudi Arabia. Saudi Journal of Biological Sciences 19, 121–130.

[15] Alattal, Y. & AlGhamdi, A. (2015). Impact of temperature extremes on survival of indigenous and exotic honey bee subspecies, Apis mellifera, under desert and semiarid climates. Bulletin of Insectology 68: 219-222.

[16] Alsherif, E. A., & Almaghrabi, O. A. (2022). Consequences of climate change on the floristic composition of Khulais Region, Saudi Arabia. Applied Ecology & Environmental Research, 20: 691-703.

[17] Reynolds, J. F., Smith, D. M. S., Lambin, E. F., Turner, B. L., Mortimore, M., Batterbury, S. P., ... & Walker, B. (2007). Global desertification: building a science for dryland development. science, 316(5826), 847-851.

[18] Sun, S., Shi, Q., 2020. Global Spatio-Temporal Assessment of Changes in Multiple Ecosystem Services Under Four IPCC SRES Land-use Scenarios. Earth's Future 8: e2020EF001668.

[19] Saudi Green Initiative, 2023. https://www.greeninitiatives.gov.sa/about-sgi/sgi-targets/protecting-land-and-sea/protecting-saudi-arabia-s-land-and-sea/ Accessed on 29th, August, 2023.

[20] Guizani, M. (2016). Storm water harvesting in Saudi Arabia: a multipurpose water management alternative. Water resources management, 30, 1819-1833.

[21] Rodriguez-Caballero, E., Stanelle, T., Egerer, S., Cheng, Y., Su, H., Canton, Y., ... & Weber, B. (2022). Global cycling and climate effects of aeolian dust controlled by biological soil crusts. Nature Geoscience, 15(6), 458-463.

[22] Weber, B., Wu, D., Tamm, A., Ruckteschler, N., Rodríguez-Caballero, E., Steinkamp, J., ... & Pöschl, U. (2015). Biological soil crusts accelerate the nitrogen cycle through large NO and HONO emissions in drylands. Proceedings of the National Academy of Sciences, 112(50), 15384-15389.

[23] Galun, M., Garty, J., 2001. Biological Soil Crusts of the Middle East, in: Biological Soil Crusts: Structure, Function, and Management. pp. 95–106. https://doi.org/10.1007/978-3-642-56475-8_8

[24] Maestre, F. T., Le Bagousse-Pinguet, Y., Delgado-Baquerizo, M., Eldridge, D. J., Saiz, H., Berdugo, M., ... & Gross, N. (2022). Grazing and ecosystem service delivery in global drylands. Science, 378(6622), 915-920.

[25] Al-Rowaily, S.L., El-Bana, M.I., Al-Bakre, D.A., Assaeed, A.M., Hegazy, A.K., Ali, M.B., 2015. Effects of open grazing and livestock exclusion on floristic composition and diversity in natural ecosystem of Western Saudi Arabia. Saudi Journal of Biological Sciences 22, 430–437.

[26] Kilani, Hala, Assaad Serhal, Othman Llewlyn, Al-Hima: A way of life, IUCN West Asia regional Office, Amman Jordan – SPNL Beirut, Lebanon, 2007.

Aseer Province, Saudi Arabia, Google Earth

“While the Red Sea stands out as a sanctuary for some of the most resilient marine ecosystems globally, both the Red Sea and the Arabian Gulf have been experiencing mounting anthropogenic pressures, posing threats to resilient ecosystem refugia.”

Prof. Raquel Peixoto, Prof. Carlos Duarte
Red Sea Research Center, Biological and Environmental Sciences and Engineering (BESE), King Abdullah University of Science and Technology (KAUST), Saudi Arabia

Marine Ecosystems

Saudi Arabia stands as the guardian of some of the world's most unique and significant marine ecosystems. Mangroves, seagrass meadows, saltmarshes and coral reefs have co-evolved not only to survive but also thrive in the face of challenging environmental extremes, contributing to crucial ecological and economic functions in the region. The Red Sea is home to some of the world's most resilient coral reefs. This positions it as a precious treasure for humanity, especially considering the rapid decline and potential functional extinction of coral reefs worldwide. These globally important marine ecosystems play a pivotal role in the reproduction and sustenance of numerous commercially valuable marine species, while enhancing the genetic diversity and complexity of marine life and services, including fostering resilient organisms adapted to the local extreme conditions. The Kingdom's ongoing ambitious efforts towards sustainable growth, coupled with substantial investments in projects like NEOM and Red Sea Global, will depend in large part on the preservation and protection of these vital marine ecosystems.

State of the Red Sea and Arabian Gulf

The diversity, abundance, and resilience of marine organisms inhabiting the region's coastal and marine ecosystems hold significant cultural, ecological, and economic value to Saudi Arabia[1]. Indeed, these ecosystems are central to sustaining seafood resources, which support a range of local and regional industries and livelihoods, while providing invaluable ecological services, such as primary production, nutrient cycling, and sedimentation and erosion control, which in turn facilitate local economic development[2]. They play a crucial role in carbon sequestration, mitigating the effects of climate change by absorbing carbon dioxide from the atmosphere. Their inherent value can also be traced back to historical utilization by human populations, and they continue to play a role in current and future economic diversification efforts, including Vision 2030.

The Red Sea and Arabian Gulf represent distinct portions of the western Indo-Pacific Ocean. They are also characterized by extreme conditions that impose challenges on even the most resilient organisms. Although being relatively shallow (40% of the Red Sea is less than 100 m, while the mean depth of the Arabian Gulf is only 35 m), spanning a wide range of water temperature (15–36°C), and having low freshwater and nutrient inputs that are coupled with high evaporation rates[2–4], they host and support a remarkable diversity of marine ecosystems.

FIGURE 1 →

Anemone bleaching observed in the Red Sea.

Corals are not the only organism threatened by the consequences of climate change. Here we see an example of anemone bleaching observed in the Red Sea in 2022 (Al-Fahal, Coral Probiotics Village).
Photos by Morgan Bennett-Smith (top) and Helena Villela (bottom).

While the Red Sea stands out as a sanctuary for some of the most resilient marine ecosystems globally[5,6], both the Red Sea and the Arabian Gulf have been experiencing mounting anthropogenic pressures, posing threats to resilient ecosystem refugia. Pollution from shipping traffic, oil and gas production, plastics and other waste is impairing water quality, biological function and chemical integrity. Warming oceans, rising sea levels, marine heat waves and the many interrelated consequences of a changing climate place further pressure on all marine organisms.

The Arabian Gulf ranks among the most degraded marine ecosystems of the Anthropocene, caused primarily (or exacerbated by) intensive dredging and pollution[2,7]. As a consequence, many organisms native to the region are now categorized as “critically endangered” by the International Union for the Conservation of Nature (IUCN). Overfishing, pollution and deep sea mining are also significant threats to marine ecosystems in the Red Sea. More than one-third of chondrichthyan, the group of fish that includes sharks and rays, is threatened by overfishing globally, reflecting a trend that is exacerbated in tropical and subtropical areas like the Red Sea[8].

The combination of anthropogenic and climate related impacts pose a compound risk to the health of the region's marine ecosystems, as well as to the viability of the many social and economic activities they support.

FIGURE 1

Anemone bleaching observed in the Red Sea.

BEFORE, OCTOBER 2021

AFTER, SEPTEMBER 2022

Climate Related Drivers of Change

Although not exhaustive, the following provides an overview of some of the anticipated impacts on Saudi Arabia's marine environment under a state of continued anthropogenic and climate-related pressure.

Sea Surface Temperature

Global warming-induced temperature changes represent a clear and present threat to the region's marine ecosystems. Recent studies have identified Red Sea surface temperature increases of 0.17°C per decade, which is nearly 60% greater than the global average[9]. Warming in the northern portions of the Red Sea is even greater, approaching 0.45°C per decade. Overall trends reflect a latitudinal gradient of increasing temperatures from north to south, with the southernmost regions exhibiting the highest maximum temperatures. For the Arabian Gulf, temperature changes have exceeded those seen in the Red Sea, with temperature increasing by 0.59°C per decade from 1982 to 2020[10]. This is likely a result of shallower water depths.

FIGURE 2 →

Daily global average sea surface temperatures.

Source: ClimateReanalyzer.org

While climate models reflect a range of uncertainties (Chapter 2), projections of increased sea surface temperatures are a certain outcome globally, although with considerable regional- and local-scale variation. The uncertainty in this region is due in large part to the complexity of natural variations in ocean-atmosphere interactions, including those related with the Indian Ocean Dipole, the El Nino Southern Oscillation, as well as other global scale teleconnections. A lack of high-resolution spatio-temporal climate models also poses a challenge for the development of plans suitable for local and regional adaptation and mitigation. As a pertinent example, the record ocean temperatures observed globally in 2023 were far above expected levels (FIGURE 2), and caused sudden and massive coral bleaching and mortality of coral reefs in Florida, the Red Sea and elsewhere. Such outliers highlight both the prediction limit of current global climate models, and the amplified impact that climate extremes are already having at both local and regional scales (FIGURE 4).

Marine Heatwaves

While even gradual changes in sea surface temperature will induce stress to the health and resilience of marine ecosystems, it is the onset of sudden and extreme events that pose the greatest short-term risk. Increasing sea surface temperatures and the subsequent rise in so-called "marine heatwaves", pose significant threats to marine ecosystems. Recent studies have shown that there has been an increase in both the frequency and length of marine heatwaves over the past century, with a 54% increase in annual marine heatwave days globally between 1925 and 2016[11]. Although less studied, the trend of increasing heatwave occurrence is consistent with reports focusing on the Red Sea[12].

FIGURE 2

Daily global average sea surface temperatures.

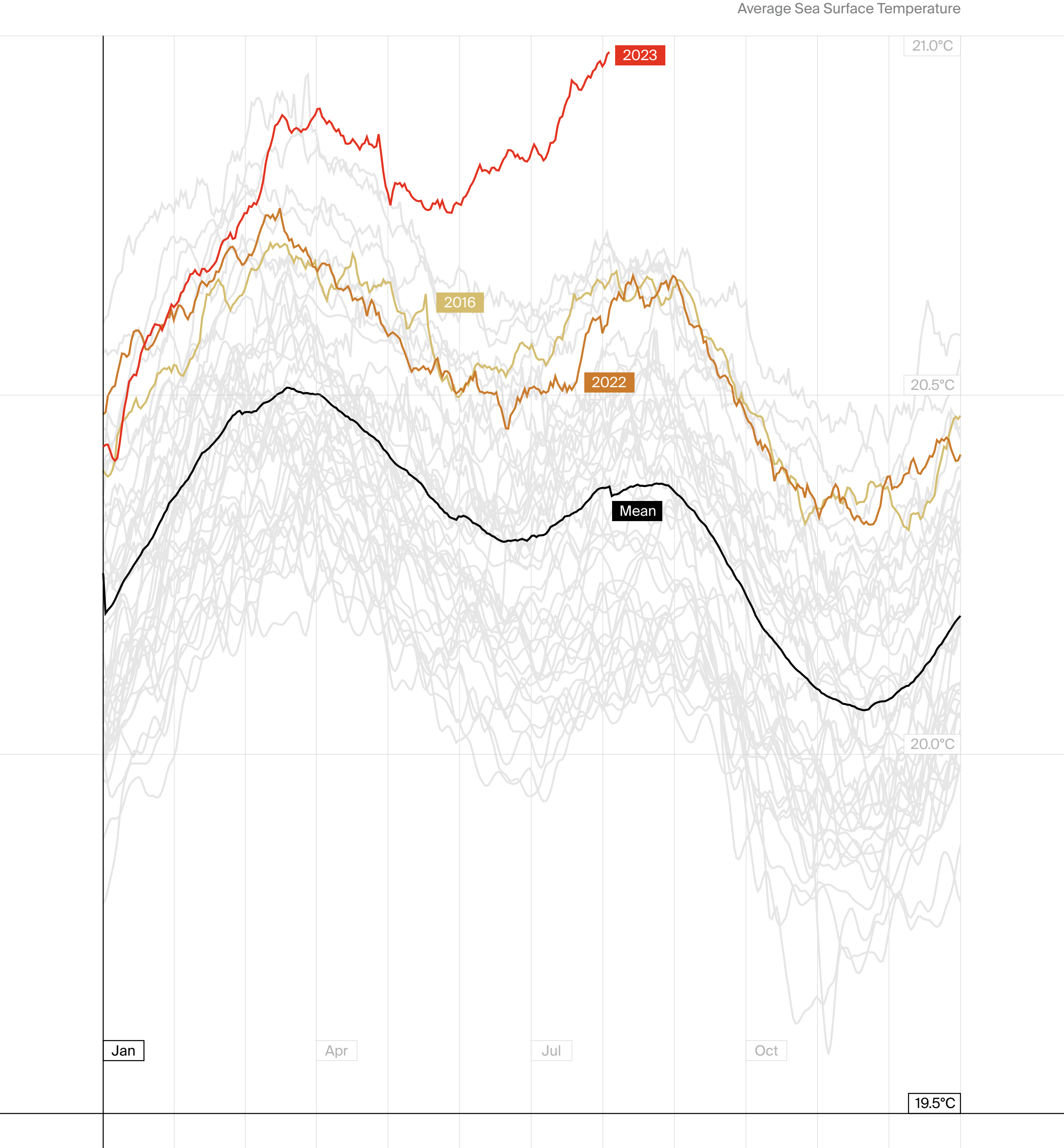
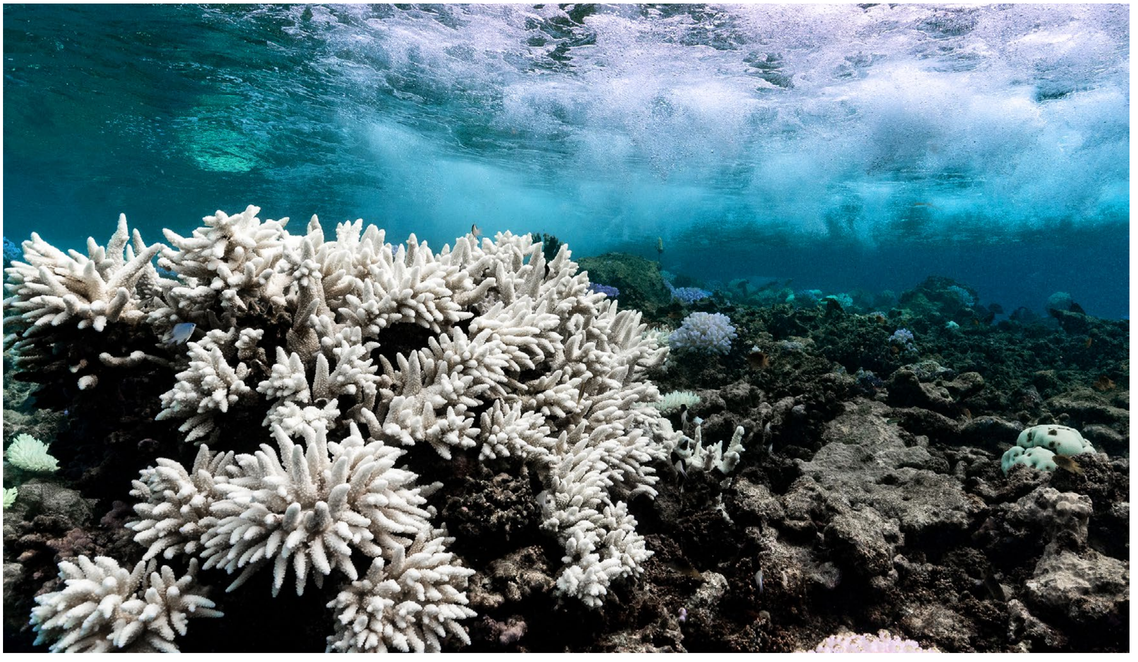


FIGURE 3

Coral bleaching event observed in the Red Sea in 2023 (Al-Fahal, Coral Probiotics Village).

BEFORE, SEPTERMBER 2021



AFTER, SEPTEMBER 2023

One of the most evident impacts of these temperature spikes is coral bleaching, which happens when corals stressed by too-warm waters expel their symbiotic algae, causing them to turn white[13]. While coral reefs are the most glaring example of an endangered ecosystem, the onset of sudden temperature increases are felt across the marine ecosystem. Sponges may be sensitive above a certain temperature threshold[14], while rapid changes in temperature can induce thermal stress across species, triggering mass mortality events in coral reef fish, kelp forests and other marine organisms[15]. The lack of long term monitoring and data regarding climate impacts on the range of marine organisms inhabiting the Red Sea and Arabian Gulf represents a major knowledge gap and source of uncertainty, raising the prospect that they may already be undergoing significant change.

Ocean Acidification

The ocean acts as a major sink for CO_2, absorbing around 30% of the emissions released into the atmosphere. Just as atmospheric concentrations have risen in sync with increasing anthropogenic CO_2 emissions, so has the amount of CO_2 being dissolved into the ocean. This increased uptake causes subtle changes in the water chemistry balance of the ocean, increasing the concentration of free hydrogen ions and making the ocean slightly more acidic. An impact of this “acidification” is that it reduces the availability of carbonate ions: the essential building block for coral reefs, shellfish and other shell-forming marine animals.

← FIGURE 3

Coral bleaching event observed in the Red Sea in 2023 (Al-Fahal, Coral Probiotics Village).

Photos by Morgan Bennett-Smith

The Red Sea and Arabian Gulf experience levels of ocean acidification that are generally comparable to other global oceans and seas. While specific regional processes like high rates of evaporation and limited freshwater influx can modulate local pH levels, projections generally point towards increasing acidification due to rising atmospheric CO_2 concentrations[16]. It is important to note that reduced pH levels do not just affect calcification rates. Other harmful consequences to marine life range from lowered immune responses and depressed metabolic rates, to the disruption of entire food chains.

Salinity Changes

The Red Sea and Arabian Gulf are characterized by salinity levels notably higher than most global oceans and seas due to intense evaporation, limited freshwater inflow, and restricted water exchanges with adjacent marine bodies. Additionally, brine discharge from the many coastal desalination plants can contribute to localized and elevated changes in salinity[17]. While the average salinity of the ocean is 35 psu (practical salinity unit), the Red Sea and Arabian Gulf have salinities ranging from 36 to 42 psu. Projections indicate increases in salinity due to the combined effects of changes in evaporation and precipitation, in addition to brine discharge[18]. However, even under the high-emissions SSP5-8.5 scenario, increases in basin-scale salinity are anticipated to stay below 1 psu.

Nevertheless, while increasing salinity levels are known to affect a range of ocean physical processes, including stratification, oxygenation and density driven flows, their impact on biological and ecosystem function remains poorly understood[19]. The potential for cascading impacts associated with increases in ocean warming (which acts to increase salinity) and ocean acidification (which is affected by increased salinity), highlights the importance of understanding how these stressors may combine to affect and alter marine ecosystems.

Sea Level Rise

Sea level rise has the potential to modify coastal habitats, impacting crucial ecosystems such as mangroves, seagrass beds, and salt marshes that serve as sanctuaries for numerous marine species. While certain organisms might adjust or relocate in response to climate-related shifts, the overarching implications of sea level rise for many ecosystems remain uncertain. Both mangroves and seagrasses possess mechanisms to counteract gradual sea level rise by accumulating sediment and elevating themselves. Similarly, coral reefs can grow vertically to some extent. However, a recent global study reported that widespread retreat of coastal habitat is likely if global warming levels reach 1.5°C above pre-industrial times[20]. Sea level rise also has obvious impacts on the terrestrial boundaries of the oceans, affecting coastal ecosystems, urban infrastructure, and bringing a range of increased risks to human settlements. It also brings other associated effects, such as alteration of currents and circulation patterns, and changes in water depth and tidal range, all of which have interlinked effects on the broader ocean system.

Tarut Bay, Saudi Arabia, May 18, 2013, NASA

Hypoxia

Hypoxia refers to conditions where oxygen concentrations in water are critically low, endangering a variety of aquatic organisms. Hypoxia can be caused by a range of both anthropogenic and climate-related changes, including warming-induced decreases in oxygen solubility, accelerated respiration, and increases in water column stratification, as well as coastal eutrophication. In the Red Sea and Arabian Gulf, high brine discharge from desalination plants represents another contributing factor. Even slight changes in ocean oxygen levels can impact marine organisms, inducing stress and affecting marine biodiversity and ocean ecosystems, and shifting the balance between hypoxia-tolerant species (e.g., some microbes and jellyfish) and hypoxia-sensitive species (e.g., fish); the consequences of which remain unclear.

Consequences of Change on Marine Ecosystems

While rapid and increased urbanization over the last several decades has taken an observable toll on the region's marine ecosystems, climate change is exacerbating and amplifying many negative outcomes. Despite the perceived resilience of Saudi Arabia's marine and coastal ecosystems, they are likely to remain highly vulnerable to both global and local changes: particularly within the context of a 3°C warmer world.

Coral Reefs

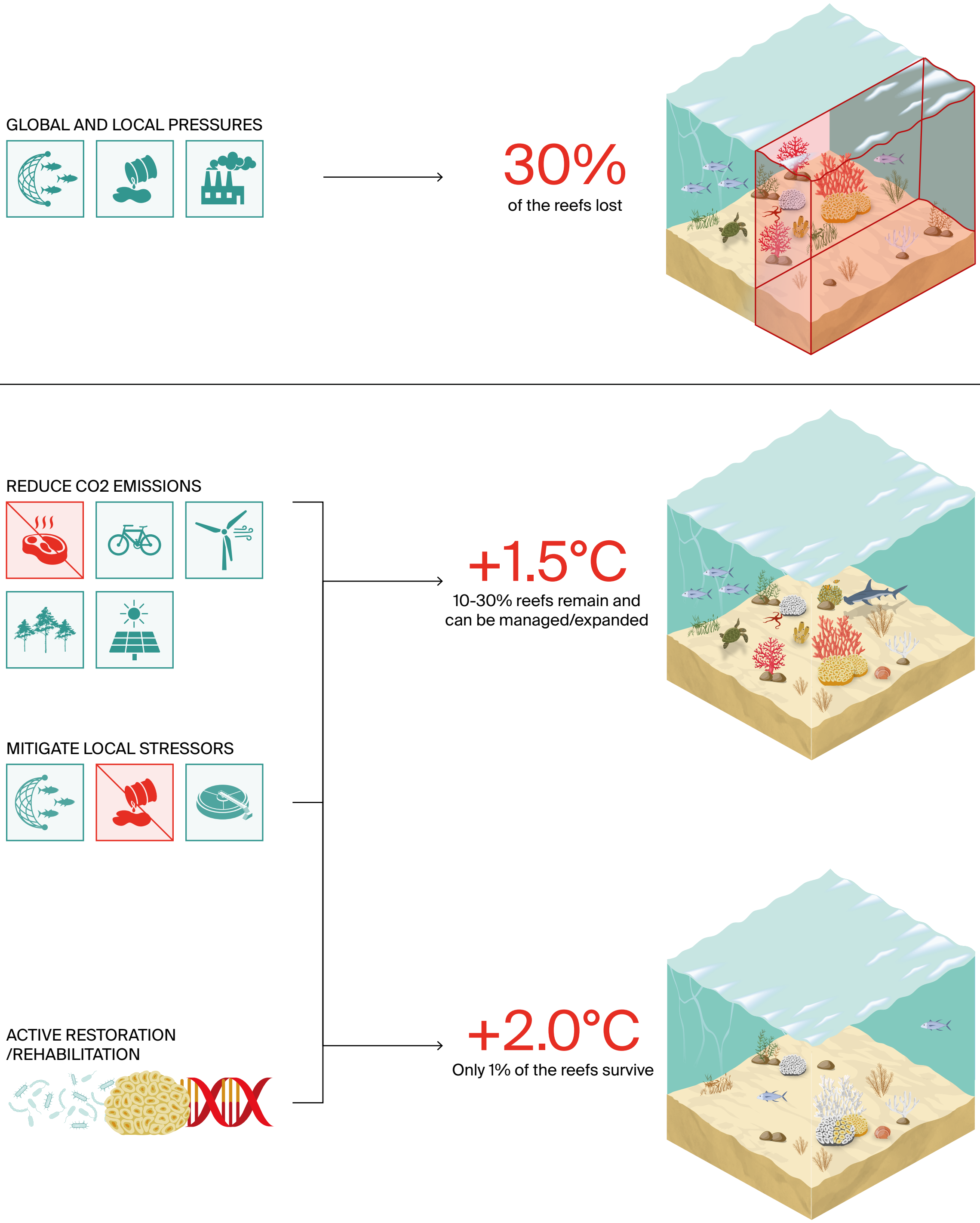
Coral reefs, and the multitude of organisms that they support, are the maritime version of "canaries in the coal mine", and serve as vital indicators of ocean health and condition[21]. While comparatively more preserved than many systems worldwide, coral reefs within the Red Sea region have not been spared from global climate changes. Emerging impacts, such as an increased incidence of coral diseases, forewarn of potential consequences resulting from both local and global stressors. Marine heatwave induced bleaching, with consecutive events making recovery challenging. Combined with ocean acidification, both act to impair the underlying carbonate-based structure of coral reefs. The rapid and consistent decline of these fragile ecosystems represent a significant global challenge, not only jeopardizing their very existence, but also endangering the range of interdependent organisms that rely upon them[13]. With projections indicating that just 1% of all corals may survive an increase of 2°C in global average temperature[13, 22] (Figure 2), there is an increased urgency to protect and preserve these invaluable ecosystems.

Mangroves, Seaweeds, Seagrasses and Salt Marshes

Marine vegetated habitats, comprising mangroves, seagrasses, seaweeds and salt marshes, occupy the intertidal zones of coastlines

FIGURE 4

Combined effects of global and local impact on Saudi Arabia's marine ecosystems.



around the world, extending from the shore to shallow depths of the ocean. Marine vegetation supports a range of ecosystem services, including acting as nurseries for marine species, delivering food and nutrients to support marine function, as well as bringing stability to coastlines from erosion and extreme events[23]. They also act as some of the most intense sinks of carbon in the biosphere, with seagrass meadows and mangrove forests in particular recognized as some of the most efficient carbon storing ecosystems, with estimates suggesting they may exceed the sequestration capacity of tropical forests (on a per area basis).

Similar to anticipated changes in terrestrial ecosystems (Chapter 3), there will be both direct and indirect effects of climate change on marine vegetation. Increases in water temperature and sea level rise enhance the risk of alterations in plant productivity and function, as well as drive potential shifts in marine vegetation distribution and extent. Importantly, while changes may not be felt across all vegetation communities equally, interdependencies means that disturbances are likely to propagate. For instance, while mangroves may be able to adapt to sea level rises through landward expansion, such shifts may impact important biogeochemical and ecological function and roles in other colocated and linked habitats, including in seagrass meadows and saltmarshes[24].

← FIGURE 4

Combined effects of global and local impact on Saudi Arabia's marine ecosystems.

The combined effects of global and local impacts have caused the loss of 30% of global reef cover (top), with projections suggesting that this may increase to 99% if average global temperatures exceed 2°C. A plan to save coral reefs was proposed by the International Coral Reef Society (ICRS), based on three equally important pillars to prevent further loss, which include: (A) the immediate reduction of CO_2 emissions; (B) the urgent mitigation of local impacts (e.g., by managing fish stocks or improving water quality); and (C) the active restoration/rehabilitation of coral reefs. The three pillars are interdependent. Source [22].

While anthropogenic pressures have severely impacted marine vegetated habitats globally, their overlooked role as "blue carbon" sinks has driven a renewed focus on preservation and restoration[25]. As an example, the decline in the extent of mangrove systems globally provides an obvious indicator of change, albeit with some promising signs of recovery[26]. Local studies along the Red Sea have highlighted the impact of recent afforestation efforts, resulting in a net expansion of mangrove cover[27]. However, this is set against a backdrop of mangrove communities that were decimated over the 20th century. While the impacts of climate change may affect marine vegetation in both positive and negative ways, the region's arid coastlines will need to overcome increased salinity levels, limited freshwater supplies and nutrient input, as well as temperature thresholds that affect physiological function[28].

Marine Life

Cataloging the diversity of marine life that inhabits the aquatic environment is an impossible task, particularly since most species remain undescribed. That challenge is made all the more difficult by the fact that there exists a general lack of knowledge on the diversity, distribution and abundance of life inhabiting the marine environment, both locally and globally. As such, identifying the entirety of marine species that inhabit the Red Sea and Arabian Gulf, and establishing individual responses to climate change, borders on the futile.

Still, there are anticipated consequences of climate change that are likely to influence the health and diversity of marine life now and into the

[A]

[B]


future[24]. At the global scale, factors such as rising sea temperatures, shifts in salinity and ocean acidification that are described earlier have already impacted habitats and migratory patterns[29]. It is important to also consider that while climate change poses an undeniable threat to all marine life, the existing threats posed by overfishing and fishing by-catch, together with habitat loss from pollution, eutrophication, coastal development, boat traffic, or oil and gas exploration, continue to threaten the current stability of both our local and global natural systems[30].

With this context, this contribution can only offer a broad overview of climate change related impacts on "marine life". Similarly, there can be no obvious separation between the impact that climate change will have on marine habitats, such as those provided by coral reefs, mangroves and other marine vegetation systems, and the species they support. A collapse in one will almost certainly drive a collapse in the other. Indeed, the high levels of endemism among marine species found in the region represent an additional challenge due to the increased risk of extinction of local organisms, and their unique associated microbiomes[31], driven by overfishing, coastal development, global change, and pollution.

Future Risks and Challenges

Saudi Vision 2030 places significant value on the protection, restoration and creation of marine ecosystems over their destructive exploitation. While diversifying the economy, Giga projects will increase the number of people living or visiting coastal areas in Saudi Arabia, placing an additional burden via waste generation and disposal, water desalination and energy consumption, as well as add pressure to the overuse of local resources. To manage this, it is imperative that such developments proceed in a sustainable manner, so as not to impose further stress on a system already under considerable strain. The foundation of sustainable development lies in recognizing that the health of the environment, humans, and all other organisms are interdependent and connected. Ultimately, the long-term success of any economic diversification efforts will be inextricably linked to the health of Saudi Arabia's marine ecosystems.

Some key actions will be required to ensure the continued health and sustainability of the region's invaluable marine ecosystems and the preservation of these for future generations:

- Local governance needs to be strengthened by equipping local authorities and stakeholders with the necessary scientific background, resources, and support to manage and protect marine ecosystems effectively and continuously.
- Given the transboundary nature of marine ecosystems, international collaboration will also be required. As such, Saudi Arabia must effec-

[A] Al Wadj Bank, Saudi Arabia, December 30, 2007, NASA
[B] Strait of Tiran, Red Sea and Gulf of Aqaba, June 23, 2013, NASA

tively and proactively engage in collaborative efforts with neighboring countries and international organizations.

- Investments in research and innovation in marine ecology, restoration, rehabilitation, monitoring, and sustainable development are also crucial to enhance the Kingdom's understanding of marine ecosystems, and should also include alternative (and often more docile, albeit overlooked) targets for rehabilitation, such as microbiomes[32]. Such technological development will also provide urgent and innovative solutions to address and mitigate local and global environmental challenges.
- In parallel, environmental awareness campaigns to engage the public can instill a sense of responsibility and ownership for marine conservation efforts. Encouraging sustainable practices and responsible consumption will further support the goals of Saudi Vision 2030.
- Implementing economic incentives and rewards for businesses and industries that prioritize sustainability and responsible resource management may also boost a shift towards eco-friendly practices that can positively, and effectively, impact the climate trajectory.

Preventive and conservative planning will be imperative for Saudi marine ecosystems to be retained. This presents an opportunity to set a benchmark for sustainable development that can be incorporated into the global race to save threatened biodiversity. While most coastal development models are based on the use and exploitation of marine resources, a shift towards prioritizing ecosystems as the keystone of any such developments will be the most strategic, cost-effective, and sustainable way forward[1].

Recent studies projecting the repercussions of business-as-usual temperature increases on marine ecosystems paint a daunting picture of mass extinctions and ecosystem collapse resulting from ocean warming and oxygen depletion alone[33]. Yet they also highlight the possibility of avoiding catastrophe via targeted action to reduce global emissions. Likewise, avenues for rebuilding marine life and the ecosystems that support them exist[34], but need to be explored and implemented now to avoid a future that risks humanities survival.

[1] Cziesielski MJ, Duarte CM, Aalismail N, Al-Hafedh Y, Anton A, Baalkhuyur F, et al. Investing in Blue Natural Capital to Secure a Future for the Red Sea Ecosystems. Frontiers in Marine Science. 2021;7. doi:10.3389/fmars.2020.603722

[2] Grillo O. Biodiversity: The Dynamic Balance of the Planet. BoD – Books on Demand; 2014.

[3] Jawad LA. The Arabian Seas: Biodiversity, Environmental Challenges and Conservation Measures. Springer Nature; 2021.

[4] Price ARG, Sheppard CRC, Roberts CM. The Gulf: Its biological setting. Mar Pollut Bull. 1993;27: 9–15.

[5] Osman EO, Smith DJ, Ziegler M, Kürten B, Conrad C, El-Haddad KM, et al. Thermal refugia against coral bleaching throughout the northern Red Sea. Glob Chang Biol. 2018;24: e474–e484.

[6] Eladawy A, Nakamura T, Shaltout M, Mohammed A, Nadaoka K, Fox MD, et al. Appraisal of coral bleaching thresholds and thermal projections for the northern Red Sea refugia. Frontiers in Marine Science. 2022;9. doi:10.3389/fmars.2022.938454

[7] Sheppard C, Al-Husiani M, Al-Jamali F, Al-Yamani F, Baldwin R, Bishop J, et al. The Gulf: a young sea in decline. Mar Pollut Bull. 2010;60: 13–38.

[8] Fine M, Cinar M, Voolstra CR, Safa A, Rinkevich B, Laffoley D, et al. Coral reefs of the Red Sea — Challenges and potential solutions. Regional Studies in Marine Science. 2019;25: 100498.

[9] Chaidez V, Dreano D, Agusti S, Duarte CM, Hoteit I. Decadal trends in Red Sea maximum surface temperature. Sci Rep. 2017;7: 8144.

[10] Al Senafi F. Atmosphere-ocean coupled variability in the Arabian/Persian Gulf. Front Mar Sci. 2022;9. doi:10.3389/fmars.2022.809355

[11] Oliver ECJ, Donat MG, Burrows MT, Moore PJ, Smale DA, Alexander LV, et al. Longer and more frequent marine heatwaves over the past century. Nat Commun. 2018;9: 1324.

[12] Genevier LGC, Jamil T, Raitsos DE, Krokos G, Hoteit I. Marine heatwaves reveal coral reef zones susceptible to bleaching in the Red Sea. Glob Chang Biol. 2019;25: 2338–2351.

[13] Knowlton N, Corcoran E, Felis T, de Goeij J, Grottoli A. et al. Rebuilding coral reefs: a decadal grand challenge. 2021. International Coral Reef Society and Future Earth Coasts, Bremen, 56 pp. DOI https://doi.org/10.53642/NRKY9386

[14] Pita L, Rix L, Slaby BM, Franke A, Hentschel U. The sponge holobiont in a changing ocean: from microbes to ecosystems. Microbiome. 2018;6: 46.

[15] Genin A, Levy L, Sharon G, Raitsos DE, Diamant A. Rapid onsets of warming events trigger mass mortality of coral reef fish. Proc Natl Acad Sci U S A. 2020;117: 25378–25385.

[16] Pandolfi JM, Connolly SR, Marshall DJ, Cohen AL. Projecting coral reef futures under global warming and ocean acidification. Science. 2011;333: 418–422.

[17] Hosseini H, Saadaoui I, Moheimani N, Al Saidi M, Al Jamali F, Al Jabri H, et al. Marine health of the Arabian Gulf: Drivers of pollution and assessment approaches focusing on desalination activities. Mar Pollut Bull. 2021;164: 112085.

[18] Paparella F, D'Agostino D, A Burt J. Long-term, basin-scale salinity impacts from desalination in the Arabian/Persian Gulf. Sci Rep. 2022;12: 20549.

[19] Röthig T, Trevathan-Tackett SM, Voolstra CR, Ross C, Chaffron S, Durack PJ, et al. Human-induced salinity changes impact marine organisms and ecosystems. Glob

Chang Biol. 2023;29: 4731–4749.

[20] Saintilan N, Horton B, Törnqvist TE, Ashe EL, Khan NS, Schuerch M, et al. Widespread retreat of coastal habitat is likely at warming levels above 1.5 °C. Nature. 2023;621: 112–119.

[21] Sweet M, Burian A, Bulling M. Corals as canaries in the coalmine: Towards the incorporation of marine ecosystems into the "One Health" concept. J Invertebr Pathol. 2021;186: 107538.

[22] Voolstra CR, Peixoto RS, Ferrier-Pagès C. Mitigating the ecological collapse of coral reef ecosystems: Effective strategies to preserve coral reef ecosystems: Effective strategies to preserve coral reef ecosystems. EMBO Rep. 2023;24: e56826.

[23] Duarte CM, Middelburg JJ, Caraco N. Major role of marine vegetation on the oceanic carbon cycle. Biogeosciences. 2005;2: 1–8.

[24] Hoegh-Guldberg O, Bruno JF. The impact of climate change on the world's marine ecosystems. Science. 2010;328: 1523–1528.

[25] Duarte CM, Losada IJ, Hendriks IE, Mazarrasa I, Marbà N. The role of coastal plant communities for climate change mitigation and adaptation. Nat Clim Chang. 2013;3: 961–968.

[26] Feller IC, Friess DA, Krauss KW, Lewis RR. The state of the world's mangroves in the 21st century under climate change. Hydrobiologia. 2017;803: 1–12.

[27] Blanco-Sacristán J, Johansen K, Duarte CM, Daffonchio D, Hoteit I, McCabe MF. Mangrove distribution and afforestation potential in the Red Sea. Sci Total Environ. 2022;843: 157098.

[28] Alongi DM. The Impact of Climate Change on Mangrove Forests. Current Climate Change Reports. 2015;1: 30–39.

[29] Poloczanska ES, Brown CJ, Sydeman WJ, Kiessling W, Schoeman DS, Moore PJ, et al. Global imprint of climate change on marine life. Nat Clim Chang. 2013;3: 919–925.

[30] 30. Díaz S, Settele J, Brondízio ES, Ngo HT, Agard J, Arneth A, et al. Pervasive human-driven decline of life on Earth points to the need for transformative change. Science. 2019;366. doi:10.1126/science.aax3100

[31] Delgadillo-Ordoñez N, Raimundo I, Barno AR, Osman EO, Villela H, Bennett-Smith M, et al. Red Sea Atlas of Coral-Associated Bacteria Highlights Common Microbiome Members and Their Distribution across Environmental Gradients-A Systematic Review. Microorganisms. 2022;10. doi:10.3390/microorganisms10122340

[32] Peixoto RS, Voolstra CR. The baseline is already shifted: marine microbiome restoration and rehabilitation as essential tools to mitigate ecosystem decline. Front Mar Sci. 2023;10. doi:10.3389/fmars.2023.1218531

[33] Pinsky ML, Fredston A. A stark future for ocean life. Science. 2022;376: 452–453.

[34] Duarte CM, Agusti S, Barbier E, Britten GL, Castilla JC, Gattuso J-P, et al. Rebuilding marine life. Nature. 2020;580: 39–51.

“Climate and geopolitical risks are amplifying existing challenges in water and food security in Saudi Arabia, a country where food production is under ever-increasing pressure due to depleting groundwater and environmental degradation.”

Prof. Yoshihide Wada, Prof. Matthew F. McCabe
Climate and Livability Initiative, Biological and Environmental Sciences and Engineering (BESE), King Abdullah University of Science and Technology (KAUST), Saudi Arabia

Food and Water Security

Saudi Arabia's arid climate, coupled with the compounding effects of climate change and anthropogenic factors, poses significant challenges to its water and food security. Saudi Arabia is warming at a rate that is faster than most other countries in the world, including those within the MENA region. These temperature increases are not uniformly distributed, with the eastern regions of the Arabian Peninsula warming faster than those along the southern and western coastlines. Continued changes in temperature projected throughout the 21st century will have direct impacts and influences on Saudi Arabia's water security and food production. Given the interconnectedness between the water and food sectors, these impacts will have both a local and global origin. While pressures on limited national water resources will become more severe, global patterns of unsustainable groundwater use will also impact international food trade. Characterizing these trends, even if imperfectly, will provide an avenue for planning and management to help deliver a more stable and secure future.

Available Water Resources

In 1980, approximately 10 billion cubic meters of water was being used in Saudi Arabia across all sectors. Today, that value has more than doubled, due in large part to the over-exploitation of stressed groundwater resources to support an expanding agricultural sector. Current annual water consumption for combined domestic, industrial, and agricultural usages is estimated at 23 billion cubic meters[1].

As Saudi Arabia does not have any permanent rivers or lakes, there has been considerable efforts to augment supplies by capturing available rainfall, with more than 500 dams built around the country, and a much larger number under consideration for future construction. These dams facilitate the capture, storage and recharge of surface runoff from rainfall, providing a potential capacity of 2.3 billion cubic meters.

FIGURE 1 →

Progression of agricultural field growth over the last three decades in Al Jouf, north of Saudi Arabia.

Saudi Arabia has witnessed a rapid expansion in its agricultural sector. Recent studies indicate that there are more than 30,000 center pivot fields distributed throughout the country, with this example from Al Jouf in the north of Saudi Arabia, showing the progression of field growth over the last three decades. Such growth has had a dramatic impact on groundwater resources, rapidly reducing these non-renewable supplies and threatening national water security.

Groundwater provides a critical component of Saudi Arabia's water budget. However, quantifying the volume of non-renewable groundwater resources stored below the nation's deserts remains challenging, with available estimates providing an uncertain range of between 250 to 800 billion cubic meters. What is more certain is that these groundwater systems receive only a small amount of annual recharge, with studies suggesting less than 1 billion cubic meters[2]. Most importantly, the rate at which groundwater resources (aquifers) are being recharged does not reflect the speed at which they are being depleted.

Recent estimates for groundwater extraction, which are used to support intensive agricultural expansion, routinely exceed 18 billion cubic meters on an annual basis[3]. As a consequence, it is estimated that 80% of Saudi's fossil groundwater has already been depleted[4]. Given current rates of withdrawal, even optimistic projections suggest that these non-renewable water supplies could be severely compromised or even exhausted within the next 50 years[5].

With agricultural activity rapidly depleting non-renewable groundwater resources, the national water account has needed to adapt accordingly. Large-scale desalination is the only viable option to offset changes in supply, or support any increase in demand due to anticipated population growth. Indeed, Saudi Arabia's desalination capacity has doubled over the last decade, rising from 1.1 billion cubic meters per year in 2010 to 2.2 billion cubic meters in 2021. Currently, desalination of seawater provides 50% of the nation's drinking water, with groundwater providing 40%, and surface water from the southwest's mountainous region accounting for the remaining 10%[6].

Food Security in a Changing Climate

Saudi Arabia has witnessed a dramatic growth in its agricultural sector over the last several decades. As a deliberate action towards attaining some form of food security, agricultural growth has been delivered via the conversion of large tracts of desert into productive farmland. Driving this conversion has been the unsustainable mining of groundwater for irrigation.

FIGURE 1 ↓

Progression of agricultural field growth over the last three decades in Al Jouf, north of Saudi Arabia.

Until recently, agricultural production focused heavily on grain crops such as wheat, corn, sorghum, barley and millet, as well as a variety of fruits and veg-

etables. In recent assessments, arable land in the Kingdom was estimated to cover approximately 3.4M ha (1.7% of total area[7]), of which around one third were being actively used for agriculture (1.18M ha[8]). Much of this arable land is under sustained pressure from various forms of degradation, with soil salinity from over-irrigation and low rainfall a major concern.

Increases in temperature have a direct consequence on agricultural water demands, with studies projecting changes of between 5–15% in the water required to maintain current levels of agricultural production under a 2-4°C warming scenario[9]. With more than 90% of crops in Saudi Arabia under irrigation sourced from depleting groundwater reserves, impacts on yield are anticipated from any reduction in water availability or quality.

Agriculture is extremely sensitive to changes in climate variables, and any variations, particularly in the extremes (Chapter 2), can have severe effects on productivity. Studies exploring changes in temperature and rainfall patterns in Saudi Arabia have projected more than 10% reductions in the yields of wheat, barley, date, and vegetables[10,11]. These impacts are compounded as the land available for traditional agriculture is fixed, with little to no scope to increase agricultural production by new areas under cultivation.

Given the proximity to surrounding marine systems (Chapter 4), aquaculture forms a critical component of the country's strategy to increase food production. With the establishment of a National Aquaculture Group in 1982 (NAQUA), Saudi Arabia charted a path towards becoming a global seafood producer. Today, NAQUA is one of the world's largest fully-integrated marine farms, specializing in shrimp and fish production and producing over 100,000 tons of marine products. The Saudi government aims to increase seafood production to 600,000 tons by 2030 with a projected investment of 3.5 billion USD. However, ocean warming and sea level rise pose (Chapter 4) a significant threat to marine aquaculture, while coastal eutrophication, algal blooms, increasing salinity, and extreme weather bring further pressure on the so-called 'blue' food production, highlighting the interconnected risks of climate change.

Any reduction in agricultural or aquaculture production, whether locally or internationally, will inevitably see a rise in the prices of food and non-food commodities, directly affecting socio-economic factors. As Saudi Arabia sources more than 80% of its food supply from international markets, any global shocks due to climate change (or geopolitical instability) will amplify the threats to food and nutritional security.

Interconnected Risks to Water and Food Security

As with any nation, water and food security is a matter of utmost concern. Since most of Saudi Arabia's food commodities are imported, identifying strategies that diversify sources and that can absorb anticipated disruptions in global food supply is of paramount importance. As an example, Saudi Arabia initiated several programs during the 1970s to protect against its exposure to fluctuations in food supply from major international food markets. To do this, the Kingdom exploited its natural reserves of groundwater aquifers, while also introducing generous agricultural subsidies, particularly for the cultivation of wheat and alfalfa. The program delivered a phenomenal growth in the production of staple foods, meat, and dairy products, while substantially reducing food imports.

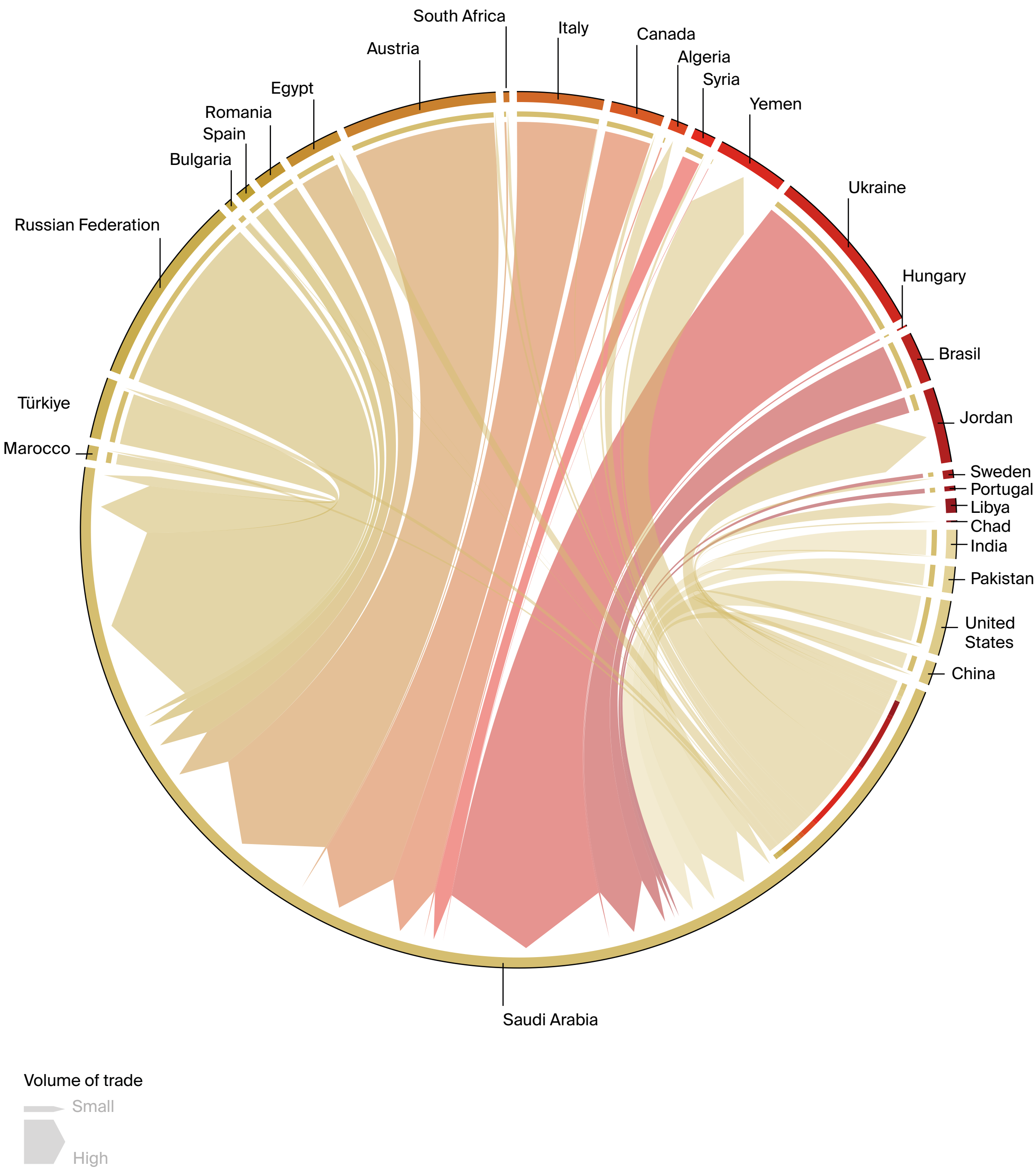
In relative terms, this drive for food security was a considerable success, in that self-sufficiency was rapidly achieved and the Kingdom became a net exporter: at one point the world's sixth-largest wheat exporting country during the 1990s. However, the economic implications of subsidization, combined with the unsustainable use of water, came at a considerable cost, and these programs were gradually phased out.

In 2009, the Saudi Agricultural and Livestock Investment Co. (SALIC) was established with a mandate to secure sources of international food supplies in order to maintain stability in the local market and to avoid food shortages. SALIC has led agricultural partnerships and investments in Argentina, Australia, Brazil, Canada, the United States and many other nations around the world, identifying priority regions for investments in various grains and red meat. Such plans are realized via a combination of direct investment, land purchase, mergers and acquisitions, and the establishment of local companies in foreign countries.

Photo by Naqua

FIGURE 2

Saudi Arabia's wheat imports (arrows coming to Saudi Arabia), averaged from 2019-2021,as sourced from major groundwater consuming countries.



In effect, Saudi Arabia has sought to outsource food production as a means to counter the constraints imposed by reduced water availability, challenging climate conditions, and poor-quality soils: aspects that are all likely to be exacerbated under a changing climate. However, the approach is not without its own risks and challenges. As witnessed with the current conflict between Russia and Ukraine, many countries including those within the MENA region, have been severely affected by uncertainties in the supplies of wheat, corn, and cooking oils sourced from eastern Europe. Following the start of hostilities in 2022, the international wheat commodity price jumped more than 50%. Such price fluctuations can perturb the global supply for many months, as crop reserves to buffer such shocks are generally limited to less than a year.

Under the most recent national agricultural strategy, Saudi Arabia is planning to substantially increase the domestic production and stock of wheat to counter a potential risk in international food trade. However, it remains a short-term fix, as this will add further pressure to Saudi Arabia's limited water resources and the long-term viability of fossil groundwater reserves. Importantly, this is not just a Saudi specific problem. Major international food producers and consumers, including the USA, Mexico, India and China, are exposed to the same risk, since they either produce or import food irrigated from regions with rapidly depleting aquifers[12].

← FIGURE 2

Saudi Arabia's wheat imports (arrows coming to Saudi Arabia), averaged from 2019-2021,as sourced from major groundwater consuming countries.

Saudi Arabia's wheat imports, averaged from 2019-2021, as sourced from major groundwater consuming countries. Many of these countries have vulnerable aquifers, including karstic and complex aquifer systems, that are under pressure from unsustainable extraction. By courtesy of Dr. Michael J. Puma (Columbia University).

Water Resource Challenges and Opportunities

As one of the world's driest and most freshwater-stressed countries, conventional water management is a perennial challenge for Saudi Arabia. Water is derived from four main sources:

- Groundwater, which is mostly pre-Holocene, is not being actively replenished, and is decreasing rapidly due to intensive agricultural irrigation;
- Desalinated seawater supplied via modern, high-tech desalination plants, albeit at a significant energy and greenhouse gas producing cost;
- Renewable surface waters collected from several large dams;
- Wastewater treatment and reuse, albeit at limited scales and volumes.

Collectively, the countries of the Gulf Cooperation Council (GCC) account for around 60% of desalinated water production globally. In Saudi Arabia, the world's largest producer, 2.2 billion cubic meters is produced annually from more than 30 desalination plants. Advances in technology have substantially reduced the cost of desalination, with the most efficient plants operating at a water production cost approaching 0.50 USD per cubic meter.

With planned capacity expected to rise in the coming years to meet growing domestic, industrial and agricultural needs, it is important to note the energy intensive nature of the process. In terms of greenhouse gas emissions, desalination contributes an average of 15.2 kg of CO_2 for every cubic meter of desalinated water, representing nearly 20% of the Kingdom's total emissions[13]. It is expected that an increasing trend towards reverse osmosis driven desalination will reduce this contribution significantly.

Under a 3°C warmer world, higher water and air temperatures, salinity, and the pH of seawater will all affect production and increase the energy demand. Harmful algal blooms resulting from increasing ocean temperature and salinity pose an operational risk for desalination plants, due to the increased biomass load on filters and chemical contaminants that the algae can produce. At the same time, increasing air temperatures affect desalination (and other industrial processes) via a reduced capacity for cooling, further impacting the efficiency and cost of production.

Under the 2023 National Water Strategy[2], Saudi Arabia is investing in wastewater reuse and associated technology. Although current rates of water reuse are relatively low in global terms, with about 20% of the 2 billion cubic meters of wastewater collected and treated being reused each year in the Kingdom, Saudi Arabia has set an ambitious goal to become the third largest market for water reuse in volume globally (after the United States and China). Current plans have set guidelines for the reuse of around 80% of the treated wastewater for all cities with a populace of more than 5000 people by 2030, with considerable investment directed towards sewage collection and treatment infrastructure.

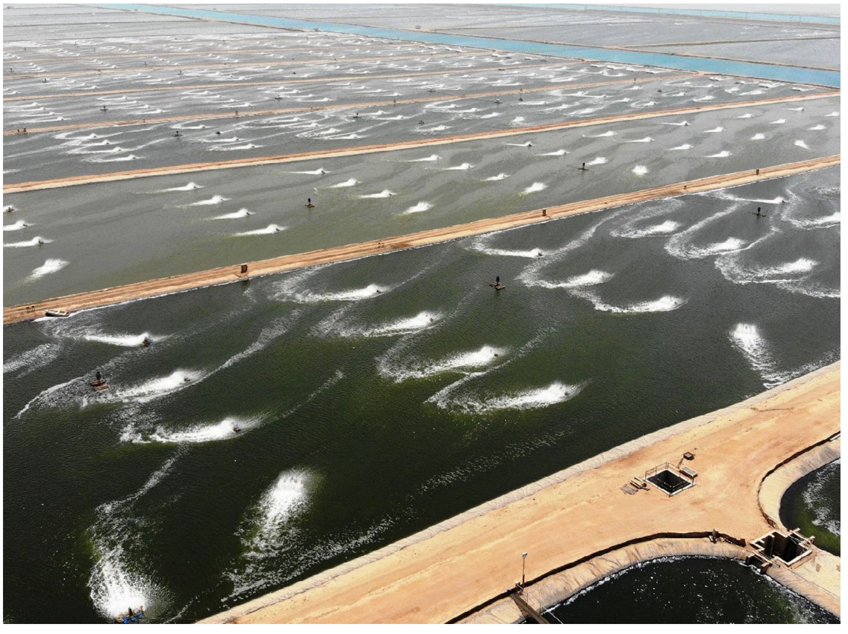


Photo by Naqua

A Water and Food Secure Future



The agricultural and aquaculture sector contributed around 27 billion USD to the national GDP of Saudi Arabia in 2022, representing approximately 2-3%. Over a similar time period (2020-2021), the sector grew at a rate of 7.8%[14]. Given the central role it plays across all aspects of society, it is no surprise that it is one of the fastest-growing sectors in Saudi Arabia. However, persistent challenges remain and there are further impacts on the horizon, stemming from the combination of an inhospitable climate, reduced water availability, poor quality soils, and a reliance on food importation. Indeed, the food sector is one of the most sensitive to climate change variability, highlighting the urgent need for adaptation and mitigation strategies.

To address these challenges, the food and water sector will need to abandon unsustainable practices and embrace innovative water-saving technologies, such as hydroponics, greenhouse farming and seawater harvesting as examples. The adoption of other more lifestyle-based dietary options can also act to increase resilience in food supplies. In the Middle East, plant-based eating and alternative proteins has been steadily rising[15]. More generally, vegan, flexitarian, and pescatarian diets all offer major health benefits[16], while acting to reduce the environmental impacts of food production and consumption. Dietary patterns with reduced environmental impact are also linked to improved land use and reduced fertilizer consumption, reversing land degradation trends. Even the introduction of feed supplements that reduce enteric greenhouse gasses in cattle, offer opportunities to reduce the environmental impact of the animal-based food sector.

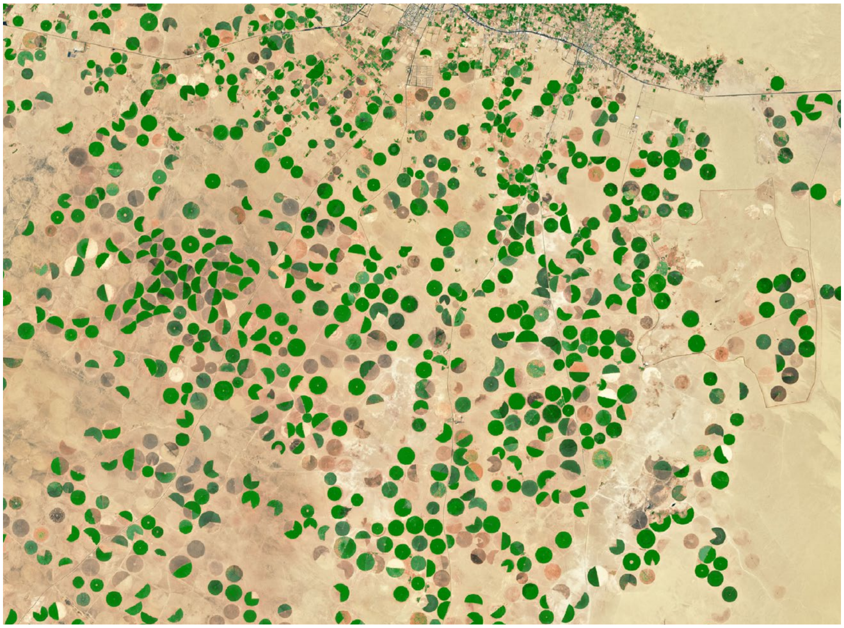
While exploring new sources of proteins and plant-based diets offer many gains, there is an urgent need to tackle food waste in Saudi Arabia. Recent studies suggest that more than one-third of food is wasted globally[17] a sobering statistic considering a similar percentage of the world's population is characterized by the United Nations as being food insecure. In line with the Kingdom's Vision 2030 and efforts to reduce food waste, more systematic assessments are needed to better understand the food ecosystem and the areas that require innovation in order to reverse food waste.

In parallel with food waste, there is also a need to raise awareness on the importance of water conservation. As evidenced in many other developed countries, the introduction of pricing schemes has been a major driver of water savings. Modern agricultural technologies, together with short-duration, high yielding and more drought-resistant crop varieties also need to be explored. The implementation of farm water meters and plans to standardize irrigation practices would further boost water use efficiency.

Focused attention on improving the characterization of future climate risks is a priority. Preparedness requires planning, as is an understanding of the consequences of action and the risks of inaction. Whether the onset of climate related impacts is sudden or gradual, climatic events tend to amplify existing

Photos showing food degradation, via Unsplash challenges, perpetuating a cycle of vulnerability. When these events converge with demographic trends, unplanned and unmanaged migration and displacement, and rapid urbanization, the negative impact of climate change can be more profound and more severe, particularly as relates to food security.

[A]



[B]

[A] Desert Crops Thrive as the Aquifer Shrinks, June 30, 2000, NASA
[B] Desert Crops Thrive as the Aquifer Shrinks, April 26, 2017, NASA

[1] Salem, H. S., M. Y. Pudza, and Y. Yihdego (2022), Water strategies and water–food Nexus: challenges and opportunities towards sustainable development in various regions of the World, Sustain. Water Resour. Manag. 8, 114, https://doi.org/10.1007/s40899-022-00676-3.

[2] Ministry of Environment, Water and Agriculture (MEWA) (2018), National Water Strategy 2030, available at https://leap.unep.org/countries/sa/national-legislation/saudi-national-water-strategy-2030.

[3] López Valencia, O. M., K. Johansen, B. J. L. Aragón Solorio, T. Li, R. Houborg, Y. Malbeteau, S. AlMashharawi, M. U. Altaf, E. M. Fallatah, H. P. Dasari, I. Hoteit, and M. F. McCabe (2020), Mapping groundwater abstractions from irrigated agriculture: big data, inverse modeling, and a satellite–model fusion approach, Hydrol. Earth Syst. Sci., 24, 5251–5277, https://doi.org/10.5194/hess-24-5251-2020.

[4] Sultan, M., N. C. Sturchio, S. Alsefry, M. K. Emil, M. Ahmed, K. Abdelmohsen, M. M. AbuAbdullah, E. Yan, H. Save, T. Alharbi, A. Othman, and K. Chouinard (2019), Assessment of age, origin, and sustainability of fossil aquifers: A geochemical and remote sensing-based approach, J. Hydrol., 576, 325-341, https://doi.org/10.1016/j.jhydrol.2019.06.017.

[5] Kajenthira, A., A. Siddiqi, and L. Diaz Anadon (2012), A New Case for Promoting Wastewater Reuse in Saudi Arabia: Bringing Energy into the Water Equation, J. Environ. Manag., 102, 184-192, https://doi.org/10.1016/j.jenvman.2011.09.023.

[6] 6 Chandrasekharam, D. (2018), Water for the millions: Focus Saudi Arabia, Water-Energy Nexus, 1, 142-144, https://doi.org/10.1016/j.wen.2019.01.001.

[7] FAOSTAT; https://www.fao.org/faostat

[8] Li, T., O. M., López Valencia, K. Johansen, M. F. McCabe (2023), A Retrospective Analysis of National-Scale Agricultural Development in Saudi Arabia from 1990 to 2021. Remote Sens. 2023, 15, 731, https://doi.org/10.3390/rs15030731.

[9] Chowdhury, S., M. Al-Zahrani, and A. Abbas (2016), Implications of climate change on crop water requirements in arid region: an example of Al-Jouf, Saudi Arabia, J. King Saud University-Eng. Sci., 28, 21-31, https://doi.org/10.1016/j.jksues.2013.11.001.

[10] Alkolibi, F. M. (2002), Possible effects of global warming on agriculture and water resources in Saudi Arabia: impacts and responses, Clim. Change, 54, 225-245, https://doi.org/10.1023/A:1015777403153.

[11] Alam, Jobair B., M. H. Hussein, S. F. Magram, and R. Barua (2011), Impact of Climate Parameters on Agriculture in Saudi Arabia: Case Study of Selected Crops, Int. J. Clim. Change: Impacts Responses, 2, 41-50, https://doi:10.18848/1835-7156/CGP/v02i04/37075.

[12] Dalin, C., Y. Wada, T. Kastner, and M. J. Puma (2017), Groundwater depletion embedded in international food trade, Nature, 543, 700–704, https://doi:10.1038/nature21403.

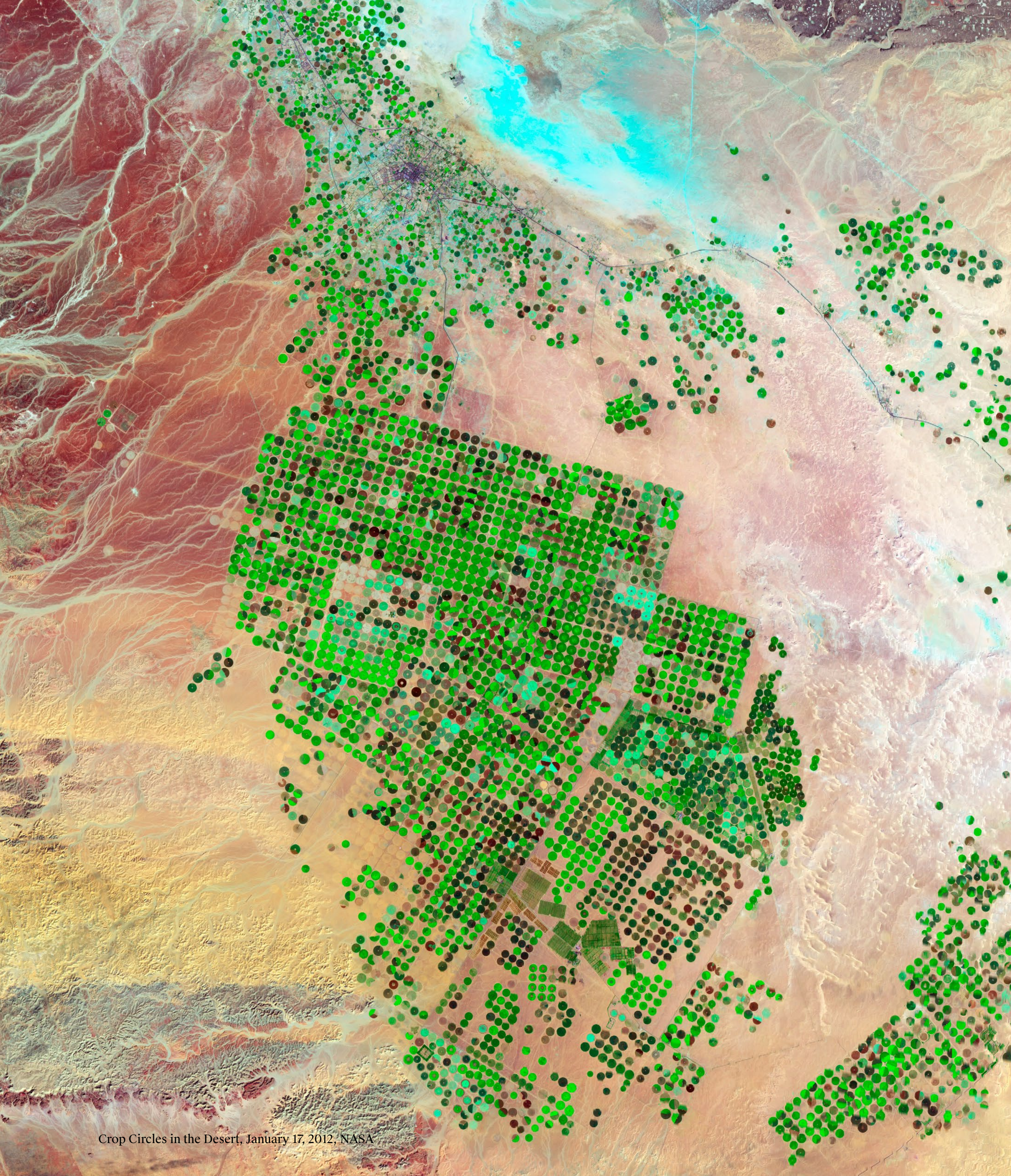
[13] Hamieh, A., F. Rowaihy, M. Al-Juaied, A. N. Abo-Khatwa, A. M. Afifi, and H. Hoteit (2022), Quantification and analysis of CO_2 footprint from industrial facilities in Saudi Arabia, Energy Convers. Manag.: X, 16, 100299, https://doi.org/10.1016/j.ecmx.2022.100299.

[14] Ministry of Economy and Planning (MEP) (2022), Saudi Arabia's agricultural sector grew at a rate of 7.8% in 2021, available at https://mep.gov.sa/en/EconomicAffairs/Pages/Saudi-Arabia%E2%80%99s-agricultural-sector-grew-at-a-rate-of-7-8-in-2021.aspx.

[15] Bahn, R., S. E. L. Labban, and N. Hwalla (2019), Impacts of shifting to healthier food consumption patterns on environmental sustainability in MENA countries, Sustain. Sci., 14, 1131-1146, https://doi.org/10.1007/s11625-018-0600-3.

[16] Willett, W., J. Rockström, B. Loken, M. Springmann, T. Lang, S. Vermeulen, T. Garnett, D. Tilman, F. DeClerck, A. Wood, M. Jonell, M. Clark, L. J. Gordon, J. Fanzo, C. Hawkes, R. Zurayk, J. A Rivera, W. De Vries, L. M. Sibanda, A. Afshin, A. Chaudhary, M. Herrero, R. Agustina, F. Branca, A. Lartey, S. Fan, B. Crona, E. Fox, V. Bignet, M. Troell, T. Lindahl, S. Singh, S. E. Cornell, K. S. Reddy, S. Narain, S. Nishtar, and C. J. L. Murray (2019), Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems, The Lancet, 393, 447-492, https://doi.org/10.1016/S0140-6736(18)31788-4.

[17] Chen, C., A. Chaudhary, and A. Mathys (2020), Nutritional and environmental losses embedded in global food waste, Resour. Conserv. Recycl., 160, 104912, https://doi.org/10.1016/j.resconrec.2020.104912.



Crop Circles in the Desert, January 17, 2012, NASA

“Projections associated with a 3°C warmer world will present new challenges, exacerbating extreme heat stress and amplifying impacts on urban health and livability. ”

Prof. Sami G. Al-Ghamdi
Climate and Livability Initiative, Biological and Environmental Sciences and Engineering (BESE), King Abdullah University of Science and Technology (KAUST), Saudi Arabia

Urban Systems and Livability

Urban areas are estimated to account for less than 2% of the Earth's surface, yet consume more than 75% of the energy produced. With Saudi Arabia representing one of the most urbanized populations in the world, understanding the impacts of a 3°C warmer world on cities and urban settlements, buildings and infrastructure, and the growing populations that inhabit them are areas of major importance. Cities of the present, as well as those of the future, will need to be resilient to extremes of heat and flooding, while also dealing with the effects of sea level rise, potential increase in the occurrence of storms, and the risks associated with increased air pollution. These climate-related drivers of change will have a direct influence on the livability, comfort, and safety that cities aim to provide, and will affect everything from public health outcomes to issues related to the stability of energy supplies, water scarcity, and the resilience of aging infrastructure networks.

Urban Heat Stress

Saudi Arabia's cities are accustomed to extreme temperatures, with summers in Riyadh and Jeddah regularly exceeding 40°C for prolonged periods. However, projections associated with a 3°C warmer world will present new challenges, exacerbating extreme heat stress and amplifying impacts on urban health and livability. Heatwaves, defined broadly as extended periods of abnormally high temperature, pose grave risks to public health. Vulnerable populations, including the elderly, young children, pregnant women, outdoor workers, and individuals with pre-existing health conditions, are particularly susceptible to heat-related illnesses and mortality. Additionally, socio-economically marginalized communities lacking access to adequate cooling infrastructure will likely bear the brunt of these impacts.

There are both recent and historical precedents that demonstrate the tragic outcomes that heat stress can have on large populations and mass gatherings: from the 60,000 heat-related mortalities associated with the European heat wave of 2022[1,2], to more local examples of stampedes occurring during the Hajj, which have been linked with the compound effects of extreme heat[3]. Many of the most serious Hajj incidents have coincided with the "extreme danger" heat stress threshold as defined by the US National Weather Service[4]. Related to the so-called "wet-bulb temperature", which accounts for both air temperature and humidity, the threshold is often used as an indicator of heat-related stress on the human body, identifying domains beyond which humans become incapable of maintaining homeostasis (e.g., the ability to self-regulate body temperature).

An important consideration in determining thermal comfort is the so-called "urban heat island effect", wherein cities can experience significantly higher temperatures than surrounding rural areas. Surfaces such as concrete and asphalt absorb and re-radiate heat, leading to high nighttime temperatures that offer little respite from daytime conditions. These elevated temperatures not only compromise outdoor comfort, but also increase energy demand via a surge in air conditioning use, further contributing to the heat island effect. Projected warming in Saudi Arabia is expected to amplify cooling needs, straining energy infrastructure and contributing to peak demand challenges. By some accounts, the demand for cooling consumes more than 55% of the energy consumption of buildings in Saudi Arabia[11,12], which is only expected to rise due to a combination of a warmer climate, rapid urbanization, and population growth. The positive feedback between elevated energy consumption and heat intensification exacerbates the urban climate challenge.

Urban Air Pollution

The intersection of rising temperatures and air pollution presents a formidable challenge to public health in Saudi Arabian cities (Chapter 8). Air quality

FIGURE 1

Temperature anomaly and number of heat stress days in major Saudi Arabian cities for the period 1080-2099, relative to the reference period 1995-2014

CITY	MAXIMUM TEMPERATURE (°C)	MINIMUM TEMPERATURE (°C)	MEAN TEMPERATURE (°C)	HEAT STRESS DAYS (>35°C)
Riyadh	+2.81	+2.85	+2.79	65.96
Dammam	+2.74	+2.81	+2.75	72.72
Neom	+2.72	+2.56	+2.60	40.55
Jeddah	+2.38	+2.37	+2.39	27.71
Mecca	+2.23	+2.19	+2.20	25.14
Madina	+2.63	+2.54	+2.58	59.74
Quassim	+2.91	+2.89	+2.85	73.57
Hail	+2.89	+2.87	+2.81	64.97
Asir	+2.31	+2.38	+2.33	15.23
Najran	+2.53	+2.60	+2.55	10.74

is strongly tied to temperature and weather patterns, with particulate matter (PM) and ground-level ozone two key pollutants that become problematic with increasingly warmer conditions. These pollutants can exacerbate respiratory and cardiovascular conditions, leading to increased hospitalizations and premature deaths, particularly among vulnerable populations. PM 2.5 concentrations in Saudi Arabia were identified as being some of the highest in the world (106.2 μg/m³), placing second only to Qatar[5] and it is estimated that persistent air pollution has reduced the average lifespan by approximately 1.5 years[7, 8].

Industrial emissions play a significant role in air pollution, particularly in urban environments. Saudi Arabia generates most of its electricity from fossil fuels, delivering adverse effects on urban populations. Additionally, transportation-related pollution emanating from both diesel and petrol vehicles is another concern within the Kingdom and its cities. Decarbonization of the energy system and increased electrification of the transport sector are the primary levers to reduce these impacts.

Indoor air quality is a critical consideration in the region, given that environmental conditions encourage people to spend significant time indoors. Indoor living is a trend that is likely to increase in line with projected escalations in temperature over the coming decades. Urban green spaces and parks that offer respite from the heat, while also providing opportunities to connect with the natural environment, will become increasingly important.

Urban greenery / landscaping and traditional architecture. Impact of cooling the city and medicating the heat island effect, Picture for King Abdulaziz Historical Center by The Royal Commission for Riyadh City.

Urban Health

Climate change induced shifts in temperature, humidity, and precipitation patterns have profound implications on the transmission of diseases. As outlined in Chapter 8, rising temperatures and altered precipitation patterns can create an increased disease burden, particularly in terms of vector-borne infections such as malaria and dengue[9]. Changes in breeding conditions and habitat expansion can increase the geographical range of vector-borne diseases, presenting new health risks to urban populations. Malaria, which was once considered rare in Saudi Arabia, may see increased prevalence under warming scenarios, with southern regions including Jeddah and Mecca at greater risk. Similarly, dengue fever could become a more prominent public health concern with an increase in the abundance and activity of Aedes mosquitoes. The introduction of water features as a means to alleviate urban heat island effect, or an increase in water utilization for cooling purposes, may inadvertently provide conditions favorable for the propagation of vector-borne diseases. Increased inundation, resulting from sea-level rises, floods or storm surges, may provide new breeding grounds, requiring active measures to ensure mosquito populations are managed.

Coastal Vulnerability to Sea Level Rise, Storms and Floods

The impacts of climate change extend beyond their influence on temperature and air quality. Saudi Arabia's coastal settlements are increasingly vulnerable to flooding, erosion, and storm surges, which jeopardize homes, businesses, essential services, and urban infrastructure. Likewise, rising sea levels pose significant and escalating threats to infrastructure, with cities situated along the Red Sea and the Persian Gulf particularly at risk. A projected sea level rise of 0.18 to 0.23 meters by 2050, coupled with the potential for increased storm intensity and frequency, increases the vulnerability of coastal settlements and communities[4].

All of Saudi Arabia's major cities are vulnerable to flash floods. Riyadh has witnessed more than ten flood events in the past thirty years, which have claimed over 160 human lives and caused substantial socioeconomic losses. Flash floods that struck Jeddah in 2009 and 2011 claimed more than 100 lives, with extensive damage to settlements and other infrastructures.

The potential consequences of sea level rise encompass a range of outcomes. Low-lying areas and critical infrastructure near coastlines could face saltwater intrusion, erosion, and inundation. There is also the risk of compromised water supplies due to saline intrusion into groundwater, in addition to the increased risk of flooding during storm surge events. The disruptive potential on the operation and function of coastal cities is a key concern, not just in terms of interruptions in the supply of basic needs (e.g. food, water and electricity), but also with regards to public health and welfare issues that often follow natural disasters.

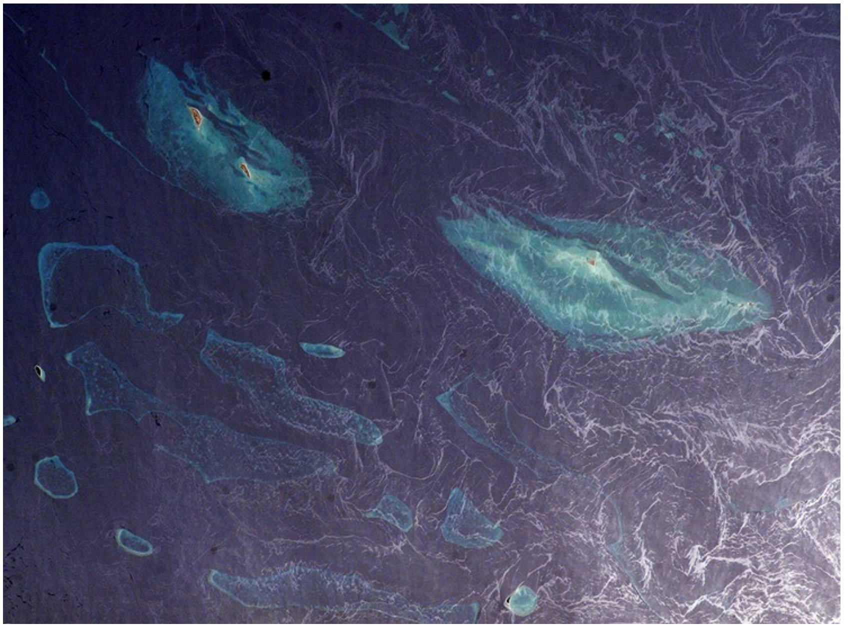
Some pictures show the devastating impact of flooding in Jeddah 2009, Wiley https://doi.org/10.1111/jfr3.12611

Disaster preparedness and response strategies will be crucial to managing climate related disruptions. Establishing robust early warning systems that provide timely alerts to residents and authorities will not only save lives, but also act to reduce damage from extreme weather events. Evacuation plans, emergency shelters, and community engagement initiatives can enhance disaster resilience and ensure a coordinated response. By prioritizing resilience, Saudi Arabia can safeguard its coastal areas, critical infrastructure, and the well-being of its coastal communities.

Urban Settlements and Infrastructure

The resilience of critical infrastructure, particularly electricity and water networks, is central to the function of any modern settlement. As witnessed in many cities around the world, climate-related events, particularly extreme heat and storms, have demonstrated their potential to disrupt water and electricity supply, generation, and distribution, leading to systemic failure.

Power blackouts witnessed across metropolitan centers in both the United States and Europe have been attributed to major heat wave events over the last decade and more. With higher temperature increasing base load demand (e.g. driven by a demand for air-conditioning), such blackouts expose the susceptibility of electrical grids and infrastructure to climate extremes. As a consequence, cities face disruptions in essential services, economic



Above and Under the Red Sea, NASA

productivity, and overall quality of life. These incidents serve as a warning of the urgent need for urban planning that integrates climate-resilient energy systems, efficient cooling strategies, and adaptable infrastructure to mitigate the impacts of rising temperatures and ensure the reliability of vital services in the face of changing climate.

While replacement of fossil fuel-based electricity generation with renewable energy sources is necessary, it is not without its own challenges. Apart from disrupting energy distribution, extreme heat can also impact the performance and lifespan of solar generation, storage and distribution. Prolonged periods of higher temperatures shorten battery life and reduce their storage capacity, affecting their reliability and efficiency in sustaining power supply at the most critical of times. In arid countries like Saudi Arabia, dust accumulation on solar panels can substantially decrease their energy-generating efficiency. Transmission lines required for electricity distribution are also vulnerable to heat-related stresses, as higher temperatures can cause power lines to expand, leading to wilting or even failure.

Several other infrastructure and supply channels that are essential to the function of urban settlements are also at risk of impact due to climate factors:

- Desalination plants, crucial for providing fresh water in Saudi Arabia, experience reduced efficiency during heatwaves. The intake of warmer waters, or those affected by algal blooms, increases energy consumption and operational costs, impacting the overall availability of freshwater resources;
- Decreasing groundwater levels and soil compaction can threaten the integrity of underground pipe infrastructure, including drinking water and distribution systems;
- Changes in precipitation patterns and extreme weather events can overwhelm existing sewerage and drainage systems, leading to poor treatment processes and potential contamination of water bodies;
- Increased flooding poses a risk of sewage overflow and cross-contamination, impacting public health in the urban environment;
- Persistent higher temperatures can accelerate the decomposition of organic waste, producing greenhouse gas emissions and odorous by-products, affecting the surrounding urban environment.

Fortunately, the integration of climate resilience into infrastructure planning can yield long-term benefits[10]. Adaptable designs that consider the potential impacts of extreme weather events can enhance the capacity of networks to withstand disruptions. In a similar manner, developing redundancies and backup systems, such as energy storage for peak demand and alternative water sources, can ensure continuity of services during emergencies.

Enhancing the resilience of infrastructure is essential to minimize disruptions in the supply of essential needs. Replacing aging pipelines and investing in advanced leak detection and repair technologies prevents water loss and increases service reliability. Likewise, sustainable urban planning, resilient design, and adaptive strategies are imperative to ensure the effectiveness and integrity of sewerage treatment and solid waste disposal systems in the face of evolving climatic conditions.

Urban Landscapes and Livability

Urban landscapes play a vital role in enhancing the quality of life in cities and mitigating the impacts of a warming climate. To address the challenges of urban landscapes, innovative approaches will be required. Air-conditioned parks, for instance, have emerged as a creative solution to provide outdoor recreational spaces during hot weather. While they offer respite from the heat, they also highlight energy consumption concerns. The resource requirements that are needed to maintain urban landscapes necessitate a holistic approach. Expectations of higher temperatures will demand the careful management of engineered “natural” systems to ensure their sustainability and optimize resource utilization. Integrating green spaces and trees into urban design can mitigate the urban heat island effect and enhance outdoor comfort. However, selecting climate-adaptive plant species that can thrive in higher temperatures and require less water is crucial. Efficient irrigation technologies and water-saving practices, such as drip irrigation and xeriscaping, can reduce water consumption while supporting greenery.

A Resilient Urban Future

The impacts of climate change on urban environments are multi-faceted and complex. Given the disruptive potential on both society and the economy, it is critical that a considered and coordinated approach to managing climate risk is pursued. Decarbonization of the built environment will play a vital role in adapting to and mitigating a 3°C warmer climate, demanding that the efficient use of energy resources and lower carbon footprints become essential elements of any urban resilience strategy. There are many low-level solutions that can have a major impact on addressing urban inefficiencies, including the use of innovative building materials with insulation properties, reuse of wastewater to lower the burden on the desalination sector, life cycle implementation in product design, innovative energy production and desalination technologies, and recycling of waste into value-added products.

By embracing climate-adaptive urban planning, promoting sustainable energy sources, advancing healthcare preparedness, and enhancing critical infrastructure, Saudi Arabia can navigate the impacts of a changing climate and create a more resilient and sustainable future.

FIGURE 2

Summary of Impacts in a 3°C Warmer World.

EXTREME HEAT STRESS

Increased heatwaves and urban heat island effects pose health risks to vulnerable populations and strain energy systems.

AIR POLLUTION

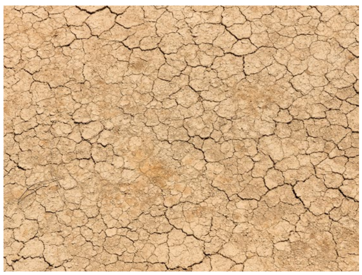
Rising temperatures worsen air quality, leading to health issues and necessitating stringent emission controls.

VECTOR-BORNE DISEASES

Altered climate patterns expand the range of diseases like malaria and dengue, affecting urban populations.

ENERGY DEMAND

Higher cooling needs amplify energy consumption, requiring efficiency measu-res and renewable energy integration.



WATER SCARCITY

Diminished groundwater recharge and reliance on desalination impact water security and ecosystem health.

SEA LEVEL RISE AND STORMS

Coastal cities face threats of inundation, saltwater intrusion, and intensified storm impacts.

SOLAR ENERGY RESILIENCE

Higher temperatures challenge solar energy efficiency, necessitating innovative designs and storage solutions.

URBAN LANDSCAPES

Balancing outdoor comfort with energy efficiency becomes essential, necessita-ting smart landscape designs.

INFRASTRUCTURE RESILIENCE

Extreme weather events strain power and water networks, requiring upgrades and redundancies.

[1] M. Salimi and S. G. Al-Ghamdi, "Climate change impacts on critical urban infrastructure and urban resiliency strategies for the Middle East," Sustain Cities Soc, vol. 54, p. 101948, Mar. 2020.

[2] J. Ballester et al., "Heat-related mortality in Europe during the summer of 2022," Nat Med, vol. 29, no. 7, pp. 1857–1866, Jul. 2023.

[3] S. Kang, J. S. Pal, and E. A. B. Eltahir, "Future Heat Stress During Muslim Pilgrimage (Hajj) Projected to Exceed 'Extreme Danger' Levels," Geophys Res Lett, vol. 46, no. 16, pp. 10094–10100, Aug. 2019.

[4] R. G. Steadman, "The Assessment of Sultriness. Part I: A Temperature-Humidity Index Based on Human Physiology and Clothing Science," Journal of Applied Meteorology, vol. 18, no. 7, pp. 861–873, Jul. 1979.

[5] S. Osipov et al., "Severe atmospheric pollution in the Middle East is attributable to anthropogenic sources," Commun Earth Environ, vol. 3, no. 1, p. 203, Sep. 2022.

[6] D. Rojas-Rueda, W. Alsufyani, C. Herbst, S. AlBalawi, R. Alsukait, and M. Alomran, "Ambient particulate matter burden of disease in the Kingdom of Saudi Arabia," Environ Res, vol. 197, p. 111036, Jun. 2021.

[7] M. Brauer et al., "Ambient Air Pollution Exposure Estimation for the Global Burden of Disease 2013," Environ Sci Technol, vol. 50, no. 1, pp. 79–88, Jan. 2016.

[8] U. L. Dano, I. R. Abubakar, F. S. AlShihri, S. M. S. Ahmed, T. I. Alrawaf, and M. S. Alshammari, "A multi-criteria assessment of climate change impacts on urban sustainability in Dammam Metropolitan Area, Saudi Arabia," Ain Shams Engineering Journal, vol. 14, no. 9, p. 102062, Sep. 2023.

[9] S. Paz, A. Majeed, and G. K. Christophides, "Climate change impacts on infectious diseases in the Eastern Mediterranean and the Middle East (EMME)—risks and recommendations," Clim Change, vol. 169, no. 3–4, p. 40, Dec. 2021.

[10] M. M. Al-Humaiqani and S. G. Al-Ghamdi, "The built environment resilience qualities to climate change impact: Concepts, frameworks, and directions for future research," Sustain Cities Soc, vol. 80, p. 103797, May 2022.

[11] A. M. Mujeebu and O. S. Alshamrani, "Prospects of energy conservation and management in buildings – The Saudi Arabian scenario versus global trends," Renewable and Sustainable Energy Reviews, vol. 58, pp. 1647–1663, May 2016.

[12] A. Demirbas, A. A. Hashem, and A. A. Bakhsh, "The cost analysis of electric power generation in Saudi Arabia," Energy Sources, Part B: Economics, Planning, and Policy, vol. 12, no. 6, pp. 591–596, Jun. 2017.

Riyadh, via Google Earth

“Saudi Arabia’s hot desert climate necessitates high energy demands for cooling. The subsequent high energy consumption of buildings makes the Kingdom one of the largest per capita consumers of household electricity in the world.”

Dr. Mohamad Hejazi
Climate and Sustainability Program, King Abdullah Petroleum Studies and Research Center (KAPSARC), Saudi Arabia

Princess Noura Al Saud
AEON Collective, Saudi Arabia

Energy and Industry

Amidst the country’s vast stretches, where modern structures and expansive networks of roads reflect the nation's relentless drive for industrial and energy advancement, the potential implications resulting from a three-degrees warmer world raise a plethora of concerns. Given that studies assessing such aspects are lacking, potential impacts are explored using existing knowledge, focusing on the role of climate variability, expectations related to extreme weather events, and known vulnerabilities within the sector. The broader context of international policy, particularly those concerning energy exports and associated geopolitics, remains a complex backdrop. That dimension warrants its own comprehensive exploration to fully grasp the impacts of both climate change and international climate policy on the Kingdom’s economy and its role in the global energy ecosystem. While climate changes will bring inevitable challenges for the energy and industrial sectors, there will also be economic opportunities that can be realized from the adoption of sustainable and adaptive strategies.

The Importance of Energy Resilience

Escalating temperatures introduce a multifaceted dynamic to the energy sector. The heightened demand across all fuel categories, amplified by an increased need for cooling, as well as sporadic colder winters, unpredictable precipitation patterns and sea level rise, all complicate the scenario, posing direct and indirect impacts on the energy sector and the country's overall economic productivity.

The human element will be at the forefront of such challenges. Between 1979 and 2019, major cities in Saudi Arabia all witnessed significant temperature changes, including Makkah (+2.28°C), Jeddah (+1.57°C), Riyadh (+2.79°C), and Dammam (+1.88°C), representing an average annual increase of 0.48 degrees per decade[1]. This rise, coupled with the Kingdom's growing population and industrial activity, intensified demands on the energy infrastructure, especially electricity with an expected 22% rise in demand by 2030 compared to 2018[2].

Another human dimension is the impact on labor productivity, particularly for those working outdoors, who are most at risk from temperature fluctuations (Chapter 8). As peak hours of daytime heat have traditionally limited outdoor work, the Kingdom has proactively adjusted working hours to ensure worker safety while optimizing productivity.

FIGURE 1 →

Average hourly temperatures and hourly power generation in the central region of Saudi Arabia for the year 2015.

Climate 2020, 8, 4; doi:10.3390/cli8010004

Concurrently, measures to enhance the electricity sector have been underway to improve delivery and reliability. Grid failures and rolling blackouts seen in other regions of the world, especially those occurring during prolonged heatwaves, bring both industrial and health related risks[3,4]. Recent restructuring within the Saudi Electricity sector reflects the importance that grid-stability has on both human welfare and infrastructural resilience[5].

A major element of industrial resilience is the national commitment to the development of renewable energy infrastructure and the building out of its industrial base, which ensures continuity in supplying local electricity demand, while also meeting the global demand for petrochemicals and other produced goods.

Climate Impacts on Industrial Activity

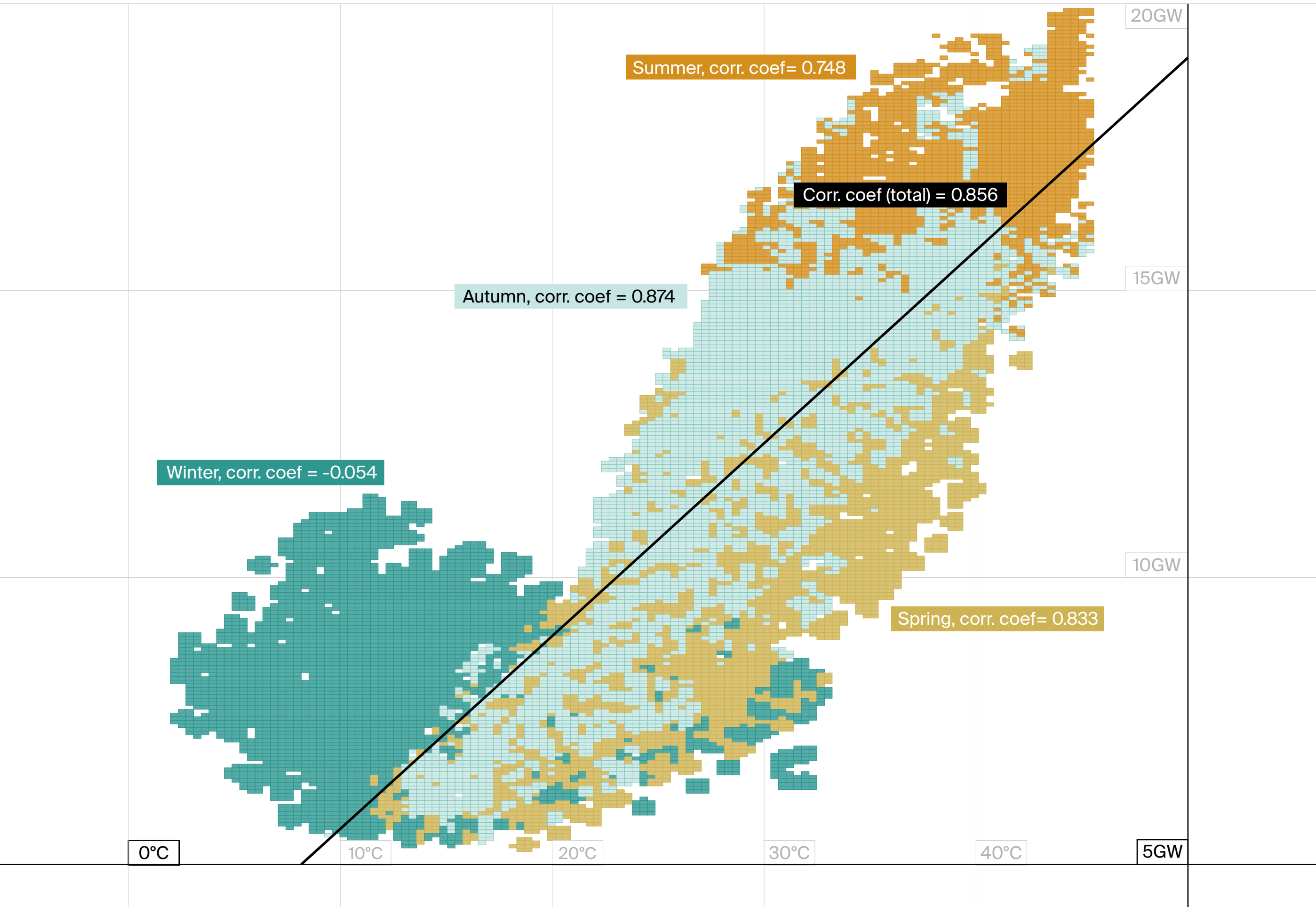
As temperatures continue to rise, the resilience of the industrial and power sectors is put to the test. The peak summer months, especially July, exert immense strain on industrial machinery and power plants. At the same time, industrial infrastructure can be impacted by sea level rise (Chapter 2) resulting in increased flooding. This is particularly a concern for coastal industries and infrastructure, where most of the nation's oil and gas infrastructure are located, representing a major component of Saudi Arabia's economy[6]. Supply chains are also at risk, potentially increasing the cost of doing business[7].

Extreme weather events such as flooding and dust storms can disrupt both on-shore and off-shore extraction and transport activities[8], while increases in temperatures and potential reduction in rainfall place additional strain on the water resources. These include those water resources used to supply domestic consumption (via energy intensive desalination) as well as the volumes required for oil extraction, ultimately affecting oil production and increasing the cost of extraction[9].

Furthermore, as the Kingdom grapples with the direct impacts of rising temperatures as well as the energy transition, new emergent technologies are taking a more prominent role. The Kingdom's commitment to a net-zero future under the Circular Carbon Economy National Program will further add to industrial activity. Hydrogen's wide-ranging applicability, in domains ranging from heavy industry to transportation, will require further energy and infrastructure. That will necessitate robust planning for durability and resilience in

FIGURE 1

Average hourly temperatures and hourly power generation in the central region of Saudi Arabia for the year 2015.



both its production and delivery: whether via pipeline or as maritime cargo, and mostly likely in the form of Ammonia or methanol. Similar energy and infrastructure considerations apply for Carbon Capture, Utilization, and Storage (CCUS) technologies, as well Direct Air Capture (DAC)[10, 11, 12].

Power Generation and Electricity Demand

Climate change will have implications on both the supply and demand of power and electricity. Indeed, the very foundation of energy provision is challenged as load curve durations stretch and morph. Saudi Arabia's hot desert climate already necessitates high energy expenditure for its various needs, ranging from its ever-expanding industrial sector to rapidly growing built environment. The increasing trend in temperatures observed within the Kingdom has exacerbated the rise in energy consumption[13]. Hotter climates negatively affect the efficiency and operating capacity of thermal power plants and transmission lines[14], placing further strain on Saudi Arabia's electricity grid and increasing the risk of power outages during times of peak demand[15]. The power grid is also vulnerable to other extreme events such as flooding, heatwaves, and droughts, which are projected to increase in frequency and intensity in the future, posing additional risks to electricity supply.

Increasing temperature may also reduce the efficiency of cooling systems in thermal power plants, further impacting power generation[16]. As half of the

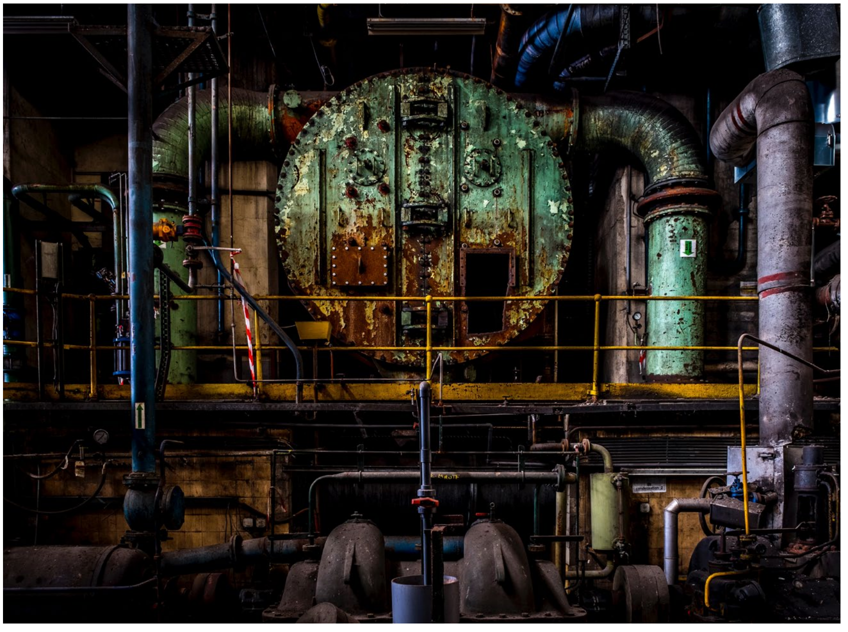


Photo by Taton Moise on Unsplash

Kingdom's planned power generation capacity will continue to rely heavily on thermal power plants using natural gas as feedstock, the potential increase in ambient temperatures creates a positive feedback resulting in increased demand for cooling, subsequently leading to a rise in electricity demand[17]. The role of "peaker plants", essential for ensuring energy continuity during periods of high variability, will have to be studied and optimized for operational and cost efficiencies amidst these shifting dynamics.

The Energy Demand of Buildings

Saudi Arabia's hot desert climate necessitates high energy demands for cooling[13]. The subsequent high energy consumption of buildings makes the Kingdom one of the largest per capita consumers of household electricity in the world, with cooling accounting for approximately 70% of overall residential sector demand and 50% of total electricity consumption[17, 18].

The increasing trend in temperatures projected for the Kingdom will further exacerbate the rise in energy consumption, in spite of efficiency improvements made to date. According to the Sixth Coupled Model Inter-comparison Projects (CMIPs)[19] model ensemble mean, the total cooling degree days in Saudi Arabia, which is a measure of annual cooling demands, will increase by 18% in 2050 and 29% in 2100 under the SSP2-4.5 scenario (see FIGURE 2)[20]. Determining the climate impacts on building energy demand in Saudi Arabia will be critical to managing the country's already heavy dependence on air conditioning systems[21, 22]. Furthermore, promoting high-efficiency cooling technologies and establishing region-specific building codes is needed, given the sensitivity of energy demand to climate conditions[23].

FIGURE 2 ↓

Projected cooling degree days (a measure of annual cooling demands) in Saudi Arabia using a multi-model ensemble[20].

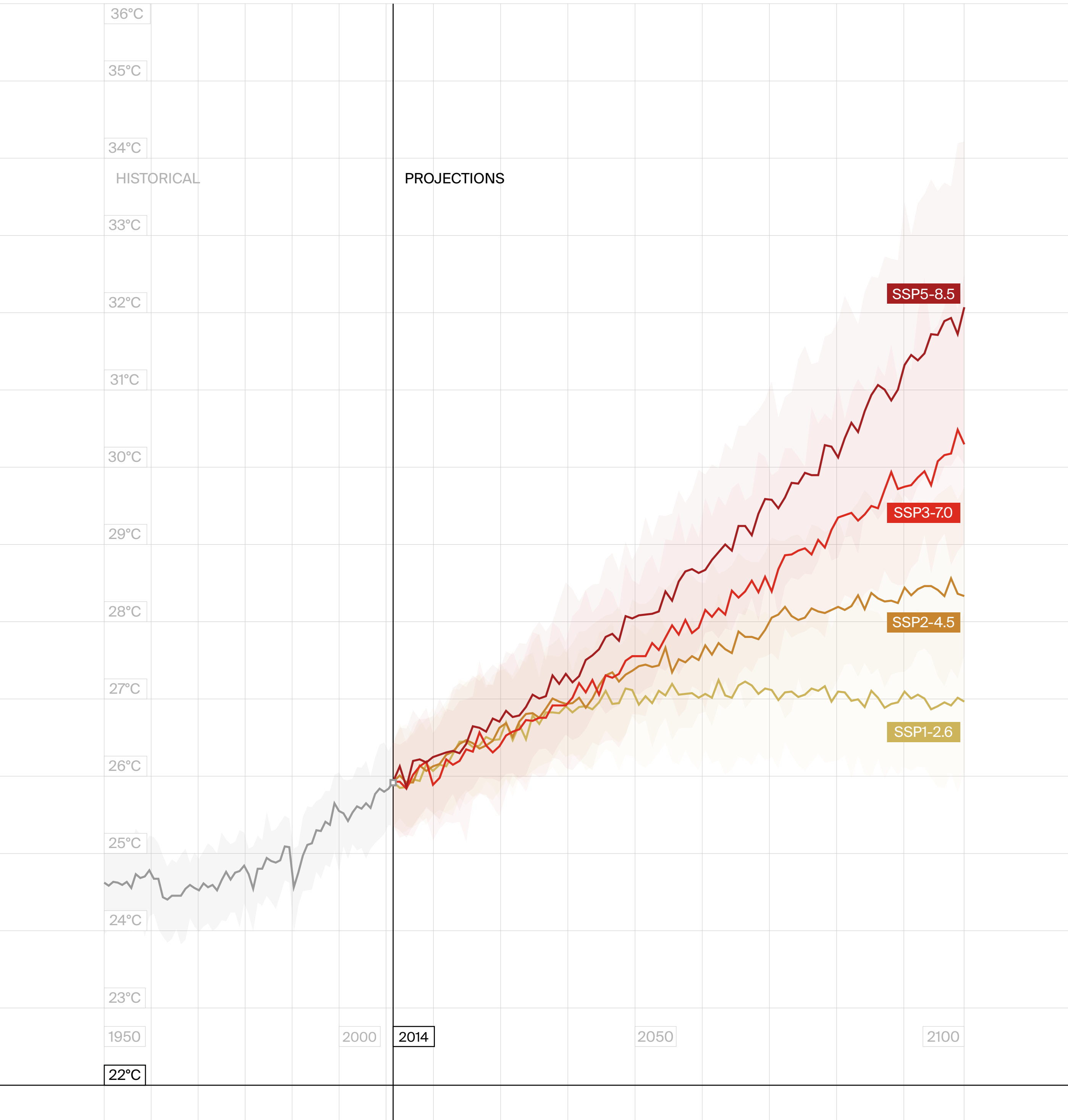
Source: https://climateknowledgeportal.worldbank.org/country/saudi-arabia/climate-data-projections

Changing Modes of Transportation

Under a changing climate, Saudi Arabia's transportation sector will both experience and bring about challenges, by creating additional stressors on energy demand and human health and safety. Rising temperatures impact fuel efficiency of internal combustion engines[24], while road durability, air pollution and visibility pose further dangers to human lives. The expected rise in the uptake of electric vehicles in major cities, in addition to the move towards increased electrification, presents another dimension to the narrative. Urban rail infrastructure, such as the Riyadh Metro[25] and the forthcoming Jeddah Metro project, while representing a shift towards sustainable urban mobility, will also contribute to increased electricity demand. Ensuring the resilience of these infrastructures against extreme weather events, potential flooding, and heat-induced material degradation will be crucial. Furthermore, the energy-intensive nature of metro systems, especially during peak hours, in addition to evolutionary changes in the transportation sector overall, necessitates robust

FIGURE 2

Projected cooling degree days (a measure of annual cooling demands) in Saudi Arabia using a multi-model ensemble[20].



[A]

[B]

[C]

[A] Jubail Desalination Plant. Source: Marafiq
[B] National Water Company's water treatment storage tanks. Source: Al Riyadh
[C] Shuqaiq 3 Desalination Plant, located on the coast of the Red Sea, in Saudi Arabia.

grid and load management, demand response strategies and deeper insights into capacity installments to ensure uninterrupted service.

Demand for Water and Desalinization

Growing water demands and worsening chronic water shortages due to climate change can have indirect effects on electricity demand. Water desalination plants, which are energy-intensive, supply the bulk of Saudi Arabia's domestic and potable water needs[26]. As the need for freshwater increases due to population growth and changing climatic conditions, so does the demand for energy and electricity to operate these plants. An increased focus on renewable energy sources and energy efficiency improvements is necessary to mitigate climate impacts on electricity demand, while also meeting the additional electricity demand[27]. Furthermore, most of Saudi Arabia's desalination plants are located along the Red Sea and Arabian Gulf coastlines, which are also vulnerable to rising sea levels, warmer sea surface temperatures, and the risks associated with algal blooms.

Opportunities and Challenges for Renewable Energy

Saudi Arabia receives some of the most consistent and highest rates of solar-irradiation globally[28]. The country receives an average solar radiation of 5.4 kilowatt-hour per square meter per day, enabling a high solar energy production potential[29].

Presently, renewables constitute a small portion of the energy system in the Kingdom. However, they are projected to play a major role in the Saudi energy mix in the coming years and decades. Wind and solar electricity generation technologies in particular are anticipated to deliver 50% of the power capacity of the Saudi electric grid by 2030. The role of renewables will inevitably increase to deliver the stated goal of climate neutrality by 2060, driving further the decarbonization of the power sector. The shift to renewables is also consistent with the Kingdom's ambition of becoming a global hydrogen production hub, in which its green hydrogen would be generated using renewables such as wind and solar.

Factors such as high temperature and dust accumulation may present challenges to the operational efficiency of solar installations, driving increased maintenance requirements. While studies on the impact of climate change on renewable energy infrastructure in the Kingdom are scarce, one study used climate projections for 2010 to 2080 to find a decrease in photovoltaic output of a few percent (-1 to -6%) in Saudi Arabia due to changes in temperature and insolation[30]. A more recent study that looks at impacts on photovoltaic output in Iraq concludes that the impact of climate change on photovoltaic power potential varies considerably based on regional factors. While determinants such as atmospheric temperature, surface insolation, and wind speed certainly play a role in influencing the efficiency of photovoltaic systems, Saudi Arabia is in a strong position economically and geographically to harness this untapped potential. Similar to photovoltaics, there has been considerable interest in harnessing wind energy as part of the Kingdom's endeavor to diversify its energy mix[31], with significant potential in regions along the Red Sea coast. However, the challenges to such installations include inconsistent and highly seasonal wind patterns specific to Saudi Arabia, as well as increasing ambient temperature which can pose a challenge to the optimal operation of the wind turbines as well energy output[32]. While ongoing research and design modifications will be required for wind turbines to endure Saudi Arabia's unique climatic conditions, the opportunities for wind-powered renewables to augment the energy mix are obvious.

Other renewables such as hydropower, geothermal, and biomass can all be affected by climate. Yet while the impacts can be substantial in some geographies, these renewable technologies will likely play a lesser role in the Kingdom's future energy mix compared to solar and wind[33].

Adapting to a Changing Energy Landscape

A deeper examination into the potential impacts of climate change must be considered and integrated into the energy planning process to ensure a resilient energy and industrial sector in the Kingdom in the coming decades. By incorporating climate change projections and assessing the potential impact of extreme events on energy and industrial sector assets and supply chains, Saudi Arabia can establish proactive strategies to ensure a resilient energy and industrial sector to future climate and other economic shocks.

Given that the climate-induced risks and vulnerabilities do not operate in isolation from other forces, especially those that are induced by human and economic drivers, it is important to understand the resilience of the Saudi power grid reliability in the face of these pressures working in tandem. It is also important to incorporate the possibility of compounding risks and the adaptive capacity of the grid system to react and absorb such shocks without interruptions.

Expected population and economic growth in the Kingdom, coupled with the need to decarbonize and to accelerate the electrification of the "end-use" sectors (i.e. transportation, industrial, residential, and commercial sectors) will dictate that electricity sector will need to increase in size and evolve in its mix. Thus, it is important to take a holistic view when addressing the electric grid stability and resilience to climate change. In other words, it is not only how resilient the current grid is, but rather how resilient the electric grid of the future is to future climate- and human-induced shocks and hazards.

[A]


[B]


Investigating the effects of climate impacts on building energy demand in Saudi Arabia is critical to manage its heavy dependence on air conditioning systems[13]. Given that the building energy demand changes significantly with different climate zones, it is important to establish building codes that are compatible with Saudi conditions. A major effort will be to integrate more energy-efficient building materials, and more efficient cooling technologies and designs in the Saudi building sector[22, 34].

The Kingdom's energy-intensive industries such as petrochemicals, cement production, and steel are likely to face pressure from climate change policies aimed at reducing greenhouse gas emissions. Thus, transitioning to carbon-neutral technologies is critical for these industries to remain competitive and sustainable in markets with stringent climate policies and trade restrictions. Adapting and implementing mitigation strategies to combat these potential effects includes infrastructure upgrading, investing in renewable energy, and adopting more sustainable practices to reduce their emission footprint (see Box at page 112).

As variations in solar and wind patterns have substantial implications for renewable energy generation in the region, tailored studies for Saudi Arabia will be needed to fully grasp the implications of climate change on both solar and wind outputs. This calls for a detailed analysis of the nuanced variations in climatic variables across specific regions of the Kingdom. Fostering research and innovation will be vital to ensure the availability of climate-resilient technologies designed for the Saudi context and climate conditions.

[A] Photo by Anatoliy Shostak on Unsplash
[B] Solar panels covered by dust. Photo by Naturalturn via Flickr

[A]

[B]

A 3-degrees temperature rise would not only exacerbate existing challenges but also introduce new complexities into the realm of energy security and geopolitics. Saudi Arabia's proactive approach, as evidenced by its Vision 2030 and other sustainability initiatives, positions it well to navigate these challenges. However, the Kingdom will need to engage in dynamic strategies and international collaborations to secure both its energy future and geopolitical standing in a 3-degrees warmer world.

Energy Security and Governance

In a world potentially facing a 3-degrees temperature rise, the geopolitics of energy security becomes an even more intricate puzzle. The Kingdom of Saudi Arabia, as a linchpin in the global energy market, faces unique challenges and opportunities. The Paris Agreement aims to limit global warming to well below 2°C, preferably to 1.5°C, compared to pre-industrial levels. However, current trajectories and commitments indicate that a 3-degrees scenario is increasingly likely, with profound implications for energy security. Thus, a 3-degrees scenario might necessitate new frameworks for global energy governance, focusing more on sustainable energy and climate resilience, areas where Saudi Arabia could lead given its investments in renewable energy and its strategic importance in global energy markets.

Geopolitical Alliances

Climate commitments under international agreements like the Paris Accord could reshape geopolitical alliances. Countries may be more inclined to form alliances based on shared climate goals rather than traditional economic or geopolitical interests. Saudi Arabia, therefore, needs to navigate this evolving landscape carefully, balancing its role as a major oil producer with the global shift towards sustainability.

Global Energy Markets and Saudi Exports

A 3-degrees rise in global temperatures could lead to more extreme weather events, affecting sea routes and thereby impacting Saudi Arabia's oil exports. Extreme weather events could disrupt key shipping routes such as the Strait of Hormuz[35], a critical passage for Saudi oil exports. This disruption could lead to increased volatility in global oil prices, affecting the Kingdom's economic stability.

Renewable Energy Transition

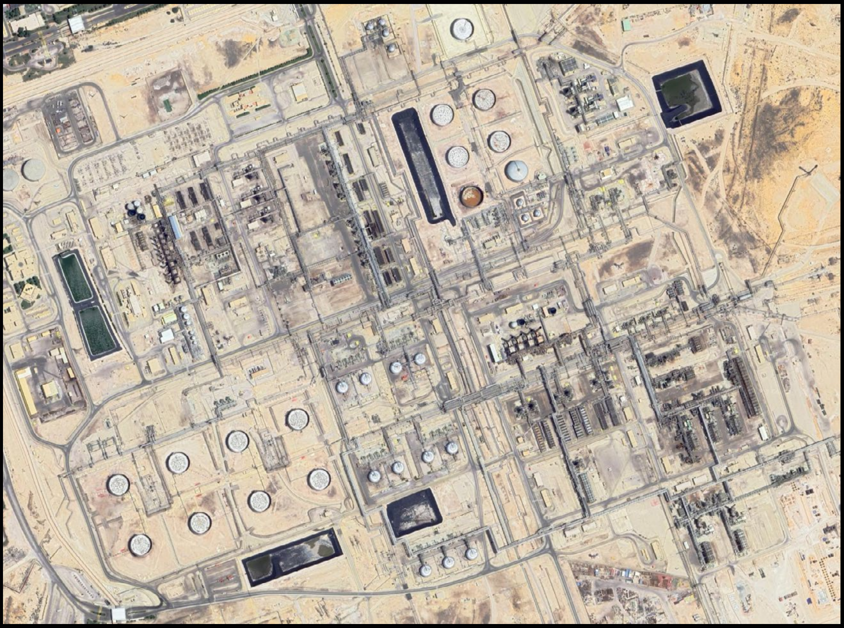
A 3-degrees scenario would necessitate an even faster transition to renewable energy sources to mitigate further climate impacts. Saudi Arabia's Vision 2030 already outlines ambitious plans for renewable energy. However, the urgency to transition could strain existing infrastructure and require significant investments in new technologies, potentially affecting the Kingdom's energy security in the short term.

Strategic Resource Allocation

Increased temperatures and extreme weather events could also affect the domestic availability of water, a critical resource for both the popula-

[A] First internationally accredited Saudi laboratory for testing the reliability of solar panels
[B] Alkhafji desalination plant using solar energy for clean water production

tion and the energy sector, particularly for cooling thermoelectric power plants. Strategic resource allocation will become crucial as water scarcity could become a significant challenge for energy production in a 3-degrees scenario.



Abqaiq Plants Saudi Aramco,
Saudi Arabia via Google Earth

[1] Aeon Collective and Community Jameel. (2022). The State of Climate & Health Research in the GCC. Aeon Collective. https://bit.ly/CHResearchGCC

[2] Salaheddine Soummane, Frédéric Ghersi,Projecting Saudi sectoral electricity demand in 2030 using a computable general equilibrium model, Energy Strategy Reviews, Volume 39, 2022, 100787,ISSN 2211-467X, https://doi.org/10.1016/j.esr.2021.100787.

[3] Do, V., McBrien, H., Flores, N.M. et al. Spatiotemporal distribution of power outages with climate events and social vulnerability in the USA. Nat Commun 14, 2470 (2023). https://doi.org/10.1038/s41467-023-38084-6

[4] Brian Stone Jr., Carina J. Gronlund, Evan Mallen, David Hondula, Marie S. O'Neill, Mayuri Rajput, Santiago Grijalva, Kevin Lanza, Sharon Harlan, Larissa Larsen, Godfried Augenbroe, E. Scott Krayenhoff, Ashley Broadbent, and Matei Georgescu. Environmental Science & Technology 2023 57 (22), 8245-8255 — DOI: 10.1021/acs.est.2c09588

[5] Al-Wathinani, Ahmed M., Dennis G. Barten, Marta Borowska-Stefańska, Paweł Gołda, Noora A. AlDulijan, Mohammad A. Alhallaf, Lujain O. Samarkandi, Abdullah S. Almuhaidly, Mariusz Goniewicz, Waleed O. Samarkandi, and et al. 2023. "Driving Sustainable Disaster Risk Reduction: A Rapid Review of the Policies and Strategies in Saudi Arabia" Sustainability 15, no. 14: 10976. https://doi.org/10.3390/su151410976

[6] Folgoso, R., Solana, M. C., & Delgado-Hernandez, D. (2020). Facing Stormy Seas: Coastal Infrastructure Resilience in the Age of Climate Change. Sustainability, 12(13), 5393

[7] Reyer, C., Adams, S., Albrecht, T., Baarsch, F., Boit, A., Canales Trujillo, N., et al. (2017). Climate Change Impacts in the Middle East and Northern Africa (MENA) Region and their Implications for Vulnerable Population Groups. Regional Environmental Change, 17, 1623–1638.

[8] Schaeffer, Roberto, Alexandre Salem Szklo, André Frossard Pereira de Lucena, Bruno Soares Moreira Cesar Borba, Larissa Pinheiro Pupo Nogueira, Fernanda Pereira Fleming, Alberto Troccoli, Mike Harrison, Mohammed Sadeck Boulahya (2012). Energy sector vulnerability to climate change: A review. Energy, 38, 1, 1-12, 0360-5442, https://doi.org/10.1016/j.energy.2011.11.056.

[9] Alghamdi. "Climate change and water scarcity impacts on oil production in Saudi Arabia." Environmental Science and Policy. 2019.

[10] Hasan, S., & Shabaneh, R. (2022). The Economics and Resource Potential of Hydrogen Production in Saudi Arabia. KAPSARC.

[11] Keith, D. W., Holmes, G., St. Angelo, D., & Heidel, K. (2018). A process for capturing CO_2 from the atmosphere. Joule, 2(8), 1573-1594.

[12] Saudi Aramco. (2022). Carbon Capture, Utilization, and Storage. Accessed in Sep 2023. https://www.aramco.com/en/sustainability/climate-change/managing-our-footprint/carbon-capture-utilization-and-storage

[13] Howarth, Nicholas, Natalia Odnoletkova, Thamir Alshehri, Abdullah Almadani, Alessandro Lanza, and Tadeusz Patzek. 2020. "Staying Cool in A Warming Climate: Temperature, Electricity and Air Conditioning in Saudi Arabia" Climate 8, no. 1: 4. https://doi.org/10.3390/cli8010004

[14] De Cian, E. (2012). Climate change and the production of energy. The Oxford Handbook of the Macroeconomics of Global Warming: 412.

[15] Al-Zohbi, G.M. (2015). "The impact of temperature rise on peak electricity demand in Saudi Arabia." Appl Energy, 143, 709-724.

[16] Khan, F.A & Abido, M.A. (2013). "Impact of high penetration of renewable energy on frequency stability of Saudi electric system." Sustain Cities Soc 12, 417–426.

[17] Almutairi, N.B., & El-Hawary, M. (2015). "Load forecasting in Saudi Arabia using artificial neural networks." Energy Conversion and Management, 92, 162-174.

[18] Alghamdi, M. and Nadeem, I., 2020. Climate change ef-

fects on building energy performance in Saudi Arabia. Renewable and Sustainable Energy Reviews, 90, pp. 109-127.

[19] IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change[Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

[20] World Bank Group, Climate Change Knowledge Portal. Accessed in Sep 2023. https://climateknowledgeportal.worldbank.org/country/saudi-arabia/climate-data-projections

[21] Al-Mofeez, I. (2015). Residential energy consumption in Saudi Arabia: Past, present and future. International Journal of Hydrogen Energy, 40(33), 10604-10610.

[22] Shahid, S. (2020). The impact of climate change on energy demand in buildings: A case study from Saudi Arabia. Journal of Building Engineering, 32, 101652.

[23] Alrashed, F., & Asif, M. (2015). Climate classification and passive solar design in Saudi Arabia. Renewable and Sustainable Energy Reviews, 41, 799-813.

[24] Hasselwander, Samuel, Anton Galich, and Simon Nieland. 2022. “Impact of Climate Change on the Energy Consumption of Passenger Car Vehicles” World Electric Vehicle Journal 13, no. 8: 146. https://doi.org/10.3390/wevj13080146

[25] RCRC. King Abdulaziz Project for Riyadh Public Transport. Accessed in Sep 2023. https://www.rcrc.gov.sa/en/projects/king-abdulaziz-project-for-riyadh-public-transport

[26] Al-Zahrani, M. A., & Baig, S. (2014). Impact of climate change on water reservoirs and potential adaptations in Saudi Arabia. International Journal of Water Resources Development, 30(4), 575-589.

[27] Wada, Y., & Hanasaki, N. (2012). Impact of climate change on renewable groundwater resources in eastern sub-Saharan Africa—a first approximation using a global water balance model. Earth System Dynamics, 37(1), 161-168.

[28] Rehman, S., Alamoud, A. R., & Shash, A. A. (2012). Global Horizontal Solar Energy in Saudi Arabia. Energy Procedia, 18, 1510–1518.

[29] Alkhars, M., 2020. Evaluating the solar power potential in Saudi Arabia. Renewable Energy, 63, pp.776-785.

[30] Crook. J.A., Laura Jones, Piers Forster. and Rolf Crook (2011). Climate change impacts on future photovoltaic and concentrated solar power energy output. Energy Environ. Sci., 2011,4, 3101-3109, DOI https://doi.org/10.1039/C1EE01495A

[31] Al Yami, H., Rehman, S., & Al Sharafi, A. (2012). Prospects of wind energy in meeting future energy demands in Saudi Arabia. Renewable Energy, 39(1), 270-278.

[32] Ramírez, P., García, M., Rodríguez, G., & Crespo, A. (2015). Seasonal and diurnal cycles of wind speed in a mesoscale model and METAR stations in Saudi Arabia. Energy Conversion and Management, 98, 333–343.

[33] Solaun, Kepa, and Emilio Cerdá (2019). Climate change impacts on renewable energy generation. A review of quantitative projections. Renewable and Sustainable Energy Reviews, 116, 109415, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2019.109415.

[34] Al-Saadi, S. N. (2016). The role of building materials in improved energy efficiency of buildings in hot climates. Energy for Sustainable Development, 34, 10-18.

[35] Lin, N. and Emanuel, K. (2016), ‘Grey swan tropical cyclones’, Nature Climate Change, 6: 106–111, doi: 10.1038/nclimate2777 (accessed 27 Mar. 2017).

“Higher temperatures, depleted water resources, ecosystem degradation, and habitat destruction, all influence the migration and ranging patterns of wild animals. With climate change exacerbating these drivers of animal movement, there is an increased risk of cross-species viral transmission.”

Ms. Malissa Underwood, Prof. Pierre Magistretti, Prof. I. E. Gallouzi
Smart Health Initiative, Biological and Environmental Sciences and Engineering (BESE), King Abdullah University of Science and Technology (KAUST), Saudi Arabia

Health and Wellbeing

The growing impacts of climate change on the health and wellness of global populations can be observed throughout the Middle East and around the world. Global air temperature distributions are shifting, such that previous extremes are now more likely to be observed. Changes in the frequency of heat waves, periods of increased humidity, or even reductions in the diurnal temperature range, will all impose additional stress on basic biological functioning in humans. Poor air quality derived from both anthropogenic pollution (e.g., via increased urbanization and economic activity) and natural sources such as forest fires and dust, has contributed to or exacerbated multiple health conditions. While Saudi Arabia has made significant progress over the past three decades in the public health domain, reducing the incidence of infectious diseases, controlling vector-borne diseases, and managing the health risks associated with Hajj, climate change and its cascading impacts are increasingly threatening these gains.

Heat Related Health Impacts

To understand the direct and indirect impacts of climate change on health, it is instructive to review some of the key drivers. Foremost amongst these are changes in the air temperature. Under SSP2-4.5, the annual average temperature across the Arabian Peninsula is set to increase by 1.74°C and 2.87°C in the near future (2030–2059) and far future (2070–2099), respectively (relative to the period from 1981–2010)[1]. Nightly minimum temperatures are predicted to rise more quickly than daytime maximum temperatures, affecting the capacity for cooling. Temperature increases will be especially evident during the cooler winter months, reducing the respite from hotter periods of the year and extending the days per year where people experience very high heat (> 40°C)[2]. Increased temperatures will disproportionately impact people living in urban areas, due to the compounding impact of the urban heat island effect.

Heat exposure increases the incidence of heat stress, a condition where the body cannot regulate temperature to cool naturally, causing a variety of health impacts ranging in severity from mild but irritating concerns such as heat rash, to deadly conditions such as heat stroke. Importantly, heat related damage to organs and blood vessels can cause ongoing health impacts long after the body returns to normal temperature.

Exposure to extreme temperatures can also exacerbate existing health conditions, including cardiovascular and respiratory diseases, diabetes, kid-

Photo by Chris Lebout, Unsplash

ney conditions, and mental health concerns. Additionally, prolonged heat exposure is associated with pregnancy complications, and poor birth outcomes. Of particular concern is that even small deviations from average temperatures are associated with increased heat related morbidity and mortality[2]. Currently, the heat-related mortality rate in Saudi Arabia is 1.03/100,000 people[3]. In the absence of effective mitigation strategies, it is expected to rise to 44.9/100,000 people by the year 2100 under SSP2-4.5[3]. Indeed, it is anticipated that Saudi Arabia will experience a sharp rise in heat related mortality even under more conservative global warming estimates[3]. People most at risk from the health related impacts of increasing heat include the elderly (> 65), very young children, pregnant women, outdoor workers, and people with pre-existing medical conditions.

Air Quality

The air quality across the MENA region is consistently threatened due to recurrent pollutant levels that exceed WHO recommendations[4]. Natural dust, sandstorms and fires, together with anthropogenic sources emanating from transportation, industry, and other activities of urbanization, all contribute to the generally poor quality of air in Saudi Arabia.

Air pollution increases the general risk of mortality and the risk of death from specific diseases, including stroke and ischemic heart disease. Poor air quality is further linked to pregnancy complications, poor birth outcomes, increased infant mortality, and cognitive delays and chronic disease development in children.

The links between air pollutants such as particulate matter (PM2.5 and PM10), nitrogen oxides, sulfur oxides, volatile organic compounds, polycyclic aromatic hydrocarbons (PAHs) and poor health are well established by the scientific community[4]. Indeed, the International Agency for Research on Cancer (IARC) has classified outdoor pollution as a carcinogen[5] and long-term exposure to particulate matter, particularly PM2.5 is shown to contribute to the development of multiple cancer types[4].

Although there remains some model uncertainty, many projections indicate that dust and sandstorms may increase as temperature (and aridity) increases and precipitation becomes more variable[6]. Apart from their direct effect on air-quality, dust storms spread pollutants, allergens, and pathogenic microorganisms (bacteria and fungi), indirectly impacting respiratory health. Dust and sandstorms also cause acute eye irritation and limit visibility, resulting in hazardous driving conditions and increasing the frequency of traffic accidents.

Globally, air pollution contributes to millions of deaths, although disproportionately impacting the Western Mediterranean region. In Saudi Arabia, particulate matter alone contributes to 9% of the country’s mortality and accounted for more than 8500 deaths in 2017[7]. If no mitigation actions are taken, the mortality rate from particulate matter and other pollutants will likely continue to increase, due to the projected aging population, even after the predicted concentrations decrease during the second half of the century.

Climate influence on Infectious Diseases

Climate sensitive infectious diseases include any infectious agents that can be affected by variables associated with climate change, such as heat, precipitation, or extreme weather events. The high diversity in the types of infectious diseases as well as the broad modes of pathogen transmission (i.e., vectors, air droplets, food/water borne, direct contact) creates multiple pathways for climate change to impact infectious diseases. While 58% of infectious diseases known to infect humans are exacerbated by climate change[8], here we focus on vector-borne diseases (VBDs), diarrheal diseases, viral respiratory infections, and emerging infections (i.e. future pandemics).

Vector-Borne Diseases

FIGURE 1 →

Effects of climate change on vectors/pathogens, environment, population movement and economy.

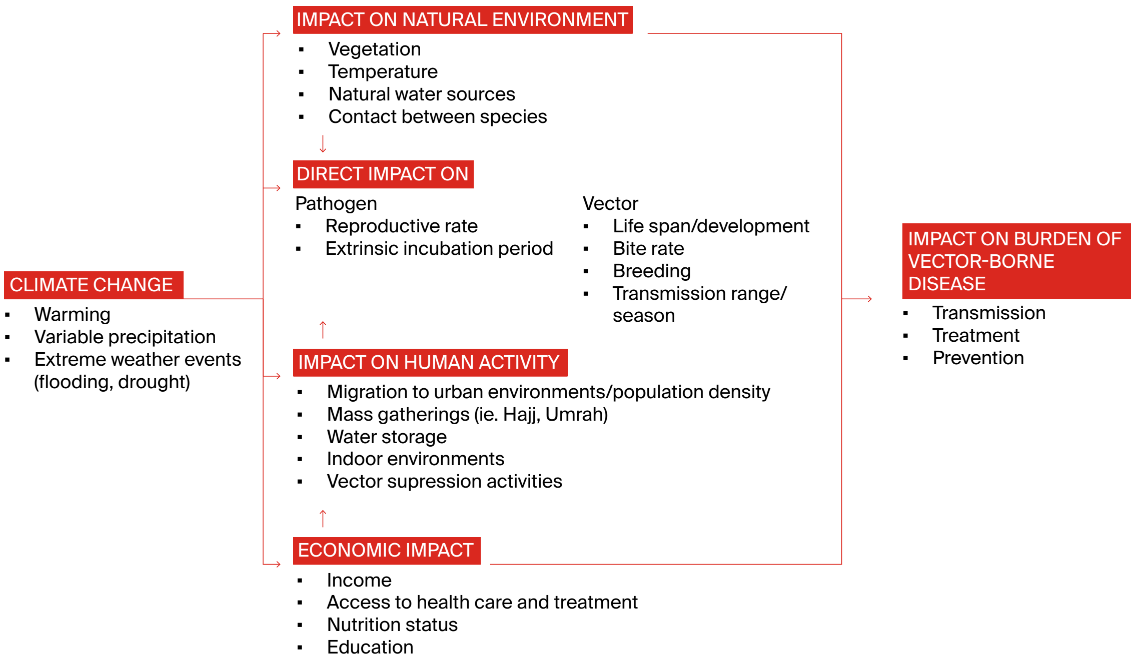
Vector-borne diseases (VBDs) are diseases that arise from the transmission of pathogens via vectors i.e. a living organism that transmits infectious agents to humans or other animals. Common vectors include mosquitoes, flies, ticks, and rodents. Climate changes, including temperature, humidity, and precipitation, can impact the transmission rate of VBDs by influencing the geographical areas under which vectors can survive and reproduce, as well as influencing their lifespan, and their biting rate. Changing climatic conditions can create environments suitable for known disease vectors in places where they had not been previously recorded, or allow for reemergence in areas where they had previously been eliminated. Conversely, climate change may render the environment unsuitable for certain vectors.

Non-climatic conditions such as urbanization and globalization also influence VBD transmissibility. In Saudi Arabia, the high number of religious pilgrims arriving for Hajj and Umrah is known to play a role in VBD incidence as a source of pathogen introduction. Pathogens and vectors are also highly adaptable and the complex interplay between climatic and non-climatic factors may influence evolution rates and the emergence of new VBDs.

The climatic conditions of the Middle East are conducive to the transmission of several VBDs, including malaria, dengue fever, Chikungunya, West Nile virus, and leishmaniasis. While these VBDs do not carry a high mortality rate in the Kingdom, they can present a high economic burden. The control of VBDs has been identified as a Health Transformation Sector initiative under Vision 2030 as the Kingdom works to reduce the incidence of these and other infectious diseases[9].

FIGURE 1

Effects of climate change on vectors/pathogens, environment, population movement and economy.



Modeling studies vary in their predictions concerning the impact that climate change will have on the variables driving VBDs in Saudi Arabia. Some studies predict a modest reduction in the risk from VBDs in the region, as rising temperatures are predicted to make conditions unsuitable for certain vectors[10]. However, these same studies acknowledge that the multiple factors by which climate change will impact the burden of VBDs in the region are difficult to measure and predict. Rapid urbanization may negate the impact of rising temperatures, particularly for Aedes aegypti mosquitoes, the vector responsible for dengue fever, Chikungunya, and other pathogens, as these mosquitoes thrive in urban environments. Of some concern is that these mosquitoes are well adapted to heat, are often found indoors, and breed in man-made containers.

Diarrheal Diseases

Diarrheal disease is prevalent throughout the world and is a leading cause of morbidity, mortality, and productivity loss in all age groups. Climate change will likely affect diarrheal disease incidence, especially by impacting water resources, as these diseases are commonly transmitted through contaminated water.

In addition to the impact of climate change on diarrheal disease via water-borne transmission, increasing ambient temperatures can impact food safety, influencing diarrheal disease incidence. Pathogens in food, such as salmonella and campylobacter, are influenced by temperature, with increasing heat linked to increasing incidence of diarrheal diseases.

Saudi Arabia enjoys a robust sanitation system and near universal access to potable water. As a result, disability adjusted life years (DALYs) lost to diarrheal diseases have steadily declined in Saudi Arabia over the last three decades[11]. However, there is a high risk of the incidence of diarrheal disease climbing as climate change impacts the availability of safe and secure sources of water in the Kingdom and throughout the region. Additionally, mass gatherings such as the Hajj increase the risk of diarrheal disease spread.

Viral respiratory infections

Respiratory infections are a leading cause of morbidity and mortality globally. The effects of climate change, expressed via increasing temperatures, air pollution, and rainfall variability are likely to increase the incidence of acute respiratory infections. Similarly, heatwaves increase the risk of morbidity and mortality from respiratory infections, particularly in children and people aged 65 and over. Expectations for Saudi Arabia suggest that rising temperatures may lead to increases in particulate matter and other air pollutants[6], further elevating the frequency, severity, and lethality of respiratory infections due to increased exposure to air pollution.

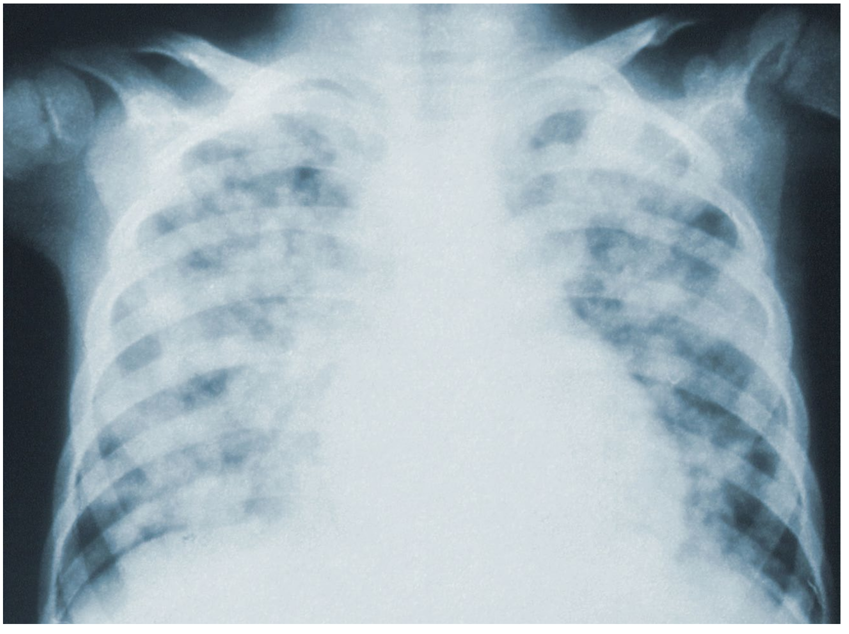


Image by Centers for Disease Control and Prevention (CDC)

The Kingdom has implemented effective infection control measures to support Hajj and Umrah pilgrims and, therefore, reduce the incidence of respiratory disease. However, respiratory infections are still a leading cause of sickness among Hajj pilgrims, with attendees experiencing symptoms after participation[12]. Strengthening infection control mitigation strategies will be required as climate change increases the risk of these infections.

Emerging infections—future pandemics

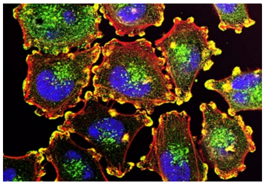
Higher temperatures, depleted water resources, ecosystem degradation, and habitat destruction, all influence the migration and ranging patterns of wild animals. With climate change exacerbating these drivers of animal movement, there is an increased risk of cross-species viral transmission: particularly between wild mammals and humans[13]. Increased interaction between previously separated species provides an opportunity for the emergence of novel pathogens, with the potential for zoonotic spillovers[13] (i.e. exchange of pathogens between animals and humans). These pathogens have the potential to spark localized epidemics or, as has been witnessed recently, devastating global pandemics. In Saudi Arabia, participants in Hajj and Umrah present an added dimension whereby novel pathogens can enter, spread within, and escape the region. Saudi Arabia has been impacted by multiple epidemics and pandemics in the past two decades, including the H1N1 influenza, Middle East respiratory syndrome coronavirus, and COVID-19. These diseases have had a significant impact on the health of the population and carried a large economic burden. The impacts of climate change will significantly increase the risk of regional epidemics and pandemics, with as of yet unknown health consequences.

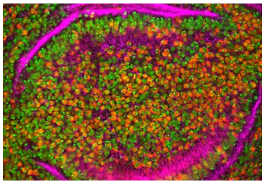
Non-Communicable Diseases

The effects of climate change, specifically increasing temperature and worsening air quality, can impact almost every bodily function and system, triggering or aggravating multiple common non-communicable health concerns. Non-communicable diseases (i.e. heart disease, cancer, diabetes) accounted for 73% of deaths and 66% of the total burden of disease in Saudi Arabia in 2016[11]. Understanding how climate change might impact the national health burden is a priority.

Cardiovascular disease

Cardiovascular disease represents the largest proportion of mortality in the Kingdom[14]. Exposure to extreme heat is associated with increased morbidity and mortality from cardiovascular diseases[2], with a 2.1% increase in cardiovascular disease-related mortality seen for every 1°C increase in temperature[15]. As noted previously, exposure to air pollutants is also associated with increased morbidity and mortality from ischemic heart disease





as well as exacerbation of pre-existing cardiovascular conditions.

Respiratory Diseases

Respiratory conditions such as chronic obstructive pulmonary disorder (COPD) and asthma are aggravated by extreme temperatures and exposure to pollutants. Hospitalizations related to respiratory diseases increase during and immediately following heat waves, particularly in elderly people. Exposure to pollutants is associated with the development of asthma, especially in children. In 2019, the prevalence of COPD in Saudi Arabia was 2053/100,000 people, almost a 50% increase since 1990[16]. Air pollution is the second greatest contributor to the burden of disease of COPD in the Middle East, after smoking[17] with PM2.5 responsible for 67/100,000 age standardized COPD deaths and 1438/100,000 DALYs in Saudi Arabia in 2016[4]. Asthma prevalence varies widely within the Kingdom, ranging between 3.5-33.6%. The weighted prevalence is estimated at 14.3% of the population[18]. Although incidence rates have remained steady in the Kingdom since the early 2000s[18], asthma remains a common cause of emergency room visits and lost productivity. The risk of COPD and asthma morbidity and mortality increase as the concentrations of PM2.5 and other pollutants increase.

Allergies and Autoimmune response

Allergies and autoimmune disorders have been on the rise globally for the last few decades. A link between changing climate and respiratory allergies is well established, with changes in temperature increasing the concentration of common allergens and air pollution. The role of climate change in the human inflammatory response is still being investigated. Exposure to heat and pollutants is linked with the disruption of the immune response and microbiota (specifically gut microbes) making a person more susceptible to respiratory and food allergies. This disruption has been linked to other autoimmune diseases such as Type 1 diabetes and multiple sclerosis.

Cancer

Cancer diagnoses and deaths have been climbing both in Saudi Arabia and across the world[14]. Exposure to common air pollutants is recognized as a contributor to lung cancer and breast cancer[4], the most common cancer in the Kingdom.

Mental Health

Mental health disorders have been on the rise in both Saudi Arabia and around the world over the last three decades[14], with depression and anxiety among the leading causes of disability in the Kingdom[19]. However, compared with other high-income countries, Saudi Arabia has fewer health care professionals and resources dedicated to mental health[19].

Cancer cells, images by National Cancer Institute (NCI)

While much of this increase may be attributed to improved mental health awareness combined with better diagnostic tools, there is a clear connection between physical and mental health. That is, negative physical health can cause mental distress, while people experiencing mental health strain often have physical health symptoms.

Higher temperatures have been linked to increased anxiety, depression, and suicide, while warmer periods can see an increase in the prevalence of behavioral problems like aggression and violence. There is evidence to suggest that people with pre-existing mental health problems are more likely to relapse or experience worsening symptoms during extreme heat events.

Life threatening extreme weather events or natural disasters, such as prolonged droughts and floods, increase the risk of post-traumatic stress disorder, anxiety, and depression[20]. People who have lost family, property, or livelihoods will experience associated grief. Droughts are significantly associated with suicide risk, particularly in the elderly and people working in agricultural sectors[20].

Additionally, the reality and knowledge of climate change is a major source of stress and distress for many individuals. Accessing news regarding climate change is associated with stress, depression, and feelings of powerlessness[20], exacerbating mental health impacts even for those not directly affected by climate change.

FIGURE 2 ↓

Reducing the impact on population health from rising temperatures.

A Healthy Future

The impacts associated with a warming climate threaten the considerable public health gains that Saudi Arabia has made over the past several decades. Increasing heat and ongoing exposure to pollutants will continue to compromise health while prematurely cutting lives short. However, the Kingdom has an opportunity to invest in climate change mitigation measures, such as enhancing bio-surveillance for existing and novel infectious diseases and their vectors, and designing public health campaigns to address knowledge of climate change on physical and mental health.

Applying evidence-based measures in the short term will help preserve the lives and health of future generations. Further, Saudi Arabia is in a position to become a global leader in under-researched areas such as investigating links between climate change and the onset of numerous health conditions such as the drivers of autoimmune disorders, cancers, and other health conditions, providing an invaluable resource in climate research regionally and beyond.

FIGURE 2

Reducing the impact on population health from rising temperatures.

CLIMATE CHANGES	IMPACTS ON HEALTH	RECOMMENDATIONS
INCREASED HEAT Annual average temperature is set to increase by 1.7 °C by 2050; 2.87°C by 2100	→ Heat stress related illnesses Conditions including heat rash, heat edema, heat cramps, heat exhaustion, and heat stroke; More serious conditions such as heat stroke can be fatal or cause lasting organ damage → Exacerbation of existing health conditions Increased morbidity and mortality for those with existing medical conditions including respiratory and cardiac conditions, diabetes and kidney disease → Mental health disorderd Increased anxiety, depression, increased incidence of suicide, aggressive behavior, and violence → Adverse pregnancy and birth outcomes	→ Investing in energy efficient infrastructure which minimizes heat emissions into the environment. → Creating green space initiatives, particularly in urban areas. → Increasing public health education in community regarding the dangers of heat-related illness. → Integrating heat health and safety into primary through tertiary curricula. → Identifying vulnerabilities in existing health care delivery systems; strengthening and supporting the health care sector to accommodate increased demands.
AIR QUALITY Concentration of pollutants dangerous to health will increase until mid-century then begin to decrease; dust and sandstorms will increase in frequency and severity	→ Increased risk of all-cause mortality → Increased morbidity and mortality from specific chronic health conditions → Development of cancers, especially lung cancer → Increased allergy development and symptoms → Poor pregnancy and birth outcomes; increased infant mortality → Increased traffic accidents	→ Further investing in renewable, clean energy → Adopting and planning robust and efficient public transportation systems. → Improving urban designs to create safe, walkable routes in urban areas.
CLIMATE SENSITIVE INFECTIOUS DISEASES 58% of infectious diseases known to infect humans are exacerbated by climate change	→ Vector-borne diseases (VBDs) Modeling studies vary in predictions, some common vectors are predicted to decrease → Increase in diarrheal diseases → Higher incidence of respiratory illnesses → Emergence of new infections Conditions will support the emergence of novel pathogens with pandemic/epidemic potential	→ Increasing public health information and programs related to climate sensitive disease control → Strengthening management of vectors → Further supporting research and development for VBD diagnosis, treatment, and vaccination → Improving bio-surveillance for vectors and associated pathogens → Supporting international efforts to enhance bio-surveillance networks for the early detection and response to novel pathogens

CLIMATE CHANGES	IMPACTS ON HEALTH	RECOMMENDATIONS
NON-COMMUNI-CABLE DISEASES Increases in heat and air pollution will likely increased the burden of disease from non-communicable diseases	→ Increased morbidity and mortality from cardiovascular conditions → Increased morbidity and mortality from respiratory conditions, particularly COPD and asthma → Increased prevalence of respiratory allergies → Possible increases in inflammatory and autoimmune disorders → Increased risk of cancer	→ Working to reduce the impact of heat and air quality on chronic conditions (see above) → Establish public health campaigns to improve knowledge about the risks of climate change on pre-existing health conditions → Strengthening existing health systems to meet the increasing demand posed by the impact of climate change → Supporting the research sector in elucidating the epidemiological connection between climate change and non-commu-nicable health conditions; working to establish Saudi Arabia as a global leader in this, as yet under-studied field
WATER AND FOOD SECURITY Increased evaporation, variable precipitation, and flooding will stress water resources, decreasing food production	→ Threatened hygiene Increases the risk of diarrheal and other diseases → Malnutrition Increases susceptibility to infectious diseases, exacerbates chronic conditions	→ Protect water and sanitation systems from contamination → Adopt robust water policies to encourage appropriate use of limited water resources → Integrate nutritional education that supports balanced diets into curricula of primary through tertiary education → Adapt strategies to reduce food waste
EXTREME WEATHER EVENTS Increased incidents of floods, droughts, and heat waves	→ Immediate loss of life or injury due to flooding → Increased diarrheal disease due to stressed and contaminated water resources → Increased vector activity following pooled water → Poor outcomes for people with chronic conditions	→ Develop early warning systems for extreme weather events → Adopt evidence-based disaster risk management strategies → Integrate robust structural measures (levies etc.) to protect against extreme weather events such floods → Improve urban designs to increase resilience to extreme weather events
MENTAL HEALTH Increases in heat and frequency of extreme weather events will likely increase the burden of disease from mental health conditions	→ Increases in anxiety, depression, post-traumatic stress disorder, and suicide → Increased incidence of violence and aggressive behavior → Exacerbation of existing mental health concerns → Grief symptoms	→ Strengthen the mental health sector to support the increased burden from climate change → Expanding training for mental health and health professionals to educate current and future practitioners on the impact of climate change on mental health

[1] Almazroui, M., Islam, M. N., Saeed, S., Saeed, F. & Ismail, M. Future Changes in Climate over the Arabian Peninsula based on CMIP6 Multimodel Simulations. Earth Systems and Environment 4, 611–630 (2020).

[2] Ebi, K. L. et al. Heat and Health 1—Hot weather and heat extremes: health risks. The Lancet 398, (2021).

[3] Hajat, S., Proestos, Y., Araya-Lopez, J. L., Economou, T. & Lelieveld, J. Current and future trends in heat-related mortality in the MENA region: a health impact assessment with bias-adjusted statistically downscaled CMIP6 (SSP-based) data and Bayesian inference. Lancet Planet Health 7, e282–e290 (2023).

[4] WHO. Ambient air pollution: A global assessment of exposure and burden of disease. https://apps.who.int/iris/bitstream/handle/10665/250141/9789241511353-eng.pdf (2016).

[5] IARC. PRESS RELEASE N° 221 IARC: Outdoor air pollution a leading environmental cause of cancer deaths. http://www.iarc.fr/en/publications/books/sp161/index.php (2013).

[6] Zittis, G. et al. Climate Change and Weather Extremes in the Eastern Mediterranean and Middle East. Reviews of Geophysics vol. 60 Preprint at https://doi.org/10.1029/2021RG000762 (2022).

[7] Rojas-Rueda, D. et al. Ambient particulate matter burden of disease in the Kingdom of Saudi Arabia. Environ Res 197, (2021).

[8] 8. Mora, C. et al. Over half of known human pathogenic diseases can be aggravated by climate change. Nat Clim Chang (2022) doi:10.1038/s41558-022-01426-1.

[9] Vision 2030. Health Sector Transformation Program Delivery Plan. https://www.vision2030.gov.sa/media/x3jbf45y/2021-2025-health-sector-transformation-program-delivery-plan-en.pdf (2020).

[10] Ryan, S. J., Carlson, C. J., Mordecai, E. A. & Johnson, L. R. Global expansion and redistribution of Aedes-borne virus transmission risk with climate change. PLoS Negl Trop Dis 13, (2018).

[11] Roser, M., Ritchie, H. & Spooner, F. Burden of disease. Our World in Data https://ourworldindata.org/burden-of-disease#citation (2021).

[12] Gautret, P., Benkouiten, S., Al-Tawfiq, J. A. & Memish, Z. A. Hajj-associated viral respiratory infections: A systematic review. Travel Medicine and Infectious Disease vol. 14 92–109 Preprint at https://doi.org/10.1016/j.tmaid.2015.12.008 (2016).

[13] Carlson, C. J. et al. Climate change increases cross-species viral transmission risk. Nature 607, 555–562 (2022).

[14] Tyrovolas, S. et al. The burden of disease in Saudi Arabia 1990–2017: results from the Global Burden of Disease Study 2017. Lancet Planet Health 4, e195–e208 (2020).

[15] Liu, J. et al. Heat exposure and cardiovascular health outcomes: a systematic review and meta-analysis. Lancet Planet Health 6, e484–e495 (2022).

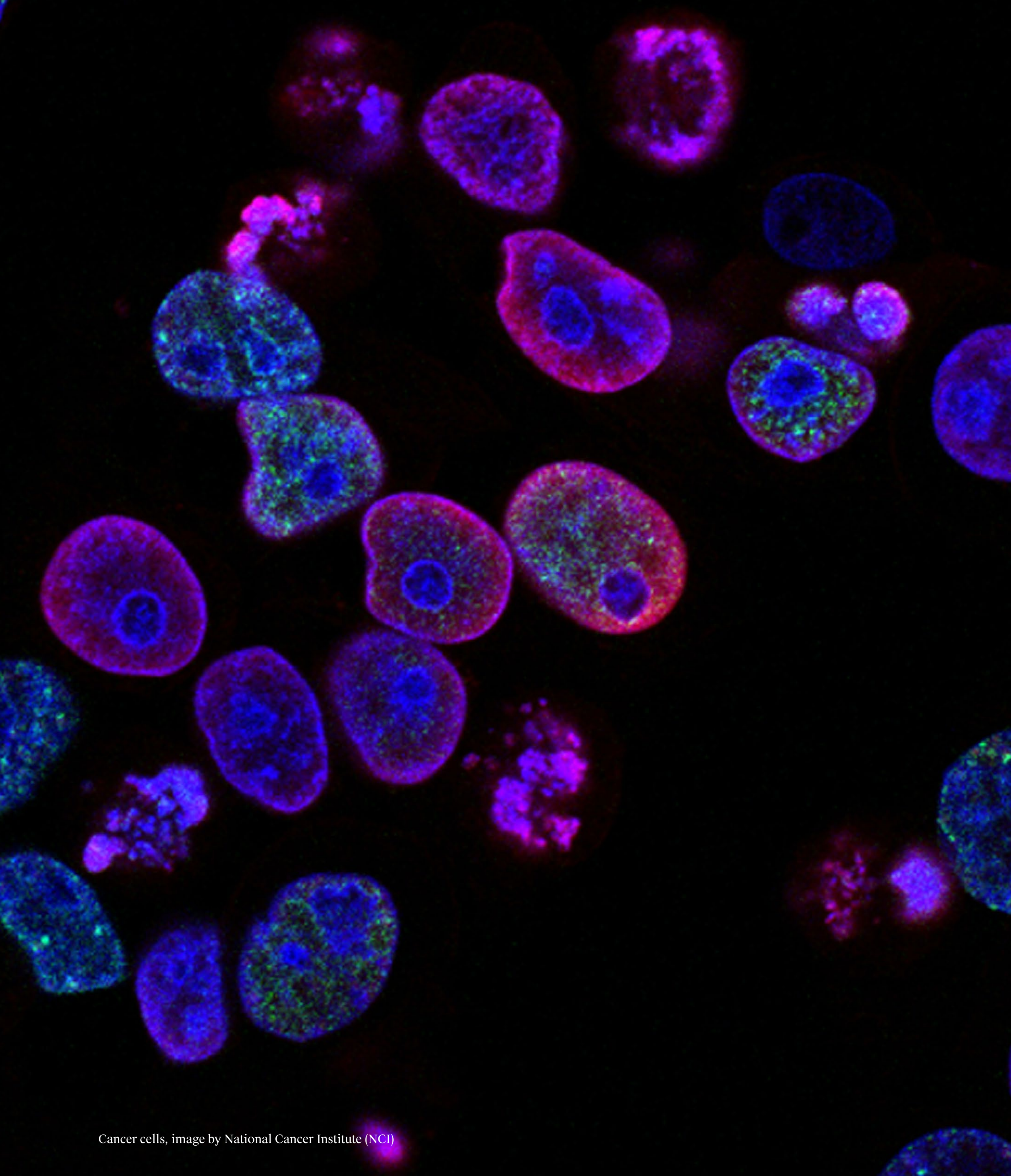
[16] Alqahtani, J. S. Prevalence, incidence, morbidity and mortality rates of COPD in Saudi Arabia: Trends in burden of COPD from 1990 to 2019. PLoS One 17, (2022).

[17] 17. Feizi, H. et al. The burden of chronic obstructive pulmonary disease and its attributable risk factors in the Middle East and North Africa region, 1990–2019. Respir Res 23, (2022).

[18] Hussain, S. M., Ayesha Farhana, S. & Alnasser, S. M. Time Trends and Regional Variation in Prevalence of Asthma and Associated Factors in Saudi Arabia: A Systematic Review and Meta-Analysis. BioMed Research International vol. 2018 Preprint at https://doi.org/10.1155/2018/8102527 (2018).

[19] Al-Subaie, A. S., Al-Habeeb, A. H. & Altwaijri, Y. A. Overview of the Saudi National Mental Health Survey. in International Journal of Methods in Psychiatric Research vol. 29 (John Wiley and Sons Ltd, 2020).

[20] Cianconi, P., Betrò, S. & Janiri, L. The Impact of Climate Change on Mental Health: A Systematic Descriptive Review. Front Psychiatry 11, (2020).



Cancer cells, image by National Cancer Institute (NCI)

“In this critical juncture, Saudi Arabia faces a momentous choice: to adapt and innovate in the face of climate adversity, or suffer the severe and potentially irrevocable consequences of inaction. ”

Prof. Matthew F. McCabe
Climate and Livability Initiative, Biological and Environmental Sciences and Engineering (BESE), King Abdullah University of Science and Technology (KAUST), Saudi Arabia

Navigating an Alternative Future

The potential impacts of a 3-degrees warmer world are complex and far-reaching. Preparing for them will require strategies that address the many multi-faceted influences and cross-sectoral challenges that such a scenario might impose. Few if any sectors can be considered in isolation, and the interconnected nature of modern societies hard-wire cascading effects that inevitably reverberate across national and international boundaries. Characterizing sectoral and cross-sectoral impacts provides a basis from which to guide policy, inform the development of adaptation and mitigation pathways, facilitate socio-economic modeling, and pave a pathway to develop more climate-adaptive and resilient natural, social, and economic systems.

To prepare for any challenge or adversity, it is prudent to identify the anticipated impacts and characterize the degree of associated risk. By doing so, we can be forewarned of what a possible and uncertain future might bring. In this context, climate change represents an imminent threat, and building a roadmap of pathways that capture the scope and scale of projected changes that a warming world might bring to Saudi Arabia is a national imperative. Armed with such knowledge, one can formulate strategies that address the specific consequences and decide, through targeted action, to chart a path that seeks to avert impending challenges.

Saudi Arabia faces a compounding set of climate driven impacts spanning our terrestrial and marine ecosystems, water and food security, urban livability, industrial and economic activity, and human health and wellbeing. These interrelated risks not only imperil the Kingdom's functional integrity, but also threaten its social and economic stability, making it crucial to not just examine the impending challenges, but also identify strategies and actions that may offer a pathway to an alternative climate future. While some of those emerging from this report are identified below, a comprehensive assessment of climate policies, solutions, and adaptation and mitigation strategies is required.

[A]

[B]

[A, B] Photo by NEOM on Unsplash

Terrestrial and Marine Ecosystems.

Saudi Arabia's rich and diverse natural systems are under threat from both anthropogenic and climate related stressors. Unabated, these pressures will reduce ecosystem capacity to absorb ongoing impacts, risking breakdown and collapse. While protection, restoration and rehabilitation efforts are critically important, targeted emission reduction is the only lever to ensure long-term ecosystem integrity. Key actions needed to enhance ecosystem resilience include:

- Investment in research, as well as in innovative approaches for restoration, rehabilitation, monitoring, and sustainable development is needed. Such efforts also need to include engagement with local communities and stakeholders, as is ensuring that local governance is strengthened by equipping authorities and stakeholders with the necessary scientific training, resources, and support required to manage and protect ecosystems;
- A catalog of the state of natural resources and biodiversity across Saudi's ecosystems, and implementation of long-term monitoring strategies to track changes in response to climate change and other human pressures. In parallel, accelerate the establishment of terrestrial and marine protected areas, controlling grazing in terrestrial systems and fishing in marine environments, and the development of an ecosystem accounting framework;
- Environmental awareness campaigns engage the public and instill a sense of responsibility and ownership for conservation and protection efforts. Likewise, implementing economic incentives for business and industry that prioritize sustainability and resource management encourages sustainable practices and

responsible consumption, advancing the goals of Saudi Vision 2030;

[A]

[B]

Water and Food Security

Saudi Arabia is one of the most water scarce nations in the world and decades of unsustainable groundwater extraction to support a domestic agricultural industry has exacerbated the water scarcity challenge. While desalination provides stability for household water needs, it comes with a significant energy and emissions burden. In light of local and global freshwater challenges, food security poses a major concern, particularly given the reliance on imported food. A shortfall in either water or food supply represents an unacceptable risk that challenges national security.

- Urgency is required to implement policies and processes to use water wisely. Current rates of consumption are unsustainable and utilization is not economical given the true cost and value of water. Putting a price on water has been shown to accelerate the adoption of water saving practices. Education and awareness also play an important role, with conservation and reduction measures, together with healthy diets and food waste management, all helping to drive a more efficient water-food sector;
- Climate changes and unsustainable groundwater extraction are impacting the stability of major food producing regions around the world. A diversity of import sources is required to manage risks and resilience in food supply. Recent international conflicts highlight the disruptive potential of geopolitical issues: which can also have a climate driver;
- Investment in aquaculture, smart agriculture, controlled environmental agriculture and the production of alternative food sources can all buffer potential changes in local and global food production. Policy changes will need to reflect domestic sustainability, global food import security and resilience to climate impacts.

Urban Systems and Livability

Located in one of the most urbanized regions in the world, Saudi Arabia is particularly vulnerable to the impacts of climate change, with extreme heat, deteriorating air quality, and flooding threatening the livability, health, and safety of urban populations. Interactions between these challenges highlight the complexity of urban climate resilience, with issues like extreme heat exacerbating air pollution and flooding creating conducive conditions for vector-borne diseases. Such connectivity underscores the need for holistic and integrated strategies:

- Resilient and adaptive measures are imperatives, particularly with regards to any urban planning and infrastructure development. Given the increasing energy footprint of modern cities, the adoption of climate-resilient energy systems, efficient cooling strategies, and climate adaptable infrastructure needs to be regulated

[A] Photo by Thomas Bermersch on Unsplash
[B] Photo by Lumin Osity on Usplash

in future developments;

- Urban areas should invest in early warning systems, evacuation plans, and disaster preparedness to protect citizens from extreme weather events like floods and storms, as well as prolonged heatwaves. Coastal cities will need to implement measures to mitigate the impacts of sea level rise and storm surges on infrastructure and the provision of services;
- Multifaceted solutions need to be guided by robust policies and integrated planning. Sustainable practices such as decarbonization, efficient resource use, and innovative technologies are key to mitigating climate-related challenges. A collaborative approach that involves policymakers, urban planners, industry stakeholders, and communities will be required. Embracing climate adaptive urban planning, promoting sustainable energy sources, and enhancing critical infrastructure will help create a more resilient and sustainable urban environment.

Energy and Industry

[A]

[B]

Despite serving as the backbone of the Saudi economy, there is a concerning gap in our understanding of how climate change will impact the energy and industrial sectors in the Kingdom.

- A dedicated national research program identifying and tracking the potential impacts of climate change on different sectors is needed. Aligned to this is the development of a framework to establish the economic value of early climate action (and cost of inaction), as well as an approach to incorporate climate impacts into planned mitigation strategies that can account for mitigation co-benefits that adaptation measures might provide;
- Given that energy and industrial sector investments generally last for decades, integrating climate impacts and climate change projections into financial decision making is vital to ensure the resilience of such investments to future climate conditions and to reduce their vulnerability to physical and transitional risks (i.e., stranded assets);
- Given the abundance of renewable resource potential in the Kingdom, continued investment into the electrification of “end-use” sectors (i.e. transportation, industrial, residential, and commercial sectors) as well as a diversification of energy sources (e.g., nuclear, hydrogen, alternative fuels) to support harder to abate sectors is required. Ultimately, nations will need to decarbonize their energy systems if we are to “drawdown” emissions that have accumulated in the atmosphere.

Health and Wellness

Anticipated climatic changes threaten human health through multiple pathways. Increases in average temperatures and worsening air quality will stress all bodily systems, inducing direct health concerns such

[A] Photo by Chttersnap on Usplash
[B] Photo by Ade on Unsplash

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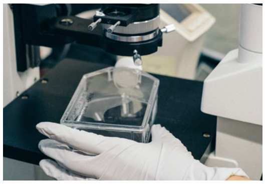

as heat stroke, and indirect issues including an increasing burden of chronic diseases such as heart disease, respiratory conditions, and cancers. Changing environmental conditions risk the spread of common communicable diseases such as viral respiratory infections and diarrheal contagions, increasing the incidence, morbidity, and mortality from these agents. Vector-borne diseases such as dengue, may also shift unpredictably, while there is a heightened risk of emergence in novel pathogens, potentially triggering the next pandemic. Targeted strategies and action will be required to combat these impacts:

- Considered urban planning can improve health outcomes, reduce the impact of rising heat and improve air quality. Evidence-based interventions include developing safe and efficient public transportation (to reduce high emission personal vehicles); incorporating green spaces to provide shade (which decreases heat related illness and mortality); and investing in energy efficient building designs that maintain optimal indoor temperatures while emitting minimal heat into the environment (reducing the energy footprint of the building sector);
- Invest in research to better understand the epidemiological connection between climate change and chronic conditions, establishing Saudi Arabia as a global leader in this under-studied, yet critical, field. In parallel, promote public health campaigns to raise awareness of the impacts that climate change (particularly climate extremes) can have on mental and physical wellbeing, educating people to recognize the early signs of heat related health concerns, particularly in at risk groups;
- Strengthen national efforts regarding infectious disease management and vector control, while participating in international collaborations to support bio-surveillance networks for the early detection and response to existing and novel pathogens, particularly those with epidemic and pandemic potential.

As Saudi Arabia and the world confront the impacts of a warming world, we must recognize the inherent interconnectedness of these challenges and prioritize integrated solutions. Strategies that are guided by robust policies and collaborations between stakeholders will be essential for building resilience and safeguarding the wellbeing of citizens. More generally, the adoption of systematic approaches across all of the different sectors explored herein will be needed to overcome potential trade-offs in climate actions, while maximizing synergies between them.

Left unchecked, climate change poses a significant threat to the global economy. Conversely, a swift transition to net-zero can help avoid some of the consequences described herein, while delivering economic gain over the coming decades. In this critical juncture, Saudi Arabia faces a momentous choice: to adapt and innovate in the face of climate adversity, or suffer the severe and potentially irrevocable consequences of inaction.

[A] Photo by Sultan Alhuthli on Unsplash
[B] Photo by Jaron Nix on Unsplash