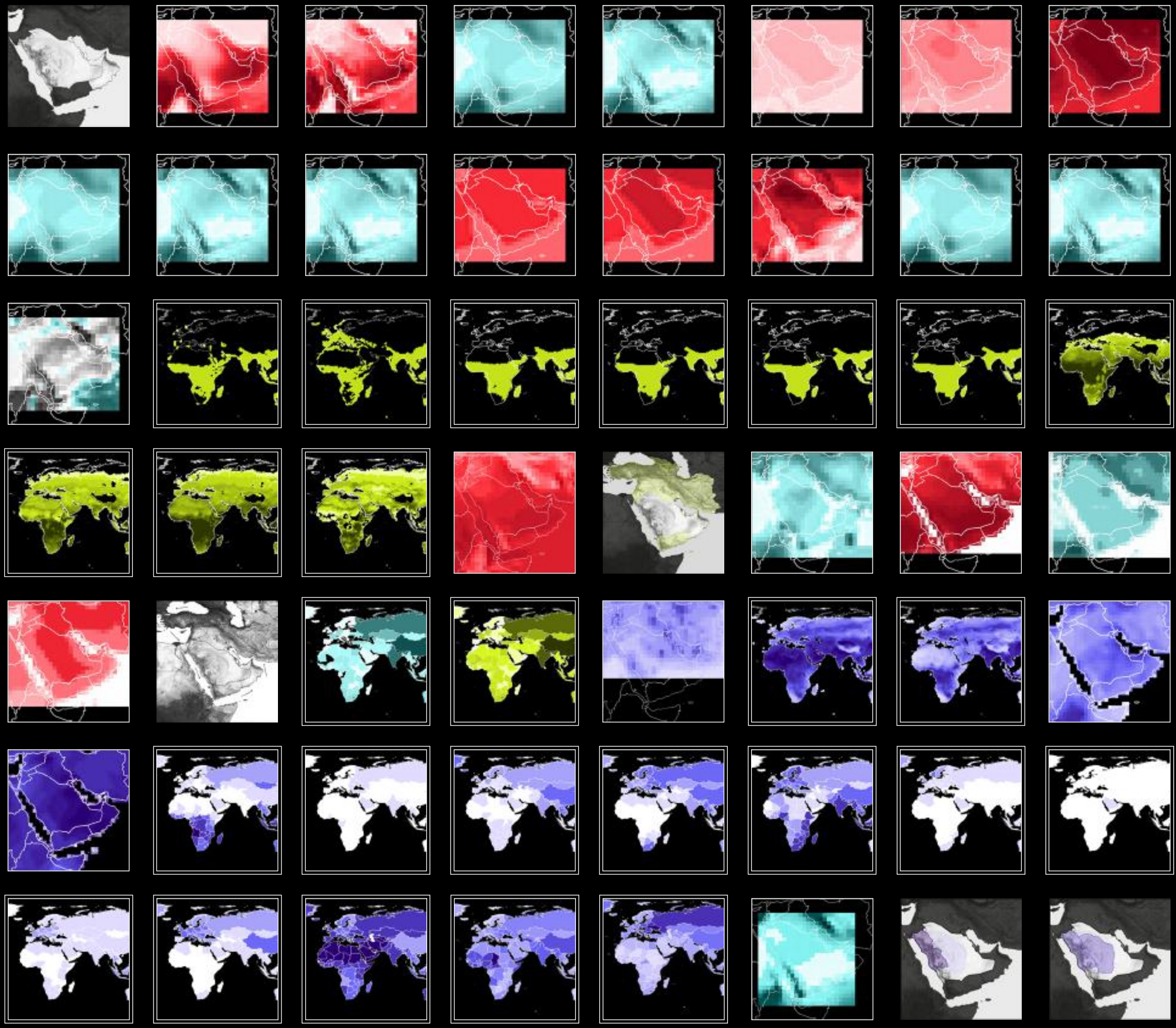

THE STATE OF CLIMATE AND HEALTH RESEARCH IN GCC

AEON COLLECTIVE X COMMUNITY JAMEEL

DESIGNED BY ACCURAT

DATE: MARCH 2022 | DOCUMENT: REPORT | REFERENCE NUMBER: CCH.I.RPT.001.V.1.0.

AEON COLLECTIVE

AEON Collective is a cross-disciplinary WAQF that produces, curates and disseminates fact-based & culturally informed knowledge around sustainability, actively building capacities for dynamic "knowledge communities" through diverse initiatives. Having played a leading role in support of the Kingdom's ambitious Net-Zero targets under the Saudi Green Initiative and the Circular Carbon Economy Framework, the Collective continues to advance its work in support of reaching and exceeding the stated targets. Under its flagship urban community-building program, The Tree Library, Aeon Collective aims to advance global action towards the socially & economically empowering theme of "Planetary Repair"; emboldening efforts to hasten sustainable human development and address the climate & biodiversity crises.

COMMUNITY JAMEEL

Community Jameel advances science to help communities thrive in a rapidly changing world. An independent, global organization, Community Jameel was launched in 2003 to continue the tradition of philanthropy and community service established by the Jameel family of Saudi Arabia in 1945. Community Jameel has led to significant breakthroughs and achievements, including the MIT Jameel Clinic's discovery of the new antibiotic Halicin, critical modeling of the spread of COVID-19 conducted by the Jameel Institute at Imperial College London, and a Nobel Prize-winning experimental approach to alleviating global poverty developed by the co-founders of the Abdul Latif Jameel Poverty Action Lab at MIT.

DESIGN & LAYOUT BY ACCURAT

Accurat is a new breed of full-service strategy and digital experience design firm, operating at the intersection of data, design, and technology. Accurat's own methodology and working philosophy —Data Humanism— strives to reconnect data to what it represents: knowledge, behaviors, people.

SUGGESTED CITATION

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LIST OF ACRONYMS

→	3D	Three-Dimensional
→	ABL	Atmospheric Boundary Layer
→	AC	Alternating Current
→	AERONET	The Global Atmospheric Model
→	AERONET	Aerosol Robotic Network
→	AIDS	Human Immunodeficiency Virus Infection And Acquired Immune Deficiency Syndrome
→	AOD	Aerosol Optical Depth
→	AP	Arabian Peninsula
→	AQMS	Air Quality Monitoring Stations
→	AQUA	-
→	AVHRR	Advanced Very High Resolution Radiometer
→	AVSD	Aerosol Volume Size Distribution
→	BC	Black Carbon
→	BPIP- PRIME	Building Profile Input Program Prime
→	CALIPSO	Cloud-Aerosol Lidar And Infrared Pathfinder Satellite Observations
→	CAMS-OA	Comprehensive Arthroscopic Management
→	CAMS-OA,	Copernicus Atmosphere Monitoring Service
→	cbr	Crude Birthrate
→	CC	Climate Change
→	CCPs	Climate Change Projections
→	CDD	Cooling Degree Days
→	CFD	Computational Fluid Dynamics
→	CH4	Methane
→	CIMEL	French Manufacturer Of Meteorological And Atmospheric Observation System
→	CMIP5	Coupled Model Intercomparison Project Phase-5
→	CMIP6	Coupled Model Intercomparison Project Phase-6
→	CO	Cobalt
→	COP	Conference Of Parties
→	COPD	Chronic Obstructive Pulmonary Disease
→	COPD	Chronic Obstructive Pulmonary Disease
→	CRF	Concentration-Response Functions
→	DALY	Disability-Adjusted Life Years
→	DB	Deep Blue

→	DISPER	-
→	DMS	Dimethyl Sulfide
→	DSSAT	Decision Support System For Agrotechnology Transfer
→	DUST	Dust Storms
→	EC	European Commission
→	ECMWF	European Centre For Medium-Range Weather Forecasts
→	EDGAR	Emission Database For Global Atmospheric Research
→	EEA	European Air Pollution Inventory Guidebook
→	EMAC	-
→	EMR	Astern Mediterranean Region
→	ENSO	El Niño-Southern Oscillation
→	ERA5	Fifth Generation Ecmwf Atmospheric Reanalysis Of The Global Climate Covering The Period From January 1950 To Present.
→	FLOW	-
→	FPU	-
→	GBD	Global Burden Of Disease
→	GCC	Gulf Cooperation Council
→	GCMs	Global Climate Models
→	GDP	Gross Domestic Product
→	GEMM	Global Exposure Mortality Model
→	GHG	Greenhouse Gases
→	GIS	Geographic Information System
→	GOCART	Goddard Global Ozone Chemistry Aerosol Radiation And Transport
→	GOCART-RACM	-
→	GSFC	Goddard Space Flight Center
→	GTAP	Global Trade, Assistance, And Production
→	GTAP 10	Global Trade, Assistance, And Production Version 10
→	GWh	Gigawatt Hours
→	H1N1	Hemagglutinin (H) And Neuraminidase (N)
→	HIST	-
→	HIV	Human Immunodeficiency Virus
→	HTAP-2.2	Hemispheric Transport Air Pollution
→	ICRC	The International Committee Of The Red Cross
→	IEA	International Energy Agency
→	IFPRI	International Food Policy Research Institute

→ IFS Integrated Forecast System
→ IHD Ischemic Heart Disease
→ IMPACT Integrated Manufacturing, Precision-Assembled, Cellular Technology
→ IPAT The Framework To Study Population (P) ,Affluence (A), And Technology (T) Impact (I) The Environment.
→ IPCC Intergovernmental Panel On Climate Change
→ J-PAL Jameel Poverty Action Lab
→ JJA June, July , And August
→ KAUST King Abdullah University Gf Science And Technology
→ KPP Kinetic Preprocessor
→ KSA Kingdom Of Saudi Arabia
→ KSA-PME Kingdom Of Saudi Arabia- Presidency Of Meteorology And Environment
→ kW Kilowatts
→ LC Lung Cancer
→ LUR Land Use Regression
→ MACC Monitoring Atmospheric Composition And Climate
→ MAIAC Multi-Angle Implementation Of Atmospheric Correction
→ MAX Maximum
→ ME Middle East
→ MECIDS The Middle East Consortium For Infectious Disease Surveillance
→ MECIDS -
→ MENA Middle East And North Africa
→ MERRA Modern-Era Retrospective Analysis For Research And Applications
→ MERS-CoV Middle East Respiratory Syndrome Coronavirus
→ MEWA Ministry Of Environment, Water And Agriculture
→ MISR Multiangle Imaging Spectroradiometer
→ MODIS Moderate Resolution Imaging Spectroradiometer
→ MODON Saudi Authority For Industrial Cities And Technology Zones
→ MR-BRT Meta-Regression Tool
→ MSA Methane Sulfonic Acid
→ NASA National Aeronautics And Space Administration
→ NH Northern Hemisphere
→ NINC No2 Related Asthma Incidence
→ NO2 Nitrogen Dioxide
→ NOAA NWS National Oceanic And Atmospheric Administration National Weather Service
→ NOx Nitrogen Oxides
→ O_3 Ozone
→ *OC* Organic Carbon
→ OGCMs Ocean General Circulation Models
→ *OM* Organic Matter
→ OMI Ozone Monitoring Instrument
→ OMI-HTAP Ozone Monitoring Instrument- Hemispheric Transport Air Pollution
→ PBL -
→ PM Airborne Particulate Matter
→ PM10 Particulate Matter

→ $PM_{2.5}$ Ambient Fine Particle Air Pollution
→ PTSD Post-Traumatic Stress Disorder
→ PV plants Photovoltaic Plant
→ RACM Regional Atmospheric Chemistry Mechanism
→ RCP Representative Concentration Pathways
→ RR Relative Risk
→ RRTMG Rapid Radiative Transfer Model
→ RSV Respiratory Syncytial Virus
→ *SEAS* Seas
→ SLCPs Short- Lived Climate Pollutants
→ SO2 Sulfur Dioxide
→ *SS* Sea Salt
→ SSP Shared Socioeconomic Pathways
→ TBE Tick-Borne Encephalitis
→ TERRA -
→ TFR Total Fertility Rate
→ TREM Transport Emission Model For Line Sources
→ UAE United Arab Emirates
→ UNFCC United Nations Framework Convention On Climate Change
→ UNICEF United Nations Children's Fund
→ URBAIR Urban Air
→ URVE Urban Vegetation
→ US-EPA Unites States- Environmental Protection Agency
→ USD He U.s. Dollar
→ UTC Coordinated Universal Time
→ UV radiation Ultraviolet Radiation
→ VADIS Pollutant Dispersion In The Atmosphere Under Variable Wind Conditions
→ VOCs Volatile Organic Compounds
→ WEF World Economic Forum
→ WHO World Health Organization
→ WRF-Chem Weather Research And Forecasting
→ YLD Years Lost Due To Disability
→ YLL Year Life Lost

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A

FORWARD

Science's innate strength is in its process. So when we often present science as a finalized product, a simple answer, we rob ourselves of the pleasure of the journey. A journey that holds invaluable lessons when tackling complex subjects like the one our report seeks.

We began this multidisciplinary effort in late 2019 in the spirit of knowledge-seeking, capturing a snapshot of the state of climate and health research on the GCC, giving equal value to what we do know and to what is still unknown.

Hidden within the threads of this report is the story of a resilient people that occupied corners of what seemed at times challenging and inhospitable lands. With the quick growth fueled by well managed resource-generated wealth and ingenuity, people of the GCC continue to thrive. In spite of being in a global hotspot of temperature increase, most of the effects have been unfelt, masked by shifting baselines, rapid development and widespread measures for adaptation.

In an ever changing and interconnected global system however, it is not only temperature increases that we must address. The threat of vector borne diseases, other non-communicable diseases, mental health and ensuring overall wellbeing highlight the importance of understanding the impacts and implications of a changing climate to better manage and mitigate potential health risks (regional & global).

It is also a chance to increase the region's resiliency to external shocks and highlight opportunities for urban planning, socio-economic and technological development.

This report equally serves as a nod of respect to pioneers, the authors (and reviewers) who sought to sprout an era of abundance instead of dearth. Knowledge is cumulative, and as such, actionable knowledge is what we collectively seek.

Finally, consider this an open invitation to the willing: to negate, add rigor, evolve, and further the report's findings, inspire action or even debate the question: what constitutes actionable science?

Mashael S. AlShalan and Noura T.A. Al-Saud
Co-Founders of Aeon Collective

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→	Jacopo Poletto	Lead Data Visualization Designer
→	Mariano Viola	Team Leader

CONTRIBUTING INSTITUTIONS

KING ABDULLAH UNIVERSITY OF SCIENCE & TECHNOLOGY:
KAUST advances science and technology through distinctive and collaborative research integrated with graduate education. They are a catalyst for innovation, economic development and social prosperity in Saudi Arabia and the world. They exist for the pursuit and advancement of scientific knowledge and its broad dissemination and benevolent application. They strive to enhance the welfare of society with a special focus on four areas of global significance – food, water, energy and the environment.
→ For more information: https://www.kaust.edu.sa/en/about/vision

MASSACHUSETTS INSTITUTE OF TECHNOLOGY:
Founded to accelerate the nation's industrial revolution, MIT is profoundly American. With ingenuity and drive, their graduates have invented fundamental technologies, launched new industries, and created millions of American jobs. At the same time, and without the slightest sense of contradiction, MIT is profoundly global. Their community gains tremendous strength as a magnet for talent from around the world. Through teaching, research, and innovation, MIT's exceptional community pursues its mission of service to the nation and the world.
→ For more information: https://www.mit.edu/about/

MRC CENTRE FOR GLOBAL INFECTIOUS DISEASE ANALYSIS, JAMEEL INSTITUTE, SCHOOL OF PUBLIC HEALTH, IMPERIAL COLLEGE LONDON, LONDON, UK:
The MRC Centre has close collaborative partnerships with public and global health agencies (notably the World Health Organization, where we are a Collaborating Center for Infectious Disease Modelling), governments and non-governmental bodies across the world.The MRC Centre was previously called the MRC Centre for Outbreak Analysis and Modelling. Reflecting their change in name, they are now increasing in size to have a broader focus, covering a wider range of disease areas, and five cross-cutting themes reflecting our revised structure; Outbreak Analysis and Modelling, Global Health Analytics, Vaccines, Antimicrobial Resistance, and Methods and Tools. With over 200 researchers, they are one of the largest centres of infectious disease modelling expertise. This gives them a unique capacity to respond to emerging threats such as Ebola and Zika with real-time analysis and predictive modelling – and to provide timely evidence-based input to urgent policy questions for major endemic diseases such as HIV, malaria and tuberculosis. Much of their work is highly interdisciplinary, spanning statistics, mathematical modelling, epidemiology, genetics, intervention science and health economics.
→ For more information: https://www.imperial.ac.uk/mrc-global-infectious-disease-analysis/about-us/

NATIONAL OBSERVATORY FOR WOMEN, PRINCESS NOURAH BINT ABDULRAHMAN UNIVERSITY:
Women's education in the Kingdom of Saudi Arabia has been receiving a great deal of care and attention, which has allowed Saudi women to take confident and steady steps toward realizing their aspirations and has given them the opportunity to demonstrate excellence in various fields. They have been able to stand out, not only at the domestic level, but also on the international stage, where Saudi women are becoming well-known scholars and intellectuals. They have made a name for themselves in international forums and in various fields of science, achieving success and proving themselves at least as competent as their peers in other developed countries. Princess Nourah bint Abdulrahman University is one of the successes of the care and attention that has been directed toward women's higher education.

→ For more information: https://www.pnu.edu.sa/en/Pages/UniversityHistory.aspx

THE UNIVERSITY OF BRITISH COLUMBIA, SCHOOL OF COMMUNITY AND REGIONAL PLANNING:
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→ For more information: https://scarp.ubc.ca/about-scarp-and-planning

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Since 2014, their investments in the MIT research community have developed transformative solutions to specific water and food sector problems, brought new technologies to market, built new knowledge from foundational research discoveries, and supported policies that are needed to ensure the resilient food and water supplies that humankind needs. In addition, they continue to grow the community of water and food researchers at MIT and the funding base to support them.
→ For more information: https://jwafs.mit.edu/about/impact

MAX PLANCK INSTITUTE FOR CHEMISTRY, MAINZ, GERMANY:
Current research at the Max Planck Institute for Chemistry in Mainz aims at an integral understanding of chemical processes in the Earth system, particularly in the atmosphere and biosphere. Investigations address a wide range of interactions between air, water, soil, life and climate in the course of Earth history up to today´s human-driven epoch, the Anthropocene. The Max Planck Institute for Chemistry is one of the two oldest institutes of the Max Planck Society. It was founded in 1912 as the Kaiser Wilhelm Institute for Chemistry in Berlin, and it was relocated to Mainz in 1949. Particularly well-known scientists in the Institute´s history are the Nobel laureates Richard Willstätter, Otto Hahn, and Paul Crutzen. In honor of the former director and president of the Max Planck Society, the Max Planck Institute for Chemistry also carries the epithet Otto Hahn Institute.
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→ For more information: https://www.ua.pt/en/structure

CESAM & DEPT OF ENVIRONMENT AND PLANNING, UNIVERSITY OF AVEIRO, PORTUGAL:
The Centre for Environmental and Marine Studies (CESAM) is a Research Unit of the University of Aveiro (UA) with the status of Laboratório Associado/Associated Laboratory since 2005, evaluated with the highest grade of Excellent since 2014. The mission of CESAM is to develop leading international research on environmental and marine sciences, following a multi-actor and multisectoral approach, framed into 4 multidisciplinary thematic lines, promoting scientific knowledge and the connection between science and policies.
→ For more information: http://www.cesam.ua.pt/?menu=89&language=eng&tabela=geral&postId=0

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They are a thriving university with a deep commitment to teaching and research excellence. Established in 1840 by the Church of England, everything we do is underpinned by an unrelenting commitment to our values. They are a community committed to making a difference, passionate about seeing individuals and communities flourish. Their values of Compassion, Individuals Matter and Spirituality shape how they do this and why – they believe academic freedom leads to big ideas which in turn lead to social justice and creativity for a better world.
→ For more information: https://www.winchester.ac.uk/about-us/

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→ For more information: https://aeoncollective.org/about

NAIF ARAB UNIVERSITY FOR SECURITY SCIENCES:

Within the framework of the Arab endeavor towards achieving integration of joint efforts in the field of combating and preventing crime and misconduct, and in supporting the fields of criminal justice, the urgent need has emerged for the establishment of an academic entity that covers joint Arab security work.

→ For more information: https://nauss.edu.sa/en-us/about-nauss/Pages/about.aspx

REPORT OVERVIEW

PURPOSE

The state of climate and health research in the GCC report provides a snapshot of the most current research on the state of climate and health in the GCC, giving equal value to what we do know, as well as what is still unknown. This report also highlights the need for further research and additional data as well as access to restricted existing data that would bring to light new science-backed evidence upon which policymakers could design sound policies and support their decision making.

STRUCTURE

The report includes 14 chapters on various topics divided into 3 main sections, 2 supporting ones and a closing note.

→ Main Sections: Climate Science, Climate Impact, and Questions Arising
→ Supporting Sections: Policy Insights, Technical Annex.
→ Closing Note: Role of Culture & the Arts.

Each chapter begins with key messages and ends with preliminary areas for further research identified by the authors of the chapters as well as members of the editorial team.

→ CLIMATE SCIENCE: reports the historical trends in temperature and various thermal indicators from 1979-2019 in the GCC and current future projection of the climate in the Arabian Peninsula over the next few decades.
→ CLIMATE IMPACTS: summarizes the evidence and implications of the climate impacts on varying human health outcomes including communicable diseases, women's health, and public health within local contexts. Section also covers the observed and modeled air pollution over the GCC and the broader Middle East region and their health impacts on years of life lost in the major cities of the KSA.
→ QUESTIONS ARISING: highlights emerging evidence of the impact of climate change on critical global issues such as mental health, impacts of changes in biodiversity on health, climate migration, food production, etc.
→ POLICY INSIGHTS: selected policy insights from J-PAL on topics discussed in some chapters such as cash and in kind transfers in support of low income communities as well as regulations targeting air pollution.
→ TECHNICAL ANNEX: provides information on water resources (water consumption, agricultural water) and impact of climate change on the energy sector in Saudi Arabia, helping further contextualizing some of the findings in the Climate Impacts Section.
→ ROLE OF CULTURE & THE ARTS: explores their role in furthering our understanding of complex topics, innate healing ability, and being an effective communication premise and tool in a time of multiple global stressors.

SOME AREAS FOR IMPROVEMENT

→ GENERAL: in addition to the dearth of available research and data on the region, it is worth noting inconsistencies in use of variables in the literature. Given that this document is a snapshot of the most current research, different authors chose to use different variables to measure the same data points e.g. Wet-Bulb vs Heat Index.
→ 1.1 STATE OF CLIMATE CHANGE AND HEALTH IN THE GCC: 1979-2019 TRENDS IN TEMPERATURE, HEAT INDEX, AND COOLING DEGREE DAYS: An updated version of this section (currently in the review process) will be released in the coming months to include data points from ERA5 ranging from 1950 to 2021 for more robust results.
→ 4. POLICY INSIGHTS: Sound policy is to be built on actionable science, several collaborations have been initiated to build

upon the current insights as well as building on future more developed ones.

INSTITUTIONALIZATION

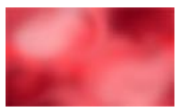
This report takes a first step at advocating for the need to institutionalize GCC wide research on the topic of a changing climate's implications on overall wellbeing. Further efforts to explore climate science, and its implications on health, livability among other topics would be best served if there were coordinated regional efforts.

NAVIGATING THE CONTENT

SECTIONS AND COLORS

The report includes 14 chapters related to 4 main macro-topics. Each chapter starts with a double spread gradient cover page, allowing the reader to relate the content thematically before diving into the content. The themes are color coded as follows:

Temperature
Water & Precipitations
Food & Health
Energy & Pollution
Others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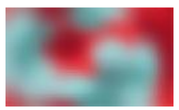
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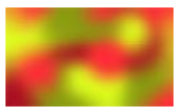
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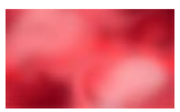
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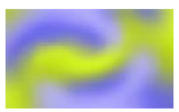
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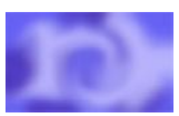
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FIGURES AND TABLES

The four core colors have been selected to work in harmony and to differentiate information without undue effort or visual stress while reading the chart. Thus, each chart comes in a color shade that identifies the topic of the data, while maximizing readability at the same time.

FIGURE 1 Example of each main topic color shade applied to a visual model.

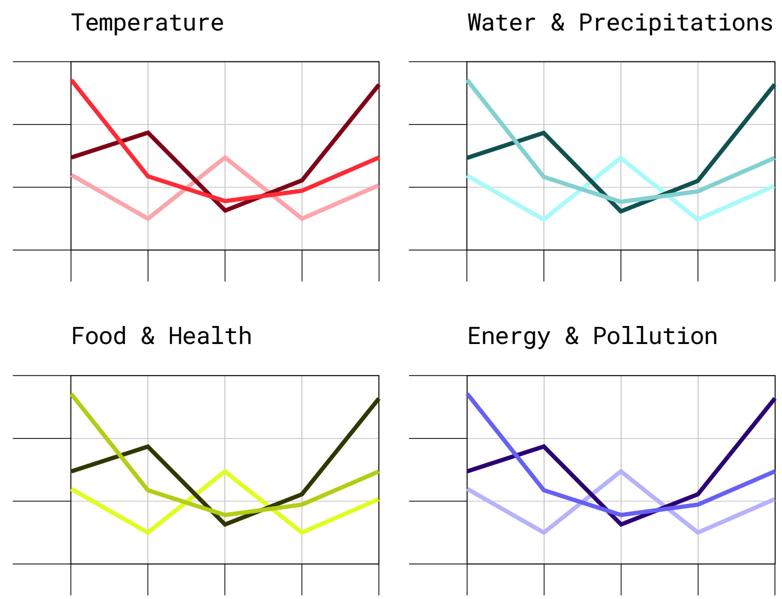
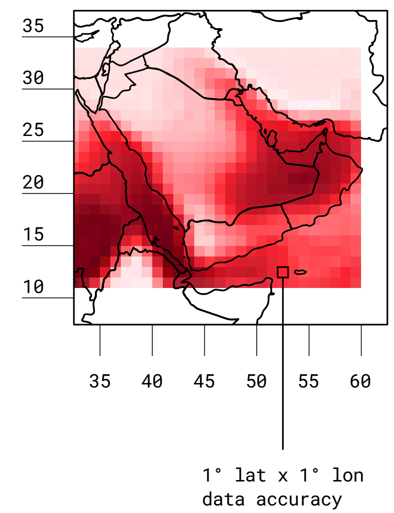


FIGURE 2 Binned map accuracy.



EXECUTIVE SUMMARY

This report presents a snapshot of the latest interdisciplinary research on climate change and health in the GCC.

OVERVIEW

CLIMATE CHANGE AFFECTS GCC COUNTRIES IN VARIOUS WAYS AND, IF NOT COMPREHENSIVELY ADDRESSED, COULD YIELD NEGATIVE IMPACTS ON THE HEALTH OF ITS INHABITANTS AND THE ECONOMY.

FURTHER RESEARCH IS REQUIRED TO BETTER UNDERSTAND AND ASSESS ASSOCIATED RISKS, OPPORTUNITIES AND THE APPROPRIATE POLICY INTERVENTIONS.

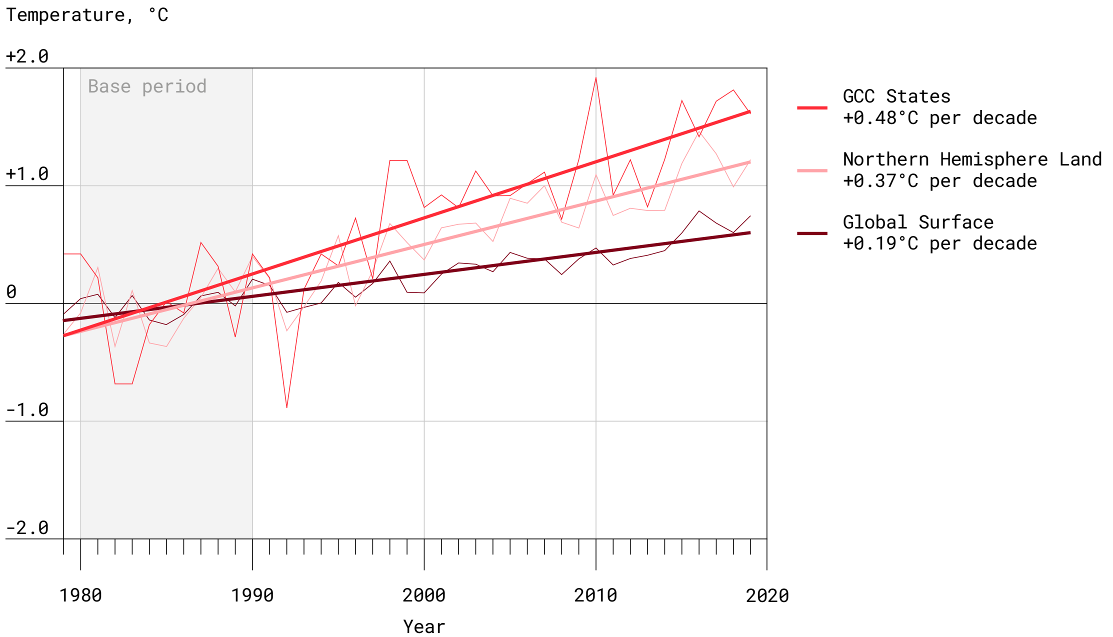
Climate science covers a wide range of topics, from the study of how greenhouse gasses trap heat in the atmosphere, to the study of the impact of climate change on human societies, with a growing body of evidence suggesting that climate change is negatively impacting human health and wellbeing.

The Gulf Cooperation Council (GCC) has been affected by historic climate change. Over the past four decades, the region has experienced an increase in average temperatures, which has led to higher summer temperatures and more frequent and intense heat waves. While the region has also experienced an increase in the intensity and frequency of dust storms, most of that is currently not directly attributed to anthropogenic climate change.

Climate change in the GCC is projected to increase the frequency and intensity of extreme weather events, which could lead to increased morbidity and mortality. Heat waves, for example, are expected to become more common and more intense, leading to increased cases of heat-related illness, such as heat exhaustion and heat stroke. In addition, climate change is expected to exacerbate existing health problems in the region, such as respiratory problems and cardiovascular disease. The increased levels of dust and pollen in the air, as well as the higher temperatures, can trigger asthma attacks and other respiratory problems. Increased heat can equally put strain on the cardiovascular system, leading to an increased risk of heart attacks and strokes.

The level of climate change related data and its granularity is particularly scant in the GCC states, with even fewer studies conducted on its impacts. Since most research has been conducted at the global level, identifying the Gulf region as a specific geographic area of study in climate change scenarios would be useful for sound planning and policy making. At present, there is a need for more research on the health impacts of climate change in the GCC in order to develop effective mitigation and adaptation strategies to protect the health of the population in the face of climate change. Additional focus should also be placed on the impacts climate change would have on women's health and mental health.

FIGURE 1 Global surface air temperature anomalies (land and ocean), Northern Hemisphere Land air temperature anomalies and average temperature anomalies over GCC states land area for the period 1979-2019 and linear trends.



Notes: Based on ERA5 dataset[2]. Temperature anomaly is the difference from the average temperature over a 1980-1990 period.

KEY TAKEAWAYS

HISTORIC & FUTURE CLIMATE CHANGE IN THE GCC

→ **MORE RESEARCH IS NEEDED TO BETTER UNDERSTAND THE DYNAMICS OF CURRENT AND FUTURE CLIMATE CHANGE IN THE GCC.**

Global mean temperature has increased by around +0.19°C per decade from 1979. The GCC is a global hotspot for rising temperatures, with the rate of warming exceeding the global land average by a factor of two (+0.48°C) FIGURE 1 . The trends in climate derived from the global climate reanalysis data such as ERA5 indicate increases in various temperature indices such as annual temperature, summer temperature, heat index (i.e., "feels like" temperature), the number of days with dangerous heat conditions, and cooling degree days in the GCC from 1979-2019.

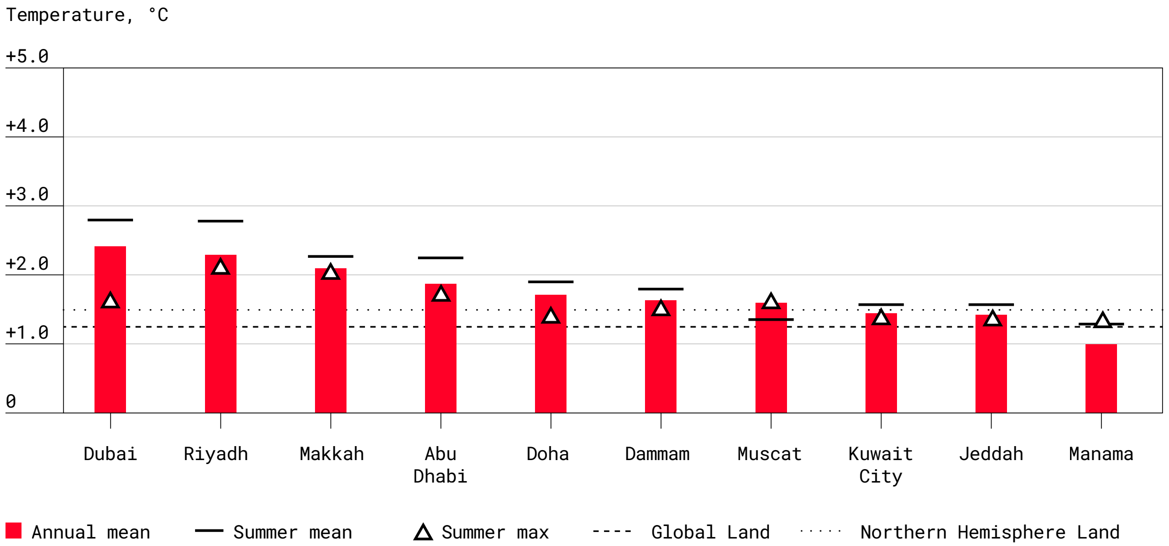
Some GCC cities such as Manama and Dubai saw average annual temperature changes in the range from 1.0 to 2.4°C. The heat index, which takes into account the effect of humidity on perceived temperature, is climbing even faster than the temperature itself FIGURE 2.

Future projection of global climate models may be subject to significant uncertainties due to various factors such as unresolved physics, imperfect parametrizations, coarse resolution, and limited observational datasets. So while most of the globally-relevant conclusions such as increasing trends in global temperatures are suggested to remain robust, the challenge comes at the local scales. Reliable spatiotemporal information about temperature and precipitation at the sub-district level under climate change conditions is critical for strategizing and developing future plans for adaptation and mitigation at the regional level. Improved resolution and downscaling with a regional model using suitable and regionally-tuned physics could reduce some of the biases in the current global models. The dynamical variations behind reported changes in temperature and rainfall patterns over KSA for example are not yet fully understood.

Within local contexts, the Coupled Model Intercomparison Project Phase-6 projections (CMIP6) estimate the climate change in the Arabian Peninsula (AP) in the next few decades. The projection indicates that the average temperature is expected to increase by 1-3°C in 2021-2060, while the annual mean precipitation is projected to increase by 25-120 mm and less than 30 mm, respectively, in the southwest AP and the rest of the region in the same time period FIGURE 3. In the long term (2081-2100), the average temperature is expected to rise by more than 5°C and the annual mean precipitation is projected to increase more than 120mm. These changes could lead to more frequent and intense heat waves and dust storms. There is a need for more research to understand how changes in heat wave intensity and frequency could pose a risk of increased number of heat strokes and possibly fatalities.

FIGURE 2 Increase in annual mean, summer mean, summer daily maximum temperature and Heat Index between 1979 and 2019, compared with the Global land and the Northern Hemisphere Land surface temperature increase over the same period of time.

A. TEMPERATURE INCREASE, 1979-2019



B. ANNUAL HEAT INDEX INCREASE, 1979-2019

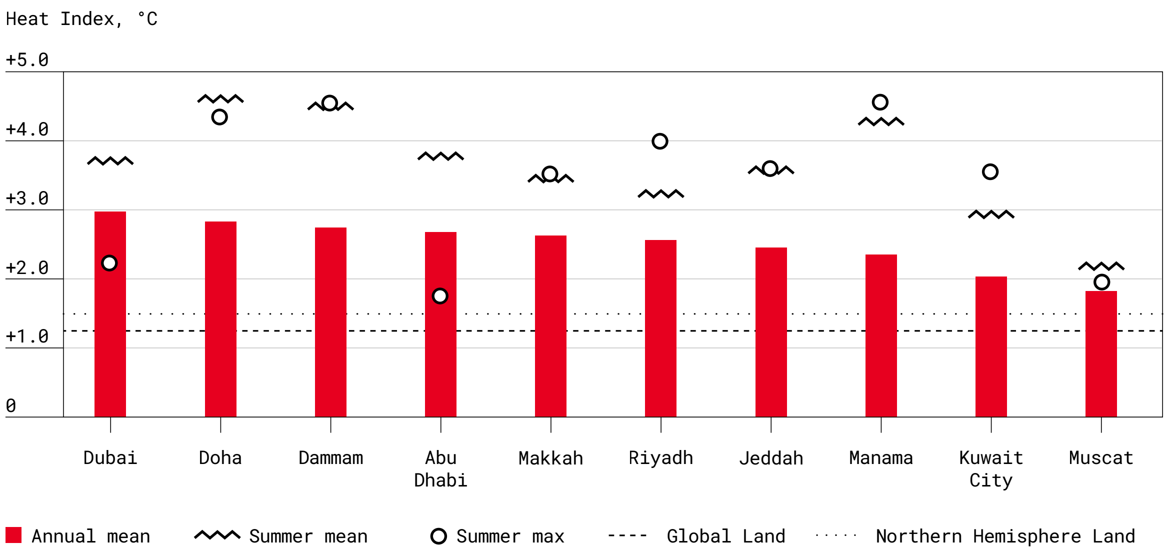
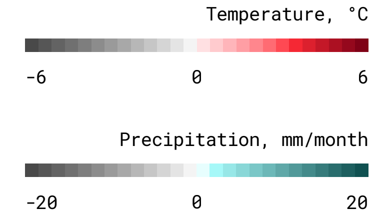
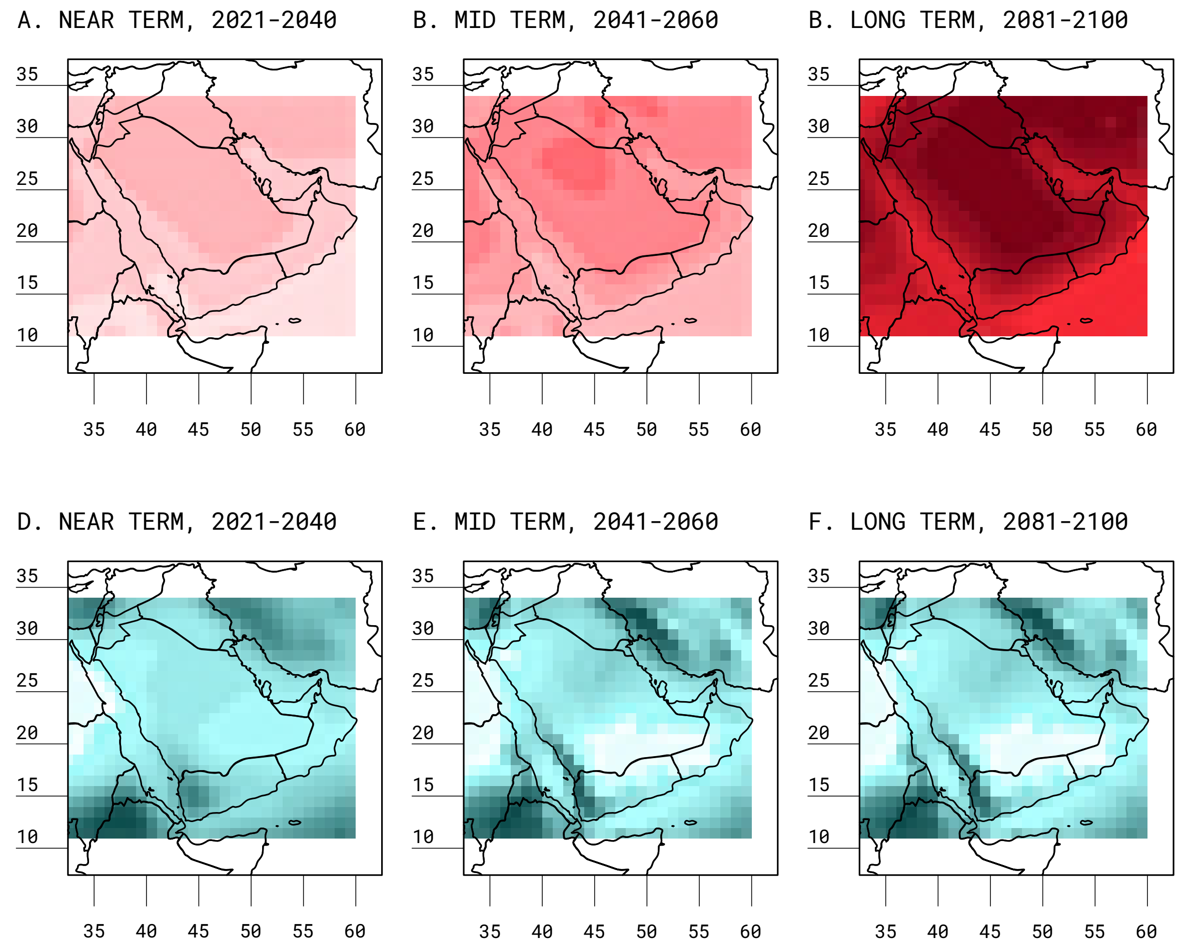


FIGURE 3 Spatial variation of projected changes in annual mean temperature and precipitation over the Arabian Peninsula for the near-term, mid-term, and long-term under the strong climate change scenario (SSP5-8.5), compared to the present climate (1986-2005), using the multi-model mean of 17 statistically independent CMIP6 GCMs.





Understanding potential risk associated with climate change impacts in the GCC and exploring preliminary pathways for adaptation

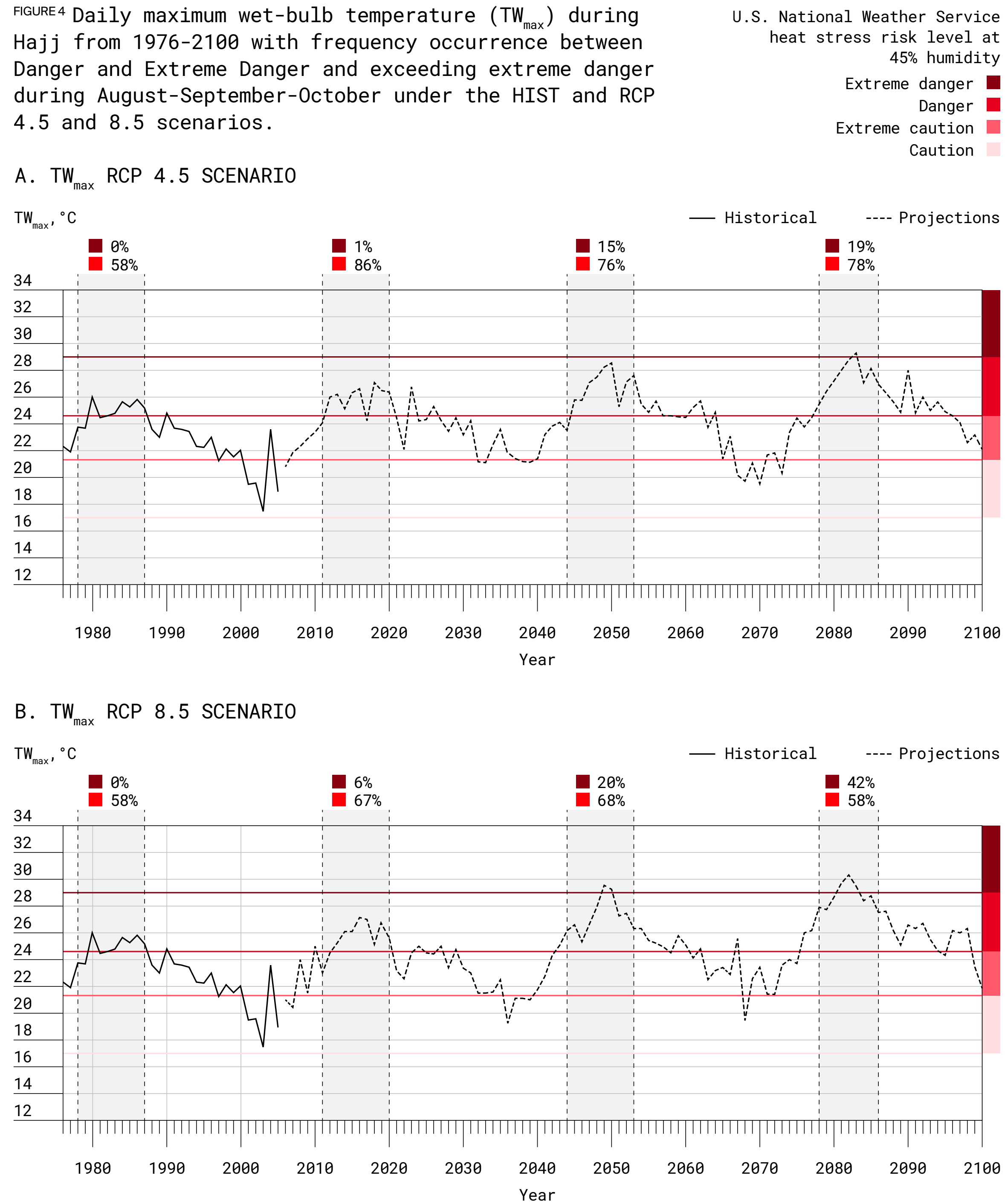
→ **HEAT STRESS COULD POSE A SIGNIFICANT RISK FOR THE VULNERABLE PERFORMING HAJJ. TO BETTER INFORM THE GOVERNMENT'S PLANNING EFFORTS, FURTHER RESEARCH IS NEEDED TO QUANTIFY HOW CHANGES IN HEATWAVE INTENSITY & FREQUENCY WOULD IMPACT PILGRIMS & HAJJ INFRASTRUCTURE.**

Makkah where the Hajj rituals are performed every year would experience significant humid heat waves under climate change, which may pose a significant health risk especially to the elderly performing Hajj. The two to three million pilgrims participating in Hajj and performing outdoor activities every year for 2 to 3 weeks could face health risks due to the increases in the intensity and duration of the natural hazards. Future climate change - with or without mitigation - will elevate heat stress to levels that exceed extreme danger threshold during the high-risk decades of 2047-2052 and 2079-2086, with increasing frequency and intensity as the century progresses [FIGURE 4].

The human health risk during Hajj depends on both the intensity and duration of the natural hazard as well as the level of vulnerability of the pilgrims in any specific year. Factors that shape this vulnerability include structural factors such as the capacity of the Hajj facilities and quality of transportation logistics as well as nonstructural factors such as the age distribution, health, and number of pilgrims.

Over the years, and particularly in recent years, hajj facilities, logistics and planning have been significantly expanded and improved to help provide refuge from extreme weather conditions and overcrowding. Similar and perhaps more aggressive efforts are likely to happen in the future. Further research is needed to support sound and sustainable strategies to manage the nonstructural human vulnerability factors, particularly during the high risk decades.

FIGURE 4 Daily maximum wet-bulb temperature (TW_{max}) during Hajj from 1976-2100 with frequency occurrence between Danger and Extreme Danger and exceeding extreme danger during August-September-October under the HIST and RCP 4.5 and 8.5 scenarios.



Source: Kang and Eltahir, 2019[2].

→ SPREAD OF COMMUNICABLE DISEASES WILL BE SIGNIFICANTLY IMPACTED BY THE CLIMATE CRISIS

The increased temperatures due to climate change are favorable for the transmission of the vector-borne diseases, and the GCC with the expected increases in temperature may experience increases in communicable diseases and excess mortality. However, the true extent of such impacts is not yet known due to the lack of comprehensive research in the GCC. There are several areas that require further research in order to improve forecasting of climate and disease in the GCC. First, targeted gathering of climate and disease data within the GCC will allow for more accurate forecasts. Second, bespoke mechanistic modeling studies of epidemiological systems need to be conducted in order to more accurately assess the impact of expatriate movement on disease transmission. Finally, ecological surveys of disease vectors in the region are needed in order to assess the risk of vector-borne diseases.

→ CLIMATE CHANGE HAS DISPROPORTIONATE IMPACTS ON WOMEN

As climate change deepens existing inequalities, women & children may face increased rates of violence, displacement & poverty. Climate change may disrupt women's maternal, sexual, and reproductive health. Focus should be placed on understanding the impacts of climate change on women's health in the GCC region.

Collaboration platforms that have come into being to address climate change at the national, regional, and global scale must consider implementing a system for the correlation of climate data with gender-disaggregated health data. Endeavors such as the Saudi Green Initiative and the Middle East Green Initiative could provide opportunities to better and more directly assess the impact of climate change on health and well-being. This would not only identify gaps in knowledge and policies, but would also pave the way to evidence-based planning and public awareness on how to best tackle effects of climate change on women's health.

TABLE 1 Vulnerability index for key food commodities by GCC and West Asian Countries.

Region	Country	Grains	Rice	Fruits and Veg	Oilseeds	Meat and Milk	Pr. Foods
GCC	Bahrain	12	0	5	14	6	3
	Kuwait	33	18	6	25	7	4
	Oman	21	0	6	49	7	3
	Qatar	11	0	4	12	6	3
	Saudi Arabia	8	32	3	25	5	2
	United Arab Emirates	19	12	2	25	5	0
Rest of West Asia	Armenia	3	0	0	4	0	0
	Azerbaijan	5	0	0	1	1	1
	Georgia	20	11	0	29	2	0
	IM	5	0	0	3	0	2
	Israel	20	5	0	13	0	1
	Jordan	20	4	0	20	3	2
	Turkey	4	6	0	7	0	0
	Rest of West Asia	2	0	1	2	1	1

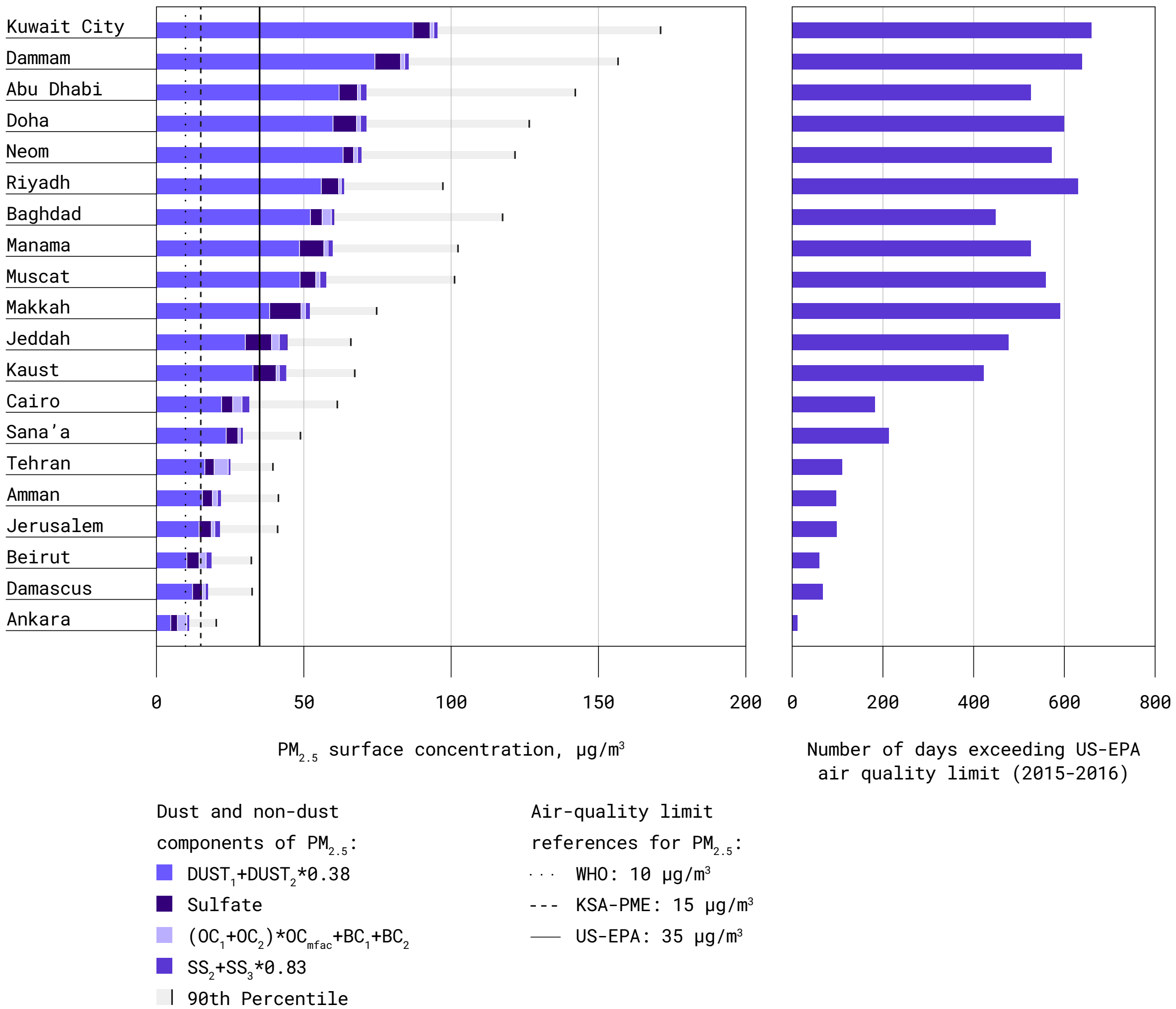
Low Vulnerability (0-5) Medium Vulnerability (6-10)
High Vulnerability (11-15) Severe Vulnerability (>15)

Source: Aguiar et al. 2019. Author calculations for rice from: United Nations 2022; FAO 2022.

Note: Vulnerability Index is created by dividing the percent of total demand for food commodity met from imports by the number of countries suppling ~80% of imports. Rest of West Asia includes Iraq, Lebanon, Palestinian Territory, Syria and Yemen.

FIGURE 5 Annual mean 2015-2016 PM surface concentrations calculated for the ME major cities and PM decomposition into dust and non-dust components.

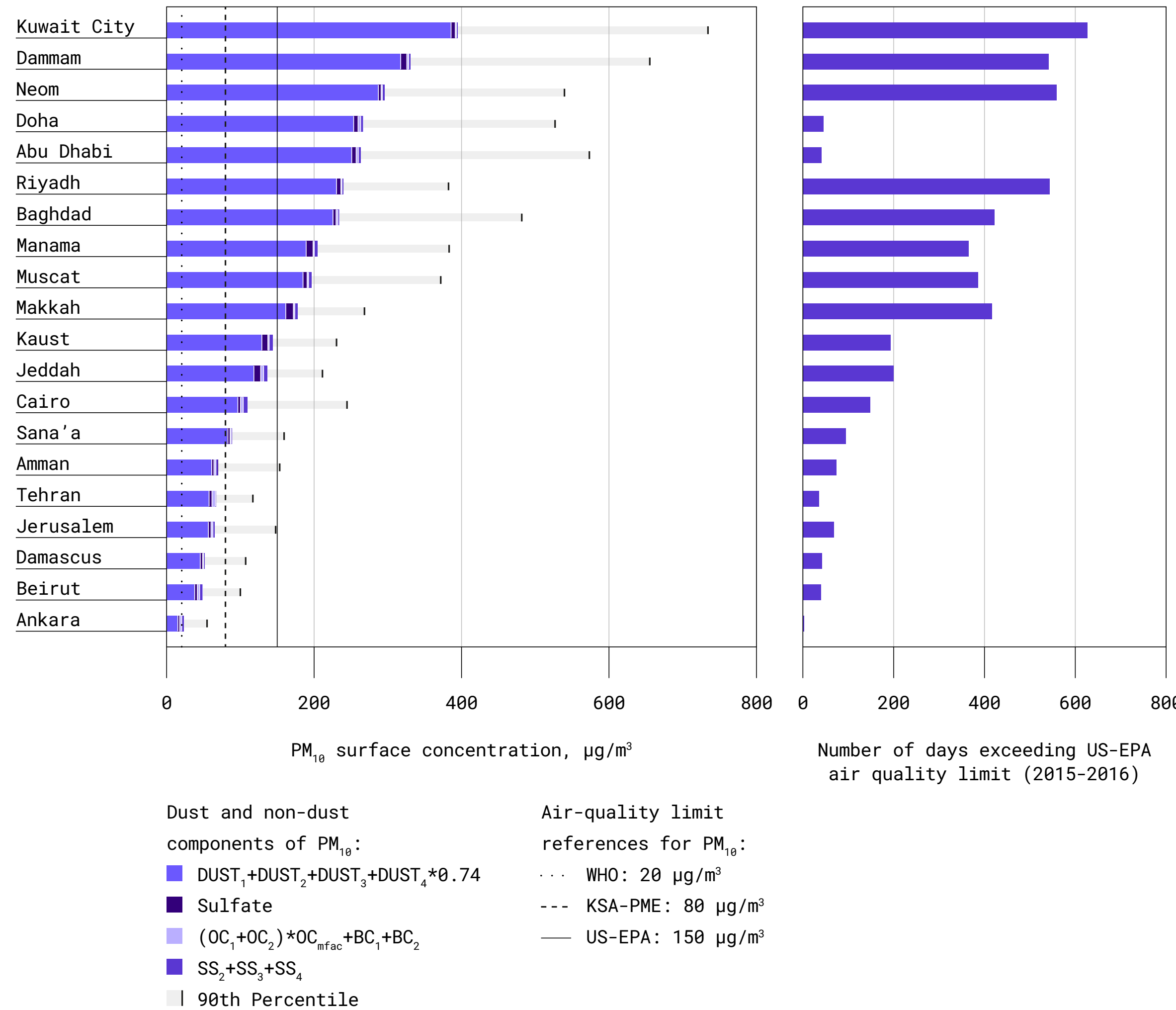
A. $PM_{2.5}$ SURFACE CONCENTRATION



Note: 90th percentiles calculated using daily mean PM concentrations.

FIGURE 5 Annual mean 2015-2016 PM surface concentrations calculated for the ME major cities and PM decomposition into dust and non-dust components.

B. PM_{10} SURFACE CONCENTRATION



Note: 90th percentiles calculated using daily mean PM concentrations.

→ **WITHOUT EFFECTIVE ADAPTATION, INNOVATION, SUPPLY CHAIN VARIABILITY AND WATER EFFICIENCY MEASURES, CLIMATE CHANGE WILL INCREASE FOOD IMPORT VULNERABILITY OF THE GCC COUNTRIES**

There is an imminent need for assessing food-related risk factors in order to guide domestic and foreign policies towards future food security for the GCC states.

GCC's current domestic food production cannot meet the demand for food and is heavily reliant on imports for some commodities from a few supplying nations, making the GCC vulnerable to geo-political events and supply chain disruptions [TABLE 1].

Future climate and demographic changes will impact world market prices and food supply from traditional trading partners of the GCC, making the GCC even more vulnerable. Desalination of seawater is an adaptation strategy employed by all GCC countries to reduce water stress and help meet urban water demand and provide a source of irrigation for highly efficient production of horticulture crops.

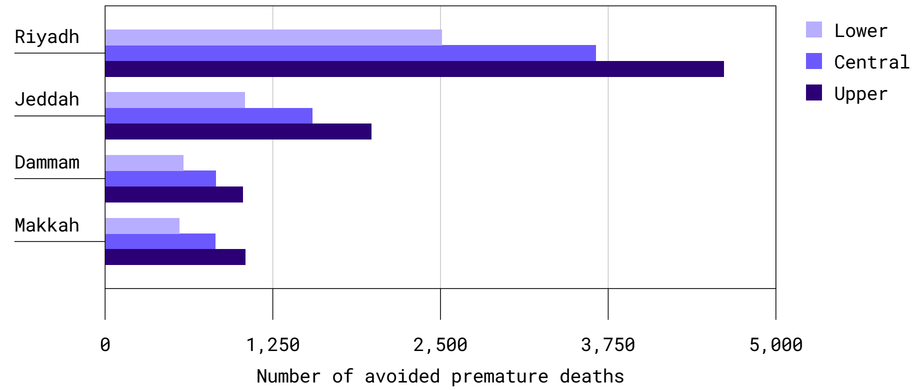
→ **EVIDENCE IS MOUNTING THAT MUCH LOWER AIR POLLUTION LEVELS THAN PREVIOUSLY THOUGHT CAN CAUSE HARM TO HEALTH, THIS THREAT IS POTENTIALLY FURTHER EXACERBATED WITH CLIMATE CHANGE**

Temperature and air pollution are highly correlated and can pose a synergetic impact on human health. Health effects of particulate matter **(PM)** air pollution are a leading environmental health concern worldwide according to the World Health Organization (WHO). This is especially important in the GCC, where natural dust can cause high levels of PM pollution in both rural and urban areas. The modeled data for air pollution levels show that the annually averaged PM surface concentrations in the Middle East's major cities are very high [FIGURE 5]. Main sources of anthropogenic sulfate aerosols were found to be industrial, traffic, and household emissions, contributing significantly to air pollution, especially on the west and east coasts of Saudi Arabia and over the Arabian Gulf. This highlights an opportunity to impose stricter requirements on anthropogenic pollution.

Furthermore, the analysis presents that a significant number of premature deaths due to $PM_{2.5}$ (particulate matter with an aerodynamic diameter smaller than 2.5 μm) exposure can be avoided if the concentration of $PM_{2.5}$ would not exceed the WHO's guideline value in major cities including Jeddah, Riyadh, Dammam, and Makkah [FIGURE 6].

Future air quality levels and excess mortality attributed to air pollution are strongly dependent on decision-making in pollution emission scenarios and the degree to which climate change mitigation will be achieved. To better quantify the health effects of air pollution in the Middle East, future research efforts need to focus on the relative toxicity and health effects of particles from various sources, monitoring and comparing air pollution levels in low and middle-income regions, monitoring and modeling for indoor air quality, and region-specific epidemiological studies.

FIGURE 6 Estimates of avoided premature deaths, on an annual basis, caused by $PM_{2.5}$ air pollution levels when the WHO guidance value is accomplished.



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CLIMATE SCIENCE

STATE OF CLIMATE CHANGE AND HEALTH IN THE GCC: 1979-2019 TRENDS IN TEMPERATURE, HEAT INDEX, AND COOLING DEGREE DAYS

Natalia Odnoletkova,
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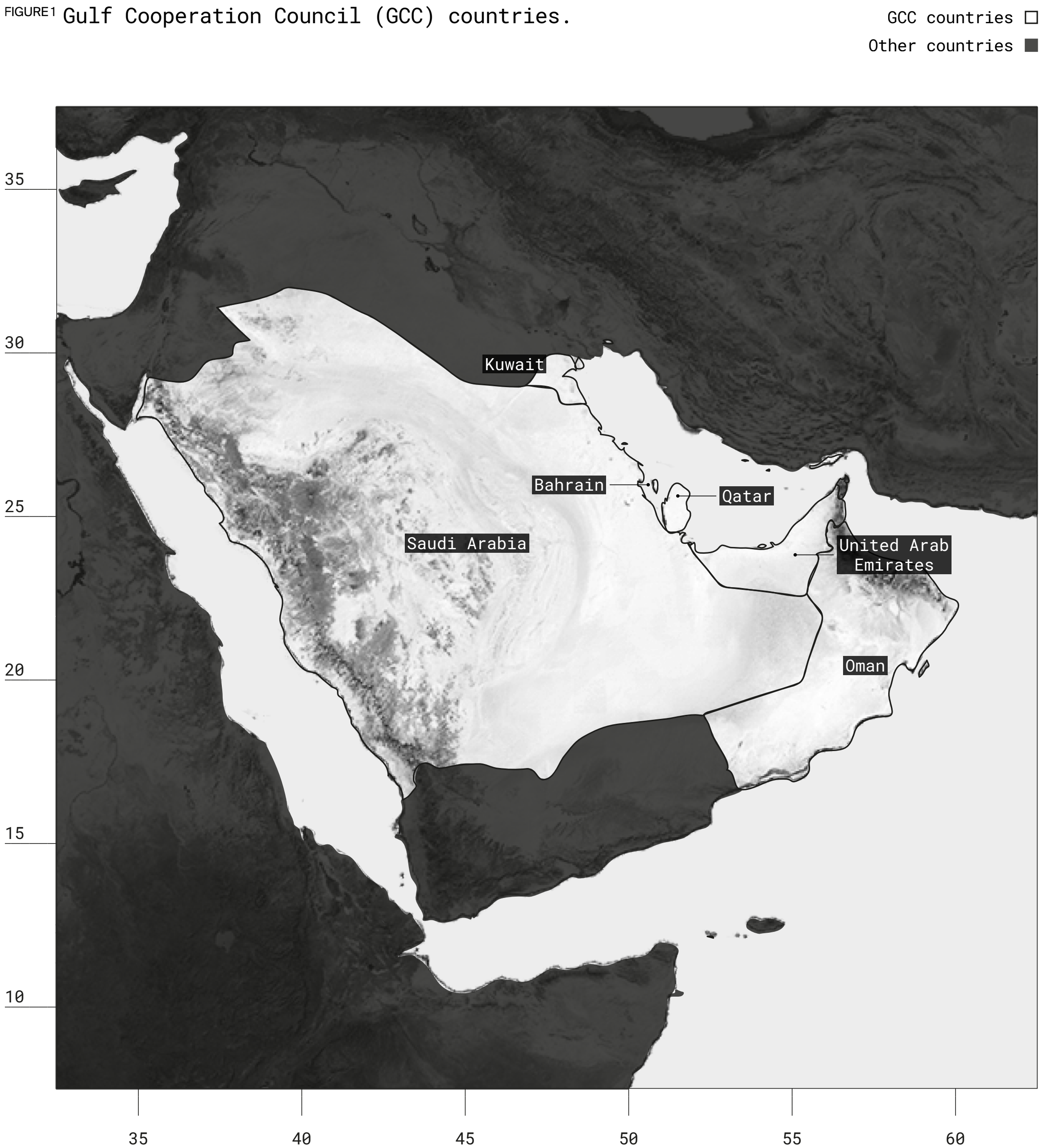
KEY MESSAGES

- GCC region is a global hotspot of temperature increase, where the warming trends surpass the global land average by a factor of two.
- Heat index is the “feels like” temperature that addresses the effect of humidity in addition to temperature. The rate of increase of this index surpasses the temperature increases across the region.
- Summer temperature and heat index are increasing faster than annual ones.
- The annual number of days with dangerous heat conditions is high and continues to grow, posing a threat to the survival of people without continuous access to cooling and drinking water.

FIGURE 1 Gulf Cooperation Council (GCC) countries.



ABSTRACT

This study seeks to provide relevant information about the state of the epochal climate change in the Gulf Cooperation Council (GCC) region between 1979 and 2019, with a focus on several key cities.

We investigated changes in temperature and several temperature-dependent parameters that have direct impact on public health and cooling demand: heat index, days with dangerous conditions, days above 100°F (~38°C), and cooling degree days (CDD). For the temperature and heat index, we assessed changes in average annual and summer values, and the average summer daily maximum values that reveal impactful trends.

Our findings indicate that the rate of temperature increase in most of the key cities in GCC far surpasses the rate of both global and Northern Hemisphere warming over land areas. Moreover, the increase in heat index, or perceived temperature, has surpassed the increase in temperature. In Gulf coastal cities, average summer heat index has increased by more than 4°C since 1979. Days with extreme heat conditions are becoming more frequent, and the demand for cooling is steadily rising. It is important to mention that our results do not account for urban heat island effects, such as excess energy stored in cement, asphalt and buildings, and waste heat from energy use, including heat released from air conditioning units and cars.

INTRODUCTION

Global near-surface air temperature has been steadily rising since the beginning of industrial revolution in the late 19th century. Global average temperature has increased by around 1.1°C from 1850–1900 to 2010–2019 [1]. However, the pace of global warming changed over time, and during the past decades it has accelerated greatly. Linear trend reveals that during 1979-2019 period global surface air temperature increased by 0.8°C.

Land areas are warming faster than the ocean and Northern Hemisphere land is heating up more rapidly than the Southern one. Global land temperature has increased by 1.3°C, and the Northern Hemisphere land temperature by 1.5°C over the same time. However, the effect of global warming varies greatly at a regional level. This warming is particularly exacerbated in the GCC countries [FIGURE 2], where the heating trends in most locations far exceed the global average values.

DATASET

The dataset we used to extract the weather data is the latest fifth generation of the global climate reanalysis by European Centre for Medium-Range Weather Forecasts (ECMWF) or ERA5 [2]. The data are provided on a regular 0.25° latitude-longitude grid. For the estimation over cities, we selected the value from the ERA5 grid box encompassing the city coordinates.

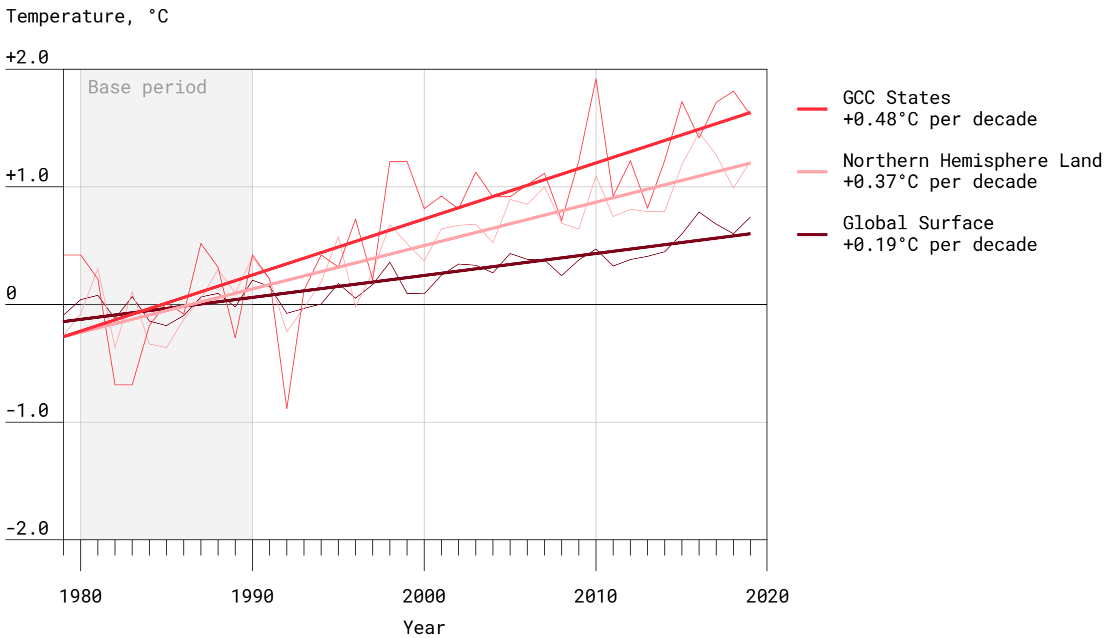
The average values over GCC are obtained as a weighted average of the data from grid cells that fall within its borders.

TEMPERATURE

We investigated changes in temperature-related climate parameters for ten major GCC cities FIGURE 2, 3. These include capitals of the GCC states and important socioeconomic centers, such as Dubai, Makkah and Jeddah. Between 1979 and 2019 the key GCC cities saw average annual temperature changes in the range from 1.0 to 2.4°C (in Manama and Dubai respectively), see FIGURE 3, 4A.

Summer temperatures have been rising faster than the mean annual ones. The average June-August temperature increases vary from 1.3°C in Manama to 2.8°C in Riyadh and Dubai over the same period FIGURE 4A. The more rapid increase of summer temperatures com-

FIGURE 2 Global surface air temperature anomalies (land and ocean), Northern Hemisphere Land air temperature anomalies and average temperature anomalies over GCC states land area for the period 1979-2019 and linear trends.



Notes: Based on ERA5 dataset[2]. Temperature anomaly is the difference from the average temperature over a 1980-1990 period.

FIGURE 3 Annual and summer mean temperatures in key GCC cities and the 1979–2019 change.

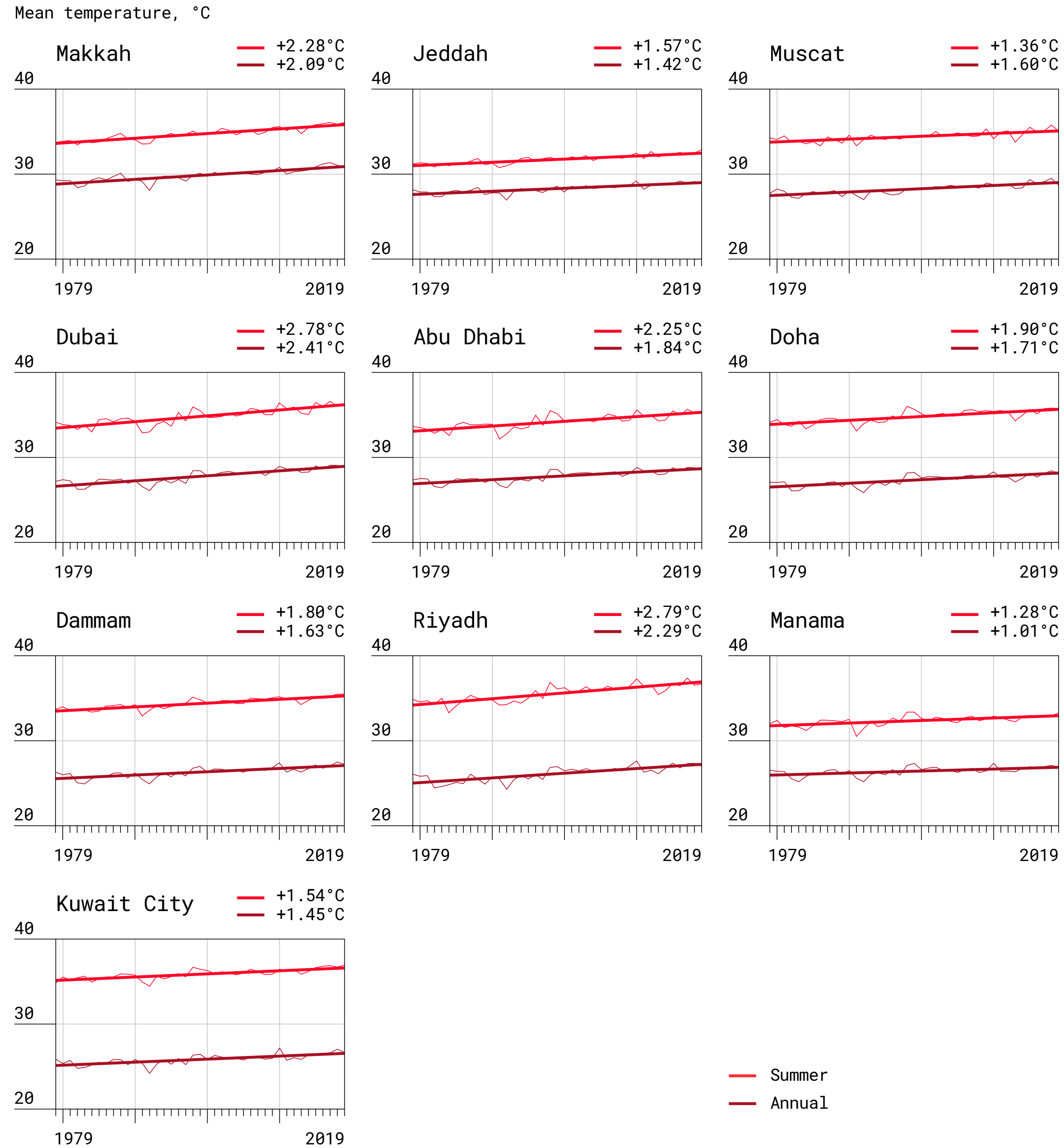
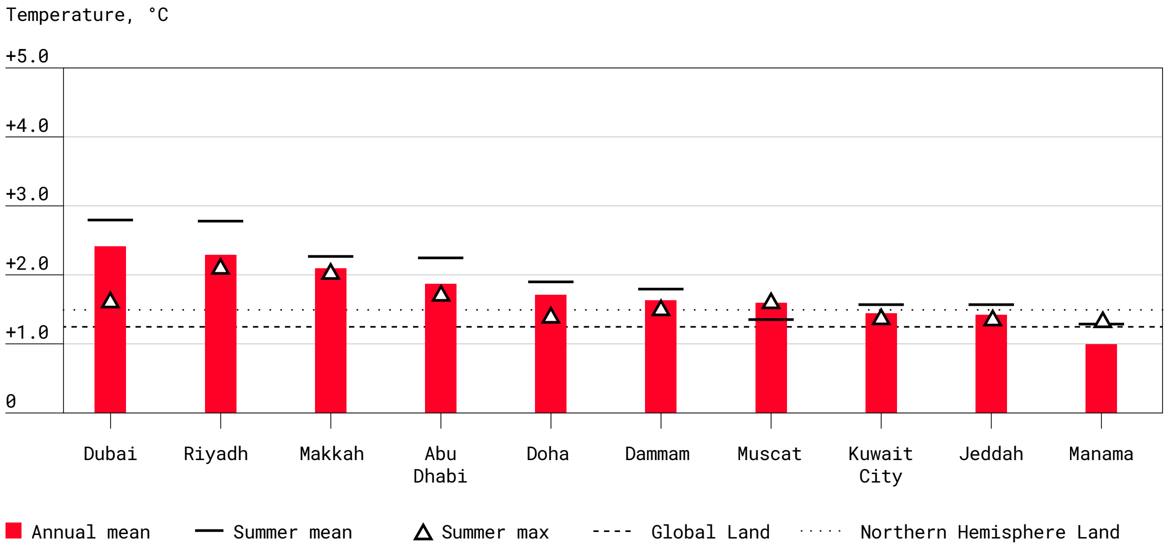
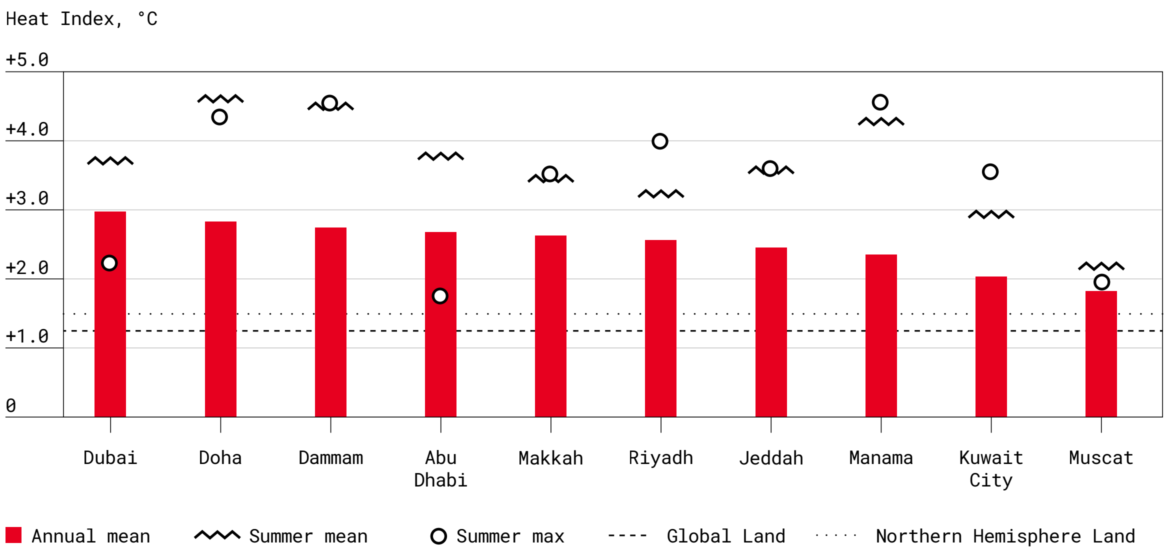


FIGURE 4 Increase in annual mean, summer mean, summer daily maximum temperature and Heat Index between 1979 and 2019, compared with the Global land and the Northern Hemisphere Land surface temperature increase over the same period of time.

A. TEMPERATURE INCREASE, 1979-2019



B. ANNUAL HEAT INDEX INCREASE, 1979-2019



pared with mean annual ones is an important concern. First, it imperils population health [3,4]. Secondly, higher summer temperatures will contribute to the rising demand for cooling and the need of power generation capacity expansion, because the peak of electricity consumption is attributed to hot summer months in this region [5].

Daily maximum temperatures are not rising as rapidly as mean daily ones in most of the GCC cities [FIGURE 4A]. This trend may seem as an advantage for outdoor labor and peak daily cooling demand. However, this advantage wanes when the increase of humidity and associated increase of daily maximum heat index, or perceived temperature, are accounted for [FIGURE 4B], as will be shown in the next section. The fact that nights are warming faster than days has multiple implications. Nocturnal temperatures above mild level may negatively alter the ability to repair heat stress injuries in ecosystems and human population [6]. The rapid nighttime temperature increase will drive the demand for cooling, which historically has not been always necessary at night. Hence, GCC residents may prefer to stay in the air-conditioned indoors rather spend time outside. All of that will necessitate an expansion of baseload power generation.

HEAT INDEX

Besides the temperature, humidity has also increased in the region, resulting in an increase of the heat index developed in 1979 by Robert G. Steadman [7]. It is a function of both temperature and humidity, and it reflects the perceived, or “feels-like” temperature. Heat index is used for the issuance of heat advisories for outdoor labor in GCC region and other countries [8]. It is also correlated to heat-related mortality [9].

The human ability to cool down by sweating diminishes with an increase in relative humidity, which results in an increase in the perceived temperature. For example, when temperature is 35°C with 70% relative humidity, common conditions in coastal Arabia’s locations in summer, the heat index is 50°C. Such conditions are considered dangerous; heat cramps and heat exhaustion are likely, and heat stroke is possible (see [TABLE 1, 10]). Heat index is calculated using an algorithm from the National Weather Service (NWS) of the National Oceanic and Atmospheric Administration (NOAA) [11] described in the Appendix. This algorithm gives the best results of heat index in terms of the consistency with the theoretical concepts behind apparent temperature [12]. To calculate heat index, the temperature and either the value of dew point temperature or relative humidity are required. We use temperature and dew point temperature from ERA5 to obtain the heat index value.

The study of this index is of particular importance, because eight out of ten major GCC cities we have focused on are coastal and subjected to much higher heat stress due to elevated humidity in comparison with the dryer inland locations. Both annual and summer mean heat index values have increased at a much higher rate than temperatures across major GCC cities. The change in summer heat index during the past 41 years is more than 2°C in all cities except Muscat. The increase of summer mean heat index is staggering: above 3°C in all cities except Kuwait and Muscat and nearly 5°C in Doha and Dammam [FIGURA 4B]. The change in summer daily maximum heat index is shown in [FIGURA 4B], and it is of the same order as the change in mean values. It is important to emphasize that such great changes in perceived temperature have happened amid global surface air temperature increase of only 0.8°C and global land surface temperature of 1.3°C since 1979 (dash-dotted line on [FIGURA 4]). Average values of temperature increase should not be used to forecast regional-scale health effects and cooling demand increases attributed to climate change.

While temperature is one of the important drivers of the demand for cooling, air humidity also plays a crucial role for warm coastal locations. The projections of electricity demand based on solely air temperature may underestimate cooling demand by 10–15% in the case of the US cities [13]. This value can be even more for GCC region, given the unique coastal locations with high humidity of major cities. The health effects of increased heat index will be addressed in the next section.

DAYS WITH DANGEROUS CONDITIONS

The effect of heat on health can be divided into four categories based on the heat index values, see [TABLE 1]. When heat index is within a dangerous level, the share of break time for outdoor labor is 50%, equally divided in time, and the amount of water intake is 1-1.5 liters per hour. If heat index is 52°C and above, the share of break time is increased to 75%, and the work should be suspended if heat index reaches 56°C and more [8].

We illustrate how exposure of the population to thermal stress has changed over the past four decades, using an example of days with dangerous conditions [FIGURE 5,6A]. Days with extreme danger are still rare and happen along the Arabian Gulf coast.

The exposure of population to thermal stress has greatly broadened in the key GCC cities, with the coastal ones subjected to the highest increase in heat index and the associated occurrence of days with dangerous heat conditions. The increase in the number of days with dangerous conditions between 1979-2019 accounts for the large proportion of the present value and varies from 21% in Dubai to 95% in Jeddah. However, Muscat is an outlier, having the lowest change in both annual and summer heat index among all the cities. The number of days with dangerous conditions in Muscat was rising at the end of 20th century, but since 2000 it has not changed essentially. The effect of wind streams may be the reason for that. The southern coast of Oman is subjected to the intense wind streams that originate

in the west part of Arabian Sea and Somalia, which are also less affected by the rising temperatures and heat index [14, 15]. It is opposite to the wind stream pattern over the rest of Arabian Peninsula which is facing milder winds from northern and western directions [16].

Historically, Dubai and Abu Dhabi used to experience the highest number of dangerous days per year, but these cities were surpassed by Makkah and Manama in the recent past. Makkah is a holy city in Islam, and it normally hosts more than 2 million pilgrims annually [17]. The rapid increase of exposure to extreme heat conditions impacts the Hajj and Umrah seasons. If the warming trend continues in the future, it will put at risk the physical ability of people to perform pilgrimage at outdoor conditions during summers.

TABLE 1 Effects of the Heat Index on health, shade values. Exposure to full sunshine can increase Heat Index values by up to 8°C[6].

Heat Index	Effects
26-32°C	CAUTION Fatigue is possible with prolonged exposure and activity
32-41°C	EXTREME CAUTION Heat cramps and heat exhaustion are possible
41-54°C	DANGER Sunstrokes, heat cramps and heat exhaustion are likely; heat stroke is possible
over 54°C	EXTREME DANGER Heat stroke is highliy likely if the exposure is continued

FIGURE 5 Days when daily high of the heat index is 41-54 °C in key GCC cities.

Number of days with danger condition, 3 year running mean

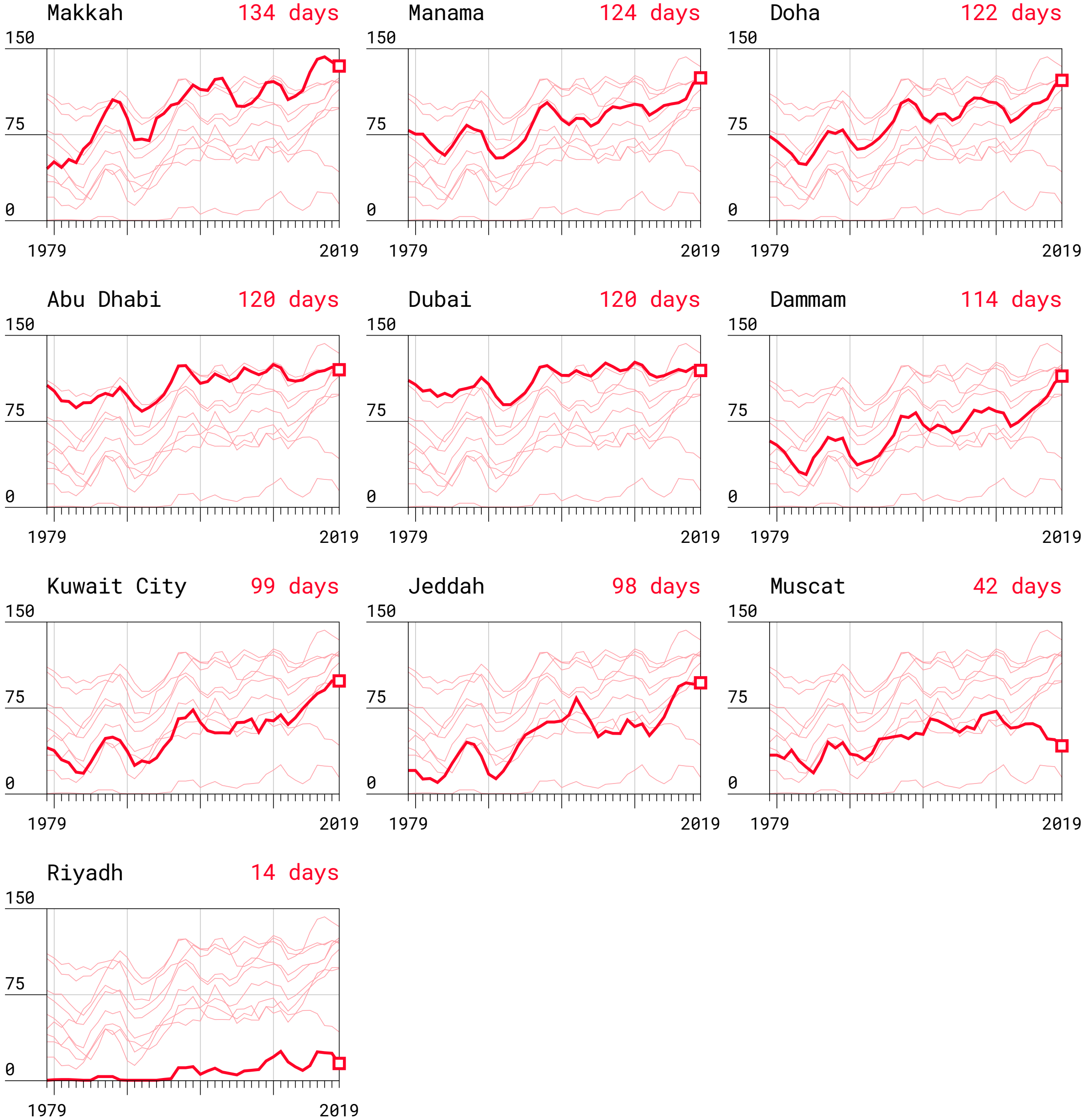
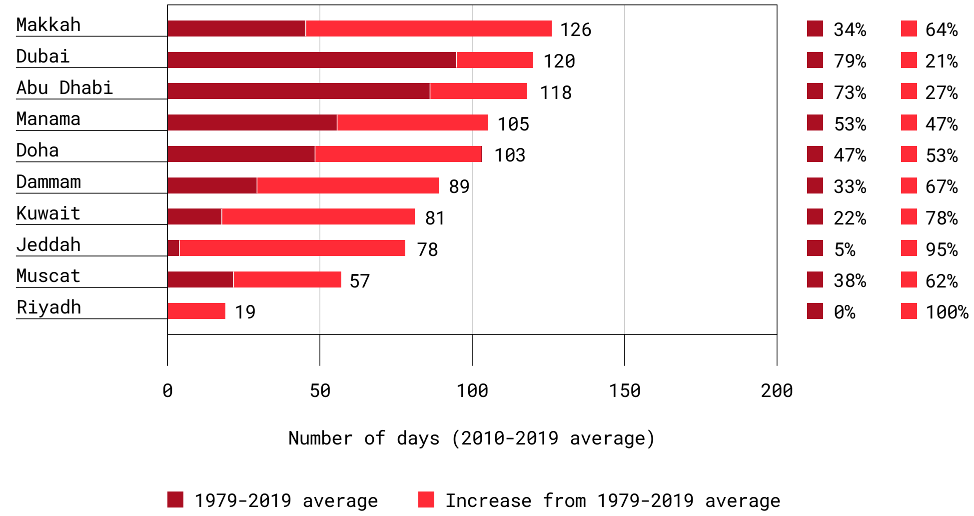
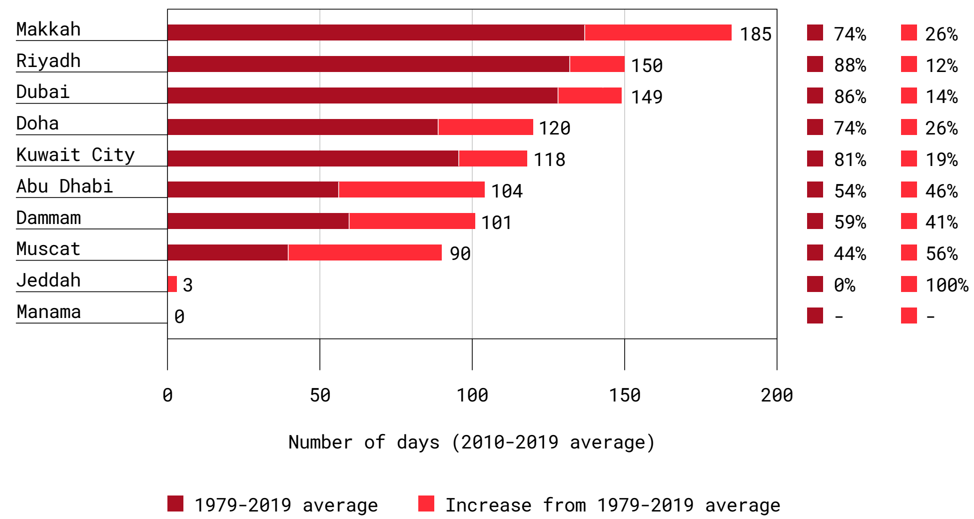


FIGURE 6 Number of days with dangerous conditions and days above 100 °F in key GCC cities.

A. NUMBER OF DAYS WITH DANGEROUS CONDITIONS IN KEY GCC CITIES (2010-2019 AVERAGE)



B. DAYS ABOVE 100°F IN KEY GCC CITIES (2010-2019 AVERAGE)



Note: The increase from 1979-2019 average as a fraction of the average 2010-2019 value is shown in percent.

DAYS ABOVE 100°F

100°F (37.8°C) is a common threshold that defines very hot conditions [18, 19]. It is an annual count of days during which daily maximum temperature exceeds 100°F, or 37.8°C. This index doesn't account for heat stress from humidity, so the result differs from the days with dangerous conditions index [FIGURE 6A]. Makkah has the highest number of days above 100°F per year (185) followed by Riyadh and Dubai (150 and 149 days respectively, [FIGURE 6B]). The biggest increase in this parameter since 1979 is seen in Muscat (56% of present value), Abu Dhabi (46%), and the lowest in Riyadh (12%). These days do not occur in Manama and are very rare in Jeddah.

COOLING DEGREE DAYS

Cooling degree days (CDD) is a parameter designed to quantify cooling load demand in buildings and to classify locations into climate zones. It is the difference in degrees between daily average temperature and base temperature, if daily average temperature is above the base value. Yearly value of CDD is the sum of the daily values over a course of a year

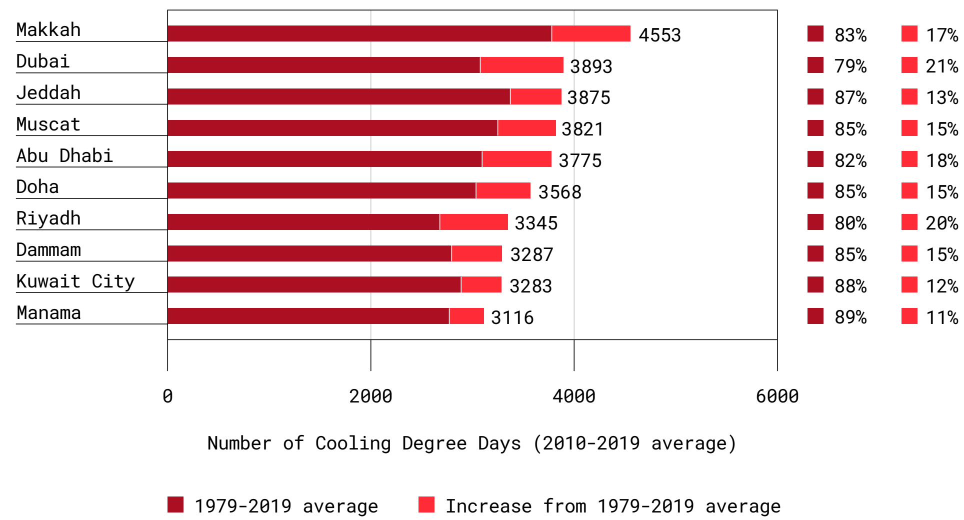
$$CDD = \sum_{i=1}^{N} \left(\bar{T}i - T_{base} \right)^{+}$$

where N is the number of days in a year, T_{base} is the reference temperature to which the degree-days are calculated, and $\bar{T}i$ is the average daily temperature calculated by adding the maximum and minimum temperatures for the day, then dividing by 2. The + superscript indicates that only positive values of the bracketed quantify are taken into account in the sum. We use standard CDD base value of 18.3 °C [20].

The yearly value of CDD varies between 3000 and 5000 in the cities we studied, and the highest values are seen in Makkah. All the cities experienced a significant increase in CDD between 1979 and 2019 [FIGURE 7]. This increase in cooling demand directly affects the total electricity generation in the region, as cooling load is substantial part of total electricity consumption. In Saudi Arabia, cooling load is associated with about 70% of total electrical consumption [21].

As mentioned earlier, the projections of cooling demand should not rely solely on outdoor temperature and cooling degree days. The humidity is an important factor in this region and notably contributes to the demand for cooling.

FIGURE 7 Number of Cooling Degree Days in key GCC cities (2010-2019 average).



Note: The increase from 1979-2019 average as a fraction of the average 2010-2019 value is shown in percent.

CONCLUSION

The GCC region has experienced a strong warming trend since the late 1970s. The temperature increase in key GCC cities has surpassed global average value of temperature change over the same time period by a factor of two. Moreover, all the cities - with the exception of Manama - have been warming faster or at least at a similar rate as Northern Hemisphere land surface. Highest increases of temperatures have been seen in Dubai, Riyadh, and Makkah, where annual temperatures increased by more than 2°C between 1979 and 2019. The lowest change in temperature among studied cities is observed in Muscat, Kuwait City, and Manama, although the change is still significant and surpasses 1°C.

Yet, the socio-economic impacts associated with climate change are not limited to the effects of temperature increase only. In the GCC region, the impact of escalated humidity is crucial, as eight out of ten major GCC cities are coastal. The average increase of annual heat index in all cities is greater than the increase of temperature. The Arabian Gulf coastal cities have the highest rate of increase in both annual and summer heat index, while the lowest increase in this parameter is observed in Manama.

The separate consideration of summer trends is essential as summer heat extremes are having direct impact on public health and annual peak electrical consumption. We showed that summer temperatures are rising faster than the mean annual temperature in this region. The increase of summer heat index and summer daily maximum heat index is far more than those values for simple temperature increase. Average value of summer heat index and summer maximum heat index has increased by more than 4°C since 1979 in Doha, Dammam and Manama, which is about two times the change in temperature across the same time period. All of these resulted in the escalated occurrence of hot extremes such as days with dangerous heat conditions and days above 100°F.

We presented the extent of changes in temperature and various temperature-related indicators the region has experienced amid the planetary temperature increase of just above 1°C since pre-industrial times. This work is of importance to policy makers, contributes to the projections of heat-related mortality and rising cooling demand in the GCC region, and serves as a basis for understanding the possible future impacts of climate change.

AREAS OF FURTHER RESEARCH

→ Projections of the effects of extreme heat waves on various sectors of GCC state economies are necessary, electricity generation in particular.

→ Measures to decrease the effect of ambient conditions on cooling and electricity demand should be studied thoroughly; these include passive cooling, district cooling, and application of non-vapor compression AC units.

PROJECTIONS OF THE CLIMATE CHANGE IN THE ARABIAN PENINSULA IN THE NEXT FEW DECADES

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KEY MESSAGES

- → CMIP6 projects the annual mean temperature over AP to increase by 1-2°C in the near-term (2021-2040) and more than 5°C in the long-term (2081-2100), with the central and northern KSA exceeding 6°C.
- → CMIP6 projects the annual mean precipitation to increase over most AP, except in the northwest. The largest increases are projected over the southwest AP by 25-60mm and more than 120mm in the near and long-term periods, respectively.
- → CMIP5 projections agree well with those of CMIP6 over the AP, but are less severe.
- → CMIP5 and CMIP6 multi-model means capture the observed spatial patterns of precipitation and temperature variability over the historical periods. However, their projections do not compare well with the observed climate patterns in recent years.

INTRODUCTION

Climate change is emerging as the most important challenge for humankind in recent history. Rising global mean surface temperatures due to climate change have exacerbated environmental anomalies such as heat waves, cold waves, storms, precipitation and flooding, and drought, posing direct and long-term hazards to people and infrastructures. Climate change projections (CCPs) are critical for mitigating the risks and costs associated with climatic changes and extremes [1]. CCPs are nowadays based on the outcomes of an ensemble of global climate models (GCMs), with the underlying assumption that the GCMs provide statistically independent information uniformly distributed around the true climate state [2].

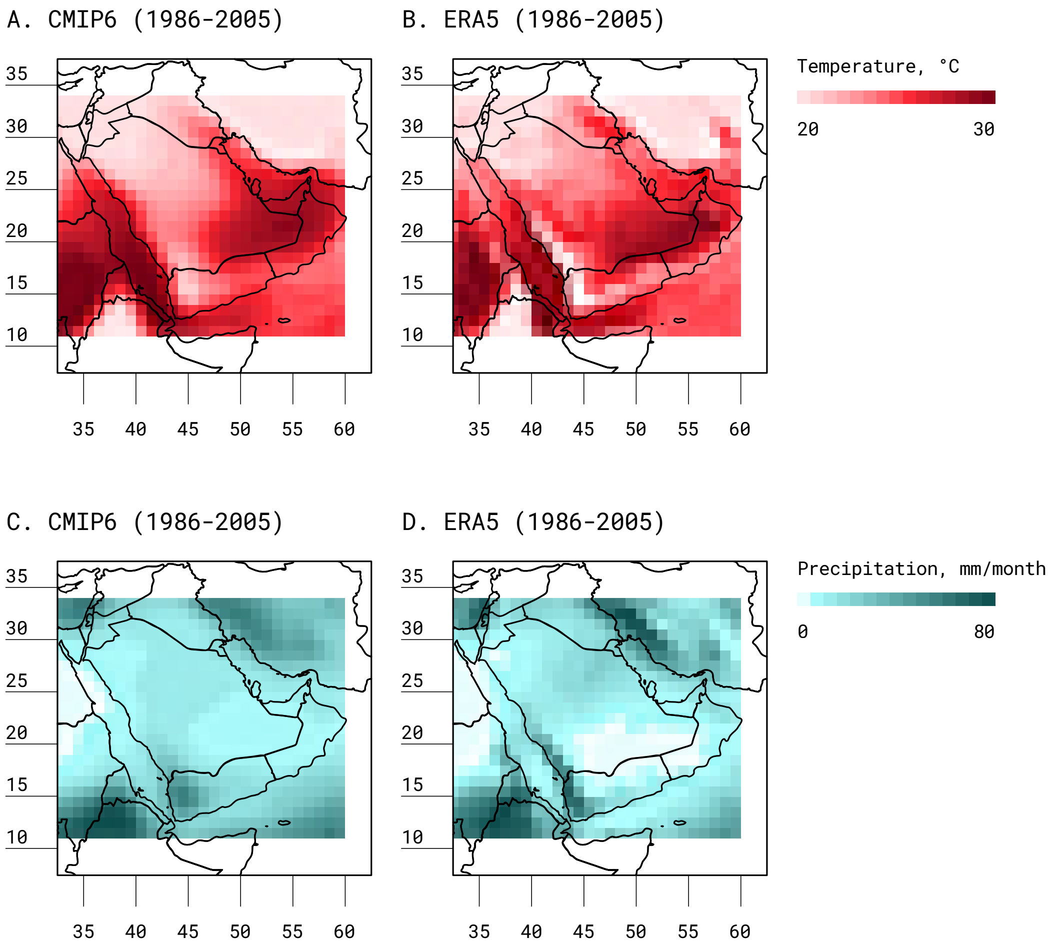
The Arabian Peninsula (AP), with the Kingdom of Saudi Arabia (KSA) occupying 80% of its total area, is one of the world's driest and most water-scarce regions, and was suggested to experience more frequent and intense extremes due to climate change [3]. Temperature and precipitation changes are also more pronounced in this region than the mean global changes [4, 5]. KSA is heavily reliant on food imports due to the limited available Agri land, which is less than 2% of its total land, and is therefore extremely vulnerable to food security [6]. The growth rates in population, industrial development, and irrigation increased the water demand and the climate change is adversely affecting the KSA's limited water resources [7]. Reliable spatiotemporal information of temperature and precipitation patterns at the sub-district level under climate change is critical to develop future strategies for adaptation and mitigation. In addition, recent studies suggested that the coastal regions adjacent to the Arabian Gulf and Red Sea may be severely impacted by rising wet-bulb temperatures (indicative of a combined temperature and humidity effect, and used as a measure of human survivability limit). This is expected to affect human livable conditions in this region by the end of the 21st century [8]. Increasing wet-bulb temperature over the Red Sea is also projected to increase the frequency and intensity of extreme heat stress events over the nearby cities [9].

GCM projections may be subject to significant uncertainties due to various factors such as unresolved physics, imperfect parametrizations, coarse resolution, and limited observational datasets [10]. For example, notwithstanding a relatively high resolution (~25 km) regional atmospheric modeling framework is used to generate region-dedicated future projections, future oceanic conditions that drive the atmosphere as boundary conditions are still taken from lower-resolution ocean general circulation models [11]. Nevertheless, most of the globally-relevant conclusions from the CCPs such as increasing trends in global temperatures are suggested to remain robust [12]. The challenge

comes at the local scales [13, 14]. Reliable spatiotemporal information about temperature and precipitation at the sub-district level under climate change conditions is critical for strategizing and developing future plans for adaptation and mitigation at the regional level [6].

Coming to the KSA, the ensemble-mean temperatures from the Coupled Model Intercomparison Project Phase-6 [15] projections show, in agreement with the observations-based 5th generation European Center for Medium Range Weather Forecasting Reanalysis [16] during the historical period 1979-2014, that the temperatures in the northwest and southwest mountain areas the AP are, in general, lower than those in the central to eastern region [FIGURE 1]. The annual mean temperature in the northwestern and southwestern regions is less than 20°C, while it exceeds 28°C in the central to the eastern areas [FIGURE 1]. In recent years, the maximum summertime temperature has even exceeded 50°C [5] . [4] analyzed observational datasets from 1978-2009 and reported an increasing trend in temperature over KSA by 0.6°C/decade; notably, this trend is significantly weaker (0.13°C/decade) when including data from previous decades [17]. The annual mean precipitation is highest (above 150 mm) in the southwest AP, and lowest (below 60 mm) in the northwest AP and over the Rub Al-Khali desert areas [FIGURE 1]. The rainfall patterns over the AP show a significant increase in rainwater over 1981-2010, relative to the earlier period (1951-1980), at 0.86% per decade [14]. However, the increase is not spatially homogeneous. The annual precipitation has actually decreased significantly over the northern AP by 0.66% per decade, whereas it has increased over the southern AP by 1.67% per decade [14]. The dynamical changes behind the reported changes in temperature and rainfall patterns over the KSA remain not fully understood.

FIGURE 1 Climatological annual mean temperature and precipitation from the multi-model mean of 17 statistically independent CMIP6 GCMs and ERA5 over the Arabian Peninsula. The climatological annual mean is calculated for 1986-2005 historical period.

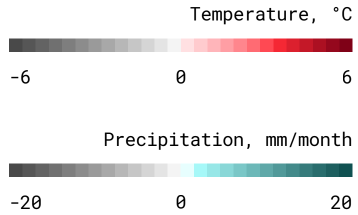


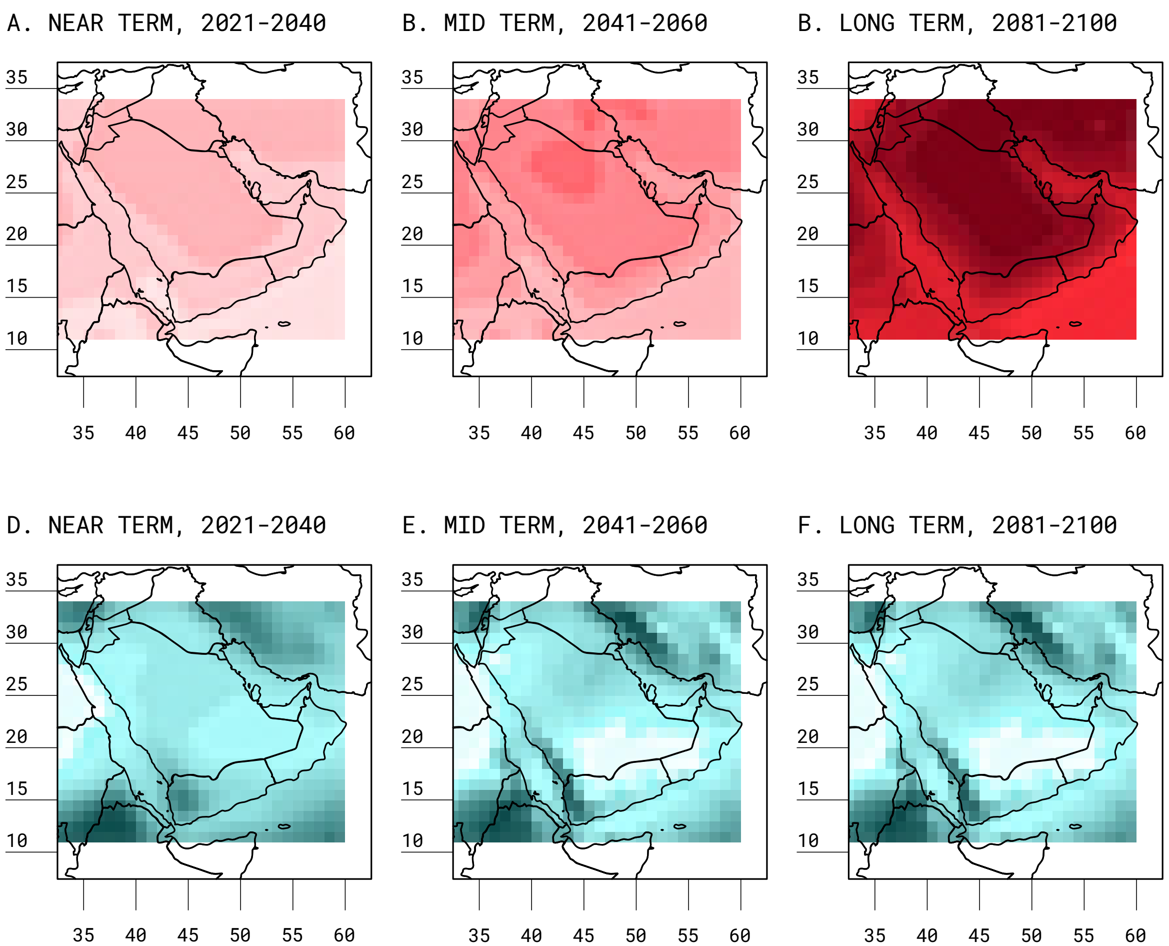
What do the climate projections portend for the future climate of the AP? The panels in the top row of FIGURE 2 depict the projected change in temperature and precipitation over the AP for the near-term (2021-2040), mid-term (2041-2060), and long-term (2081-2100) periods compared to the present climate (1986-2005) under the business-as-usual climate change scenario (SSP5-8.5) from the CMIP6 predictions. The annual mean temperature over the AP is projected to increase by 1-2°C in the near-term, 2-3°C in the mid-term, and more than 5°C in the long-term, with that over the central and northern KSA exceeding 6°C.

The annual mean precipitation is projected to increase over most of the AP, except in the northwestern region, where it is projected to decrease in all above-mentioned periods (bottom row panels of FIGURE 2). The highest annual increase in precipitation is projected over the southwest AP regions by 25-60 mm, 50-120 mm, and more than 120 mm, respectively, in the near, mid, and long-term periods. Over the rest of the region, precipitation is projected to increase (i.e., over the eastern to northwestern region) by less than 10 mm, 20 mm, and 30 mm in the near, mid, and long-term, respectively. While we do not discuss the inter-model uncertainty of these latest analysis in this report, these temperature and precipitation change patterns from CMIP6 are qualitatively consistent with findings from the earlier generation projections, e.g., CMIP5[18].

As mentioned earlier, the climate change projections, are potentially in the nation's future planning; however, the GCMs simulations must be more exhaustively validated with updated observations and also from the context of dynamics, appropriately downscaled, and uncertainties quantified and addressed wherever possible through bias correction. Climate models have undoubtedly evolved greatly over the last three decades[15]. Constant efforts are being made to improve the models and the fidelity of the simulated climate and multiple models are being used to account for the uncertainties in their outputs. However, with the availability of multiple projections, the multi-model simulations are subject to some important concerns other than what we discussed earlier. For example, most models are developed based on similar physics and by sharing code/components and ideas, resulting in skewed projections towards a highly weighted model. On another note, there are new indications suggesting that climate variability and relationships, particularly teleconnections of ocean drivers such as ENSO, are non-stationary in the last 50 years[14]. Therefore, the climate system of a region, its variability and changes need to be understood, and natural causes delineated before conducting the projections. In this context, the inability to reproduce important local atmospheric phenomena or appropriately and precisely account for the influence of local climate drivers adequately (e.g., a proper representation of in-

FIGURE 2 Spatial variation of projected changes in annual mean temperature and precipitation over the Arabian Peninsula for the near-term, mid-term, and long-term under the strong climate change scenario (SSP5-8.5), compared to the present climate (1986-2005), using the multi-model mean of 17 statistically independent CMIP6 GCMs.

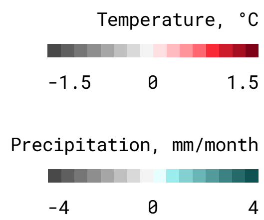


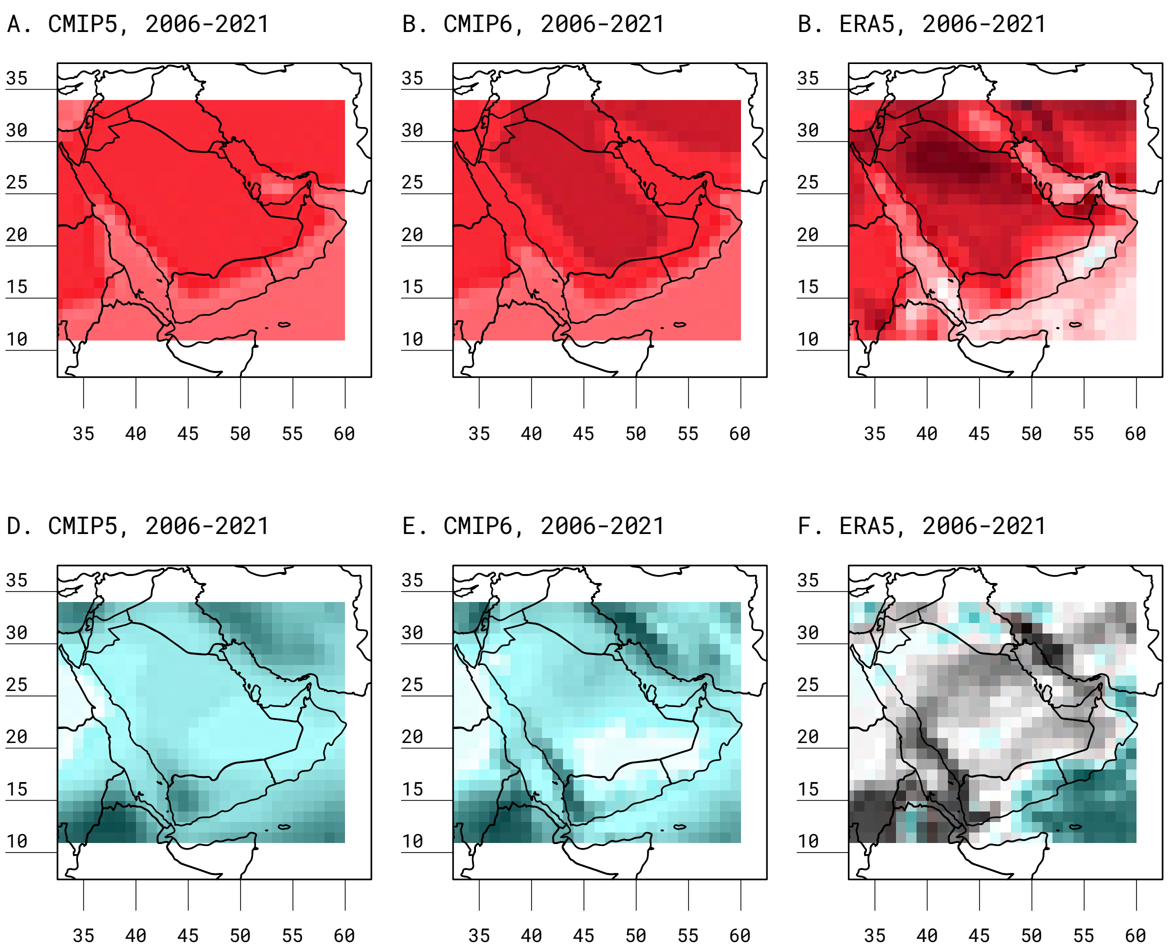


teractive dust aerosols and a fine resolution of the Red Sea from the perspective of the AP Climate) need to be focused upon, and so on. These concerns can sometimes limit the utility of the findings from climate projections, depending upon the region of interest.

It is also often assumed that a model performing well in the present climate will perform well for future climate simulations. However, this assumption is not always valid, as the models are tuned to reproduce the mean climate and its variability/change as seen in the available (recent 150 years or so) observations, and therefore may not be able to capture the hitherto unforeseen non-stationarities and tipping points [10]. To demonstrate, FIGURE 3 shows the spatial distribution of temperature and precipitation change from 2006-2021, which was the projection period for CMIP5 simulations under the business-as-usual climate change scenario, but a 'historical' period for CMIP6, and the latest ERA5 datasets. The spatial temperature pattern from the ERA5 data shows a large increase of above 1°C. This is largely underestimated (higher cold bias) in the projected CMIP5 simulations, but underestimated moderately (less cold bias) in the historical simulation by CMIP6. The relatively weak cold bias in CMIP6 could be due to a higher resolution or better model physics in this case. Physics improvements are generally based on tuning the models over the most recent 20-30 years, that is, the latest models are expected to perform better over the recent periods. The problem seems to be more pronounced with precipitation, where observations-based datasets suggest a decrease in precipitation whereas CMIP5 projections, and even CMIP6 historical simulations show an increase. This confirms that though the climate models perform well during the historical climate, they may not necessarily do so for the future climate. Improved resolution and downscaling with a regional model using suitable and regionally-tuned physics could reduce some of the biases in the current global models [19]. In addition, innovative and out-of-the-box ideas to properly constrain the biases at least in the near future projections (20-30 years horizon), based on how the climate has been evolving in the last decades, need to be explored. This also gives the added benefit of improving seamless prediction capacities. In our ongoing research, we are addressing several of the aforementioned challenges for the nation's needs.

FIGURE 3 Spatial distribution of temperature and precipitation change from 2006-2021, compared to the present climate (1986-2005) using the multi-model mean of 17 statistically independent CMIP5 and CMIP6 GCMs, and ERA5. The period 2006-2021 used here is the projection period for CMIP5 GCMs under a strong climate change scenario and the historical period for CMIP6 GCMs and ERA5.





AREAS OF FURTHER RESEARCH

→ Examine the projected changes in the AP climate dynamics.
→ Investigate approaches for reducing the biases of climate projections over the AP.
→ Assess benefits from regional climate models for simulating and projecting the AP climate.
→ Study and account for the role of dust aerosols in the changing climate over the AP.

2

CLIMATE IMPACTS

HEAT STRESSORS, HEAT STROKES AND IMPLICATIONS ON HAJJ

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KEY MESSAGES

- → Wet bulb temperature conditions in cities such as Dhahran and Dubai are projected to exceed the threshold of 35°C, which defines the limit of what may be tolerated outdoors for an exposure of six hours or longer.
- → Locations such as Riyadh in the middle of the Arabian desert are saved from such extreme conditions due to the dry nature of the local climate.
- → Makkah will likely experience significant humid heatwaves conditions under climate change which may pose a significant risk, specially to the elderly.
- → Current projections of the potential distribution of Aedes aegypti - main vector for dengue - under different scenarios of climate change suggest that the potential distribution of this vector in the Gulf region is insensitive to climate change.

INTRODUCTION

The Gulf region faces the same challenges encountered by other regions of the world, namely how to achieve sustainable development by managing economic and population growths in ways that protect and preserve the regional and global environment. The main environmental challenge of our times is global climate change driven by changes in the chemical composition of the atmosphere due to increasing anthropogenic emissions of greenhouse gases (GHG). Global climate change will result in a range of regional impacts on ecosystems, extremes of weather, water availability, and agriculture. However, the most significant potential impact of climate change is likely on human health.

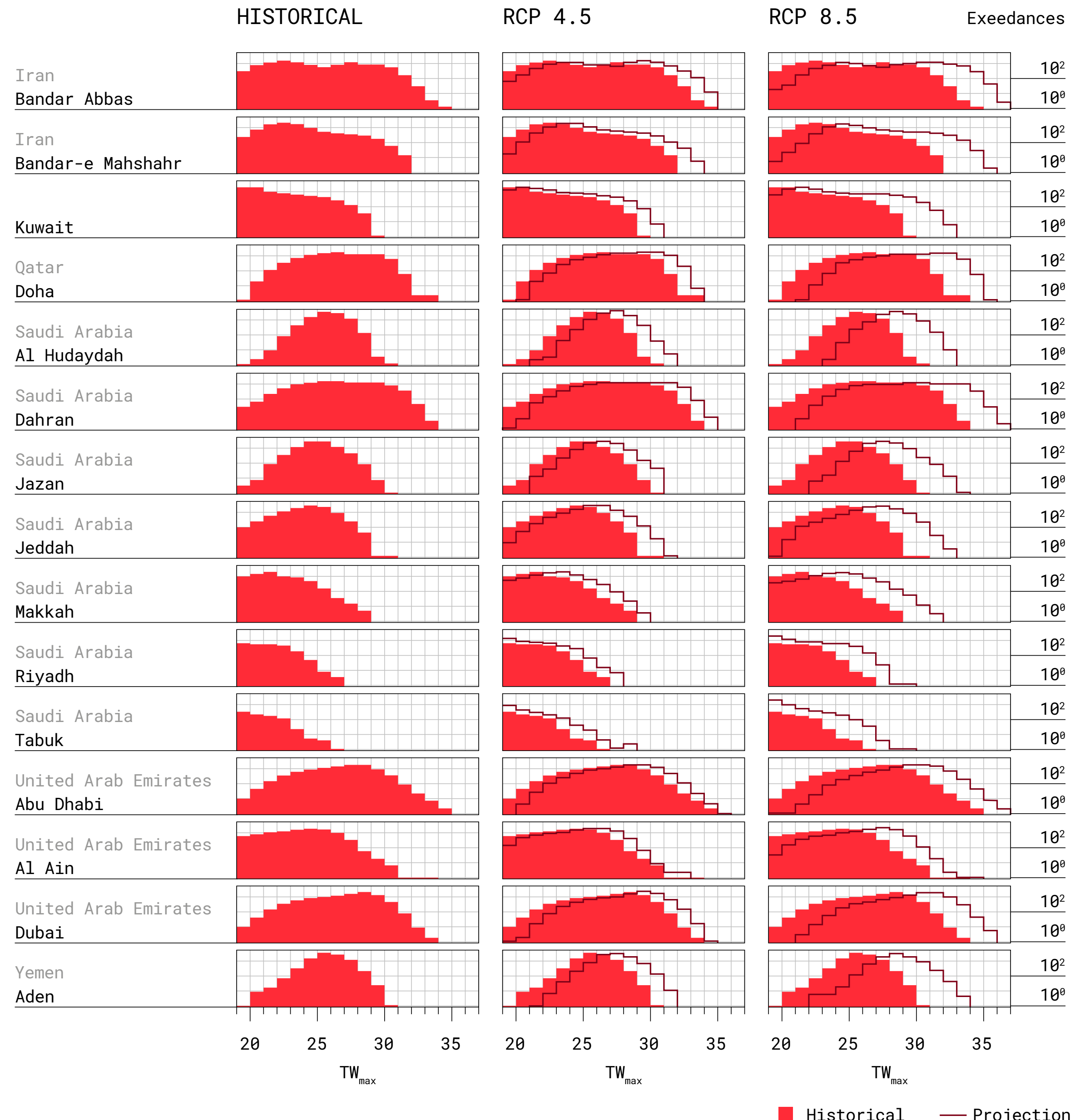
In this section, three specific examples on how climate change may impact human health in the Gulf region are discussed: heatwaves and associated heat-strokes; climate change and Hajj conditions; and potential emergence of vector-borne viral diseases such as Dengue.

HEATWAVES

Even under the current climate, the cities around the Gulf experience extreme conditions of humid heatwaves in summer. A recent study[1] identified the Gulf region as a “hotspot” for future heat waves. They arrived at this conclusion by analyzing observations and future simulations of a measure of humid heatwaves: wet bulb temperature, a variable that combines temperature and humidity effects. Under the business as usual scenario of global emissions, the region will experience extreme heatwaves that cannot be tolerated by humans without the use of air-conditioning. As shown in FIGURE 1, wet bulb temperature conditions in cities such as Dhahran and Dubai are projected to exceed the threshold of 35°C, which defines the limit of what may be tolerated outdoors for an exposure of six hours or longer. Interestingly, locations such as Riyadh in the middle of the Arabian desert are saved from such extreme conditions due to the dry nature of the local climate.

However, Makkah where the Hajj rituals are performed every year will likely experience significant humid heatwaves conditions under climate change which may pose a significant risk, specially to the elderly. There is need for further research to quantify how these changes in heatwaves intensity and frequency would translate into enhancement of the incidence of heat strokes and possibly fatality among humans in this region.

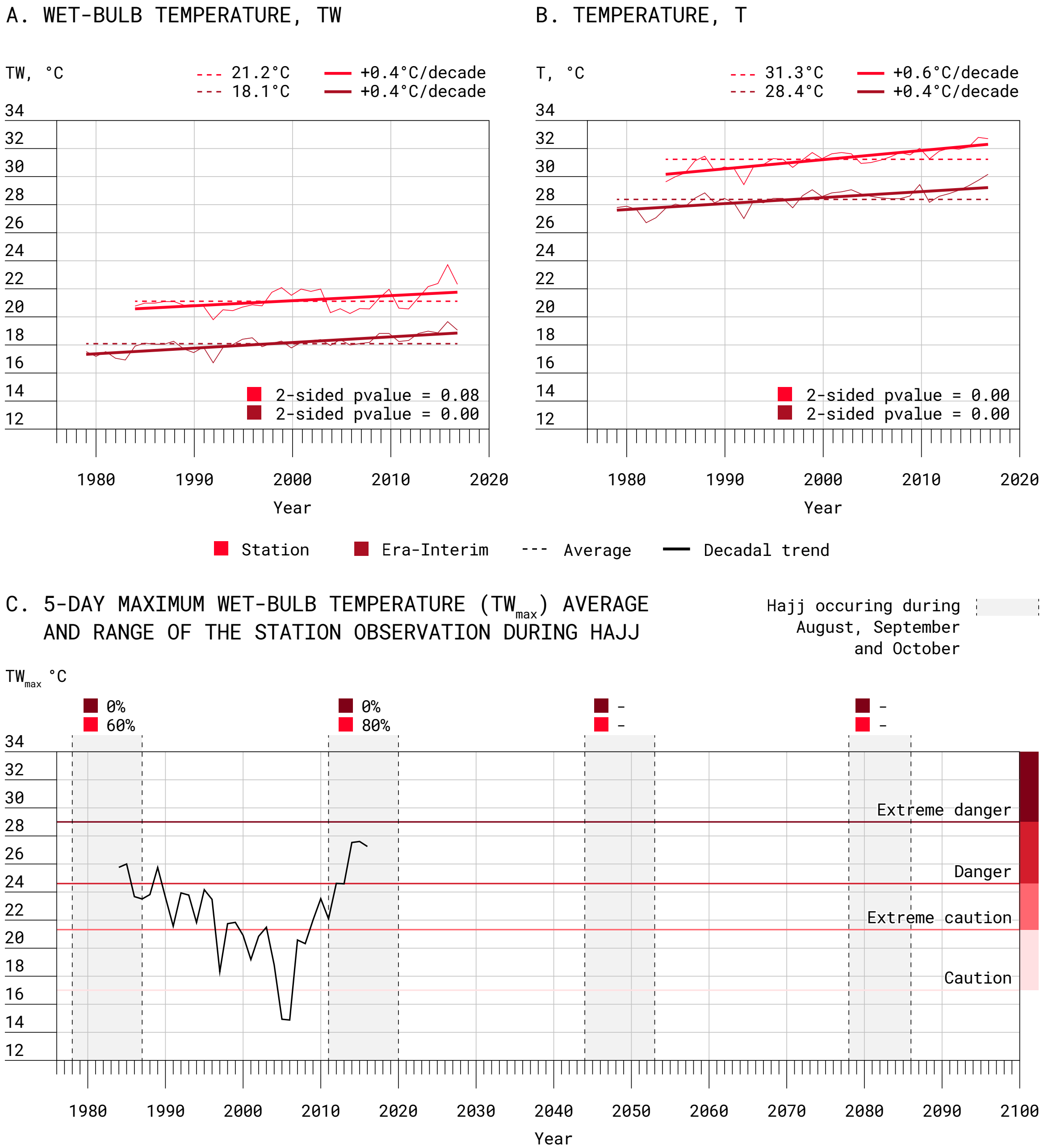
FIGURE 1 Histogram of the daily maximum wet-bulb temperature (TW_{max} averaged over a 6h window) during summer for each GHG scenario’s ensemble.



Source: Pal and Elfaith, 2015[1].

Note: RCP stands for Representative Concentration Pathway. The histogram bin interval is 0.5°C and the values on the y-axis indicate the number of exceedances. Values indicated within each plot represent the 50th and 95th percentile event thresholds.

FIGURE 2 Time series of the observed annual mean for wet-bulb temperature and temperature and the 5-day maximum for wet-bulb temperature during Hajj.



Source: Kang and Eltahir, 2019[2].

CLIMATE CHANGE AND HAJJ

Millions of Muslims participate in the Hajj each year, and those who are in good health and can afford it are obligated to participate in it at least once in their lifetime. The followers of Islam represent nearly one quarter of the world's human population, and most of them aspire to perform Hajj as an important part of their faith, with their desire to participate becoming more urgent as their age advances. As a result, among the two to three million pilgrims participating in Hajj every year for 2 to 3 weeks, a dis-proportionate fraction is elderly coming from Muslim communities around the world and visits the holy sites around Makkah in the Kingdom of Saudi Arabia. The ritual of Hajj involves spending roughly 20–30 hr outdoors over a period of about 5 days. The main outdoor activities occur in and surrounding Makkah. Outdoor activities take place over a period of five pre-specified days each year where all the pilgrims in any specific year must participate at the same time, resulting in very high-density crowds.

These 5 days are observed every year over the same days of the Muslim calendar, which follows the lunar cycle. Since the lunar year is shorter than the solar year by on average 11 days, Hajj defined within the solar calendar shifts by about 11 days earlier on average every year and cycles back to the same date in the solar calendar after roughly 33 years [FIGURE 2].

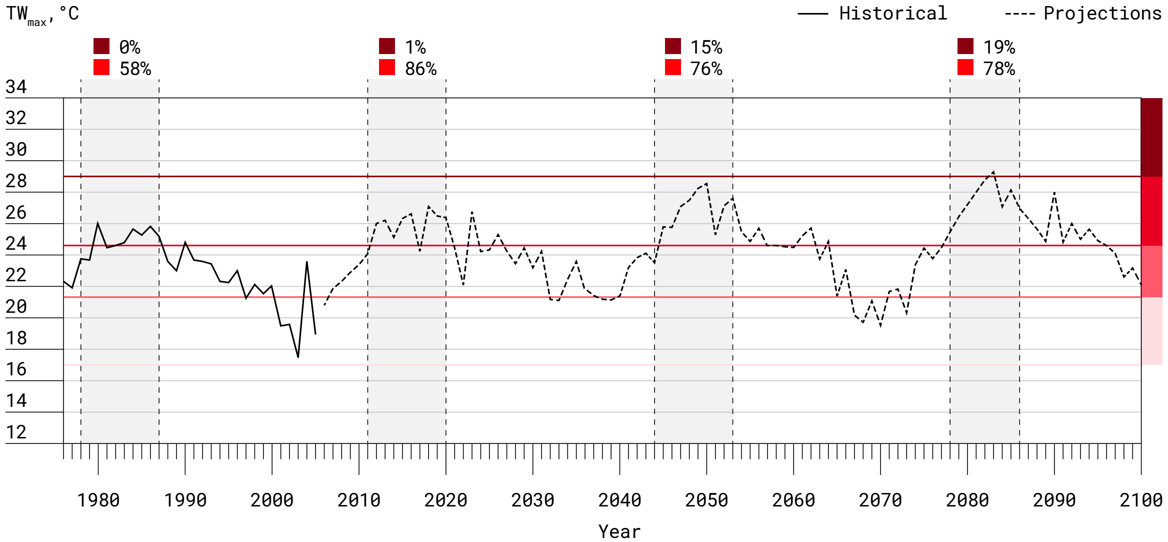
Kang and Eltahir[2], based on results of simulations using an ensemble of coupled atmosphere-ocean global climate models, project that future climate change with and without mitigation will elevate heat stress to levels that exceed extreme danger threshold through 2020 and during the periods of 2047 to 2052 and 2079 to 2086, with increasing frequency and intensity as the century progresses [FIGURE 3]. If climate change proceeds on the current trajectory or even on a trajectory with considerable mitigation, aggressive adaptation measures will be required during years of high heat stress risk.

The human health risk during Hajj depends on both the intensity and duration of the natural hazard as well as the level of vulnerability of the pilgrims in any specific year. The factors that shape this vulnerability include structural factors such as the capacity of the Hajj facilities and quality of transportation logistics and nonstructural factors such as the age distribution, health, and number of pilgrims. If anthropogenic GHG emissions and associated atmospheric concentrations remain unabated, the hazard associated with the future projected intensity, frequency, and duration of heat stress during Hajjis will require carefully planned strategies, especially in summer, and measures in order to avoid serious risk to human health during Hajj in the future. As Islam is the world's fastest-growing major religion and is projected to continue to be, strategies that manage the projected increases in those interested in performing Hajj are expected to be challenging, even in absence of climate change. Should pilgrims shift their prefer-

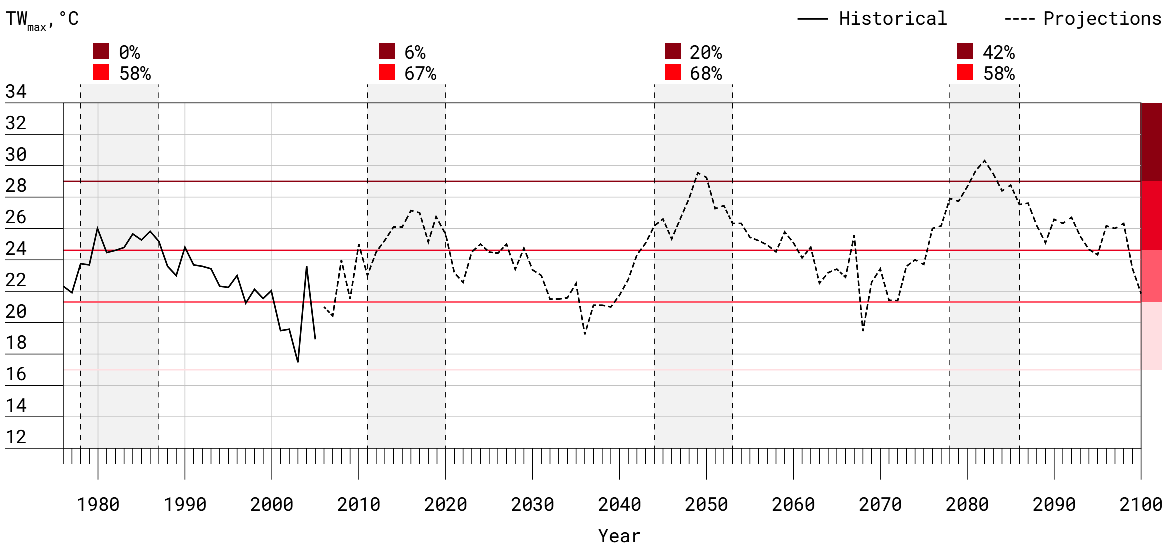
FIGURE 3 Daily maximum wet-bulb temperature (TW_{max}) during Hajj from 1976-2100 with frequency occurrence between Danger and Extreme Danger and exceeding extreme danger during August-September-October under the HIST and RCP 4.5 and 8.5 scenarios.

U.S. National Weather Service heat stress risk level at 45% humidity
Extreme danger
Danger
Extreme caution
Caution

A. TW_{max} RCP 4.5 SCENARIO



B. TW_{max} RCP 8.5 SCENARIO



Source: Kang and Eltahir, 2019[2].

ence of when they observe Hajj to milder climatic months avoiding the summer, these infrastructural challenges would likely be considerably amplified due to further increase in the number of those interested in performing Hajj during non-summer months. Any mitigation efforts favoring something similar to or more robust than RCP 4.5 will likely have significantly positive impacts by reducing the projected heat stress intensity and frequency. Nevertheless, the risk of heat stress increases substantially regardless of the scenario.

In recent years, Hajj facilities and logistics have been significantly expanded and improved to help provide refuge from extreme weather conditions, and similar continued and perhaps more aggressive efforts are likely to happen in the future. However, a well-planned strategy would be required to manage the nonstructural human vulnerability factors as well. Further research is needed to develop such sound strategies. One such strategy to be investigated is to reduce the number of pilgrims during the high-risk decades identified above and limit Hajj only to those pilgrims performing obligatory Hajj in good health.

POTENTIAL EMERGENCE OF DENGUE FEVER

Dengue fever is the fastest spreading viral disease, transmitted by Aedes mosquitos. In the past, Dengue did not pose a serious public health challenge in the Gulf region. However, the future could be different. Given the current trends in population, urbanization, climate change, and increasing level of travel, special attention needs to be given to this disease in order to ensure that Dengue would not spread in this region in the future.

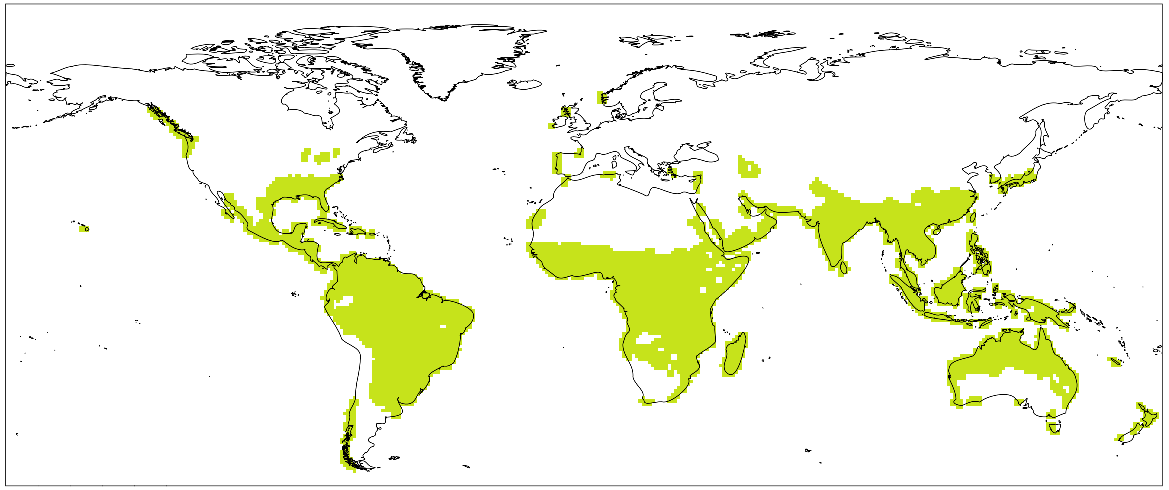
Many of the expatriates working in the Gulf come from Asian countries where Dengue is prevalent and widely spread such as India. Hence, it is likely that a significant reservoir of the virus itself exist in the Gulf countries. What could be limiting the transmission of Dengue is the absence of the Aedes mosquito vector. Aedes Aegypti, the main vector for Dengue breeds indoors in water containers. As such this vector may find ways to establish new breeding sites in the urban environments of the large cities on the Gulf. Even under the current climate, there is a significant potential for the spread of Aedes aegypti in the Gulf region, and significantly less potential for the spread of Aedes albopictus. See FIGURE 4.

The lesson from the of experience of Singapore with Aedes mosquitoes and Dengue is that prevention of the establishment of this disease at early stages and other prevention measures are likely to be much more efficient than fighting the vector and the disease after they find ways to establish themselves in the urban environment. The same mosquitoes that transmits Dengue are responsible for transmitting Chikungunya and Zika. Hence, prevention of Aedes establishment may prove fruitful beyond Dengue control.

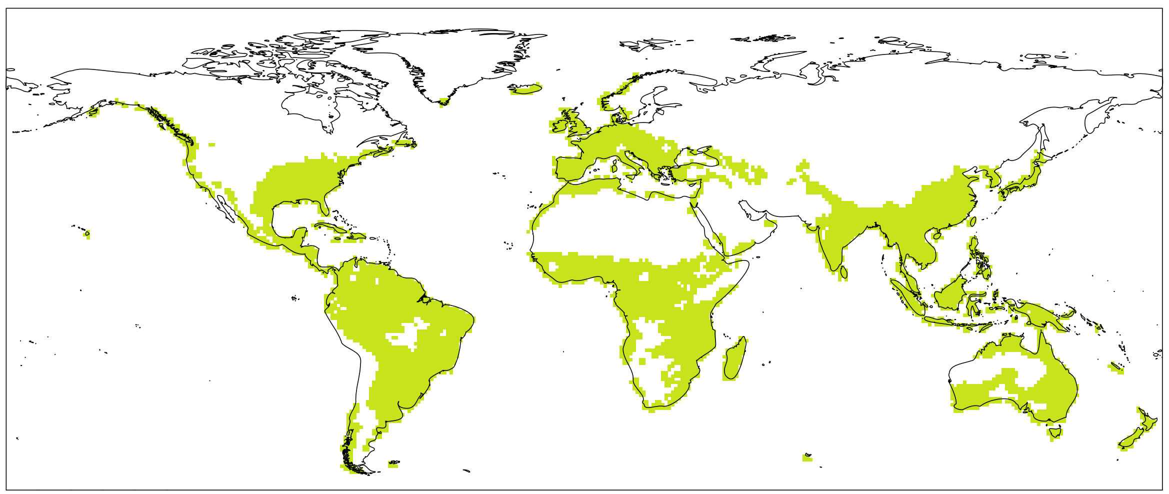
FIGURE 4 Current potential distribution of Aedes aegypti and Aedes albopictus based on present-day climatic conditions.

Suitable Areas
Unsuitable Areas

A. AEDES AEGYPTI



B. AEDES ALBOPICTUS



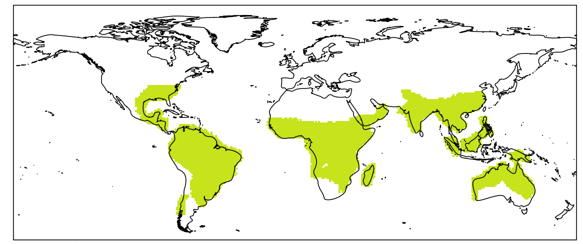
Source: Kamal et al, 2018[3].

The current projections of the potential distribution of Aedes aegypti under different scenarios of climate change suggest that the potential distribution of this vector in the Gulf region seems insensitive to climate change FIGURE 5. Further local and regional research, including field studies, is urged to confirm this welcome conclusion.

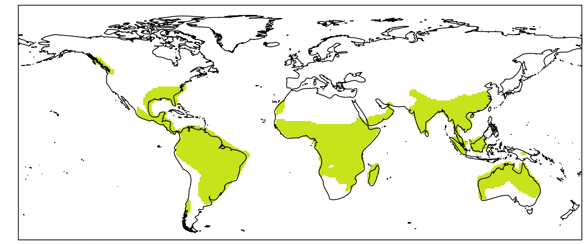
FIGURE 5 Predicted future potential distribution of Aedes aegypti under four future representative concentration pathways of climate conditions in 2050.

Suitable Areas
Unsuitable Areas

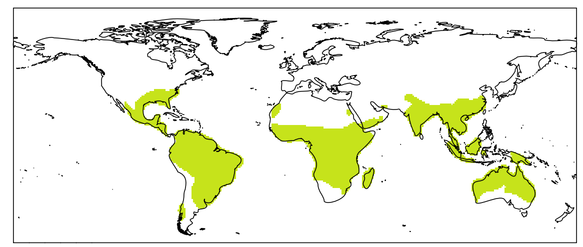
A. RCP 2.6



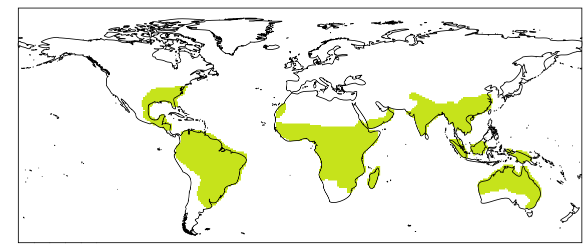
B. RCP 4.5



C. RCP 6.0



D. RCP 8.5



Source: Kamal et al, 2018[3].

AREAS OF FURTHER RESEARCH

- → There is need for further research to quantify how changes in heatwaves intensity and frequency would translate into enhancement of the incidence of heat strokes and possibly fatality among humans in this region.
- → In recent years, Hajj facilities and logistics have been significantly expanded and improved to help provide refuge from extreme weather conditions, and similar continued and perhaps more aggressive efforts are likely to happen in the future. However, a well-planned strategy would be required to manage the nonstructural human vulnerability factors as well. Further research is needed to develop such sound strategies. One such strategy to be investigated is to reduce the number of pilgrims during the high-risk decades identified above and limit Hajj only to those pilgrims performing obligatory Hajj in good health.
- → The current projections of the potential distribution of Aedes aegypti under different scenarios of climate change suggest that the potential distribution of this vector in the Gulf region seems insensitive to climate change. Further local and regional research, including field studies, is urged to confirm this welcome conclusion.

2.2

CLIMATE IMPACTS ON COMMUNICABLE DISEASES

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KEY MESSAGES

- → The spread of communicable diseases will be significantly impacted by the climate crisis.
- → Much of the existing literature does not adequately capture how this will be observed in the GCC nations.
- → Greater investment in public health research and disease surveillance will be required to better forecast the imminent epidemiological landscape.
- → Such research will require a cross-border, trans-disciplinary, approach to assure that such investigations are appropriate and effectively communicated.

INTRODUCTION

Over the last two years the Jameel Institute have built a reputation for their work with governments and international organizations around the world to provide rigorous policy advice on the pandemic response, providing advisory support to national agencies and bodies in many countries hardest hit by the pandemic, including Brazil, France, Italy, India, Indonesia, Malawi, Mozambique, Philippines, South Africa, Sri Lanka, the USA and Zimbabwe. This has involved the development of multiple mathematical tools and models requiring close consideration of key factors such as population density, seasonal variation, international travel, and socioecological systems and behaviors (such as the use of non-pharmaceutical interventions). All of these factors are intrinsically linked to the ongoing climate crisis, and will be considerably altered in the coming years [1], necessitating substantial further research into the expected changes to these elements, and how this will require adaptation to our communicable disease responses, and the targeted policy advice given.

In this section we initially summarize the extant scientific evidence on the association between climate change and communicable disease. We describe the mechanistic impact of mediating factors such as droughts, flooding, and increased temperature, as well as the more complex vulnerabilities introduced by interactions between environmental and social factors such as habitat loss and further urbanization. We then critically assess current disease forecasts, with a particular focus on how they apply to the countries of the Gulf Cooperation Council (GCC) - the intergovernmental union consisting of Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates. We separately consider the risk posed by vector-borne and non-vector-borne diseases, and highlight areas where there is currently insufficient evidence regarding the future risk posed by such diseases. We conclude by reiterating the policy advice issued by the wider community in preparing for the challenges ahead.

CLIMATE CHANGE AND COMMUNICABLE DISEASE

The majority of the relevant literature to date is primarily focused on the climate-induced changes likely to be seen in the spread of vector-borne diseases. This is partly due to the vast existing knowledge base on vector responses to changes in their environment, and an urgency driven by an increasing number of vector-borne disease outbreaks in areas previously unchallenged by such diseases, primarily in Europe [2, 3]. By far the most prolific disease vector is the many species of mosquitoes that transfer disease from host to host via their bite. Like many other insects, mosquitoes are unable to self-regulate their body temperature, meaning that most features of their life-histories are temperature dependent [4], and leaving them particularly susceptible to thermal stress. Most mosquito species are unable to survive

at temperatures outside of 10-40°C [5]. Within this range however they are observed to hatch quicker and survive longer within the higher end of this temperature range [5, 6]. Crucially, these warmer temperatures are also favorable for the transmission of the viruses and parasites carried by mosquitoes [7]. Falciparum malarial protozoa for example are observed to develop in just 13 days at 25°C, but require 26 days at a milder 20°C [8]. Dengue similarly is observed to propagate faster within host mosquitoes in climates of greater temperature and humidity, with a proposed optimum temperature of 24-31°C [9]. Mosquitoes lay their eggs on the surface of standing water pools, meaning that increased vector populations are often correlated with periods of heavy rainfall [10]. The exact mechanistic impact however is often dependent on the life-stage of the affected mosquito, as unexpected sudden rains may dislodge larval mosquitoes from spawning pools [11], whereas periods of drought may also cause increases in mosquito populations in certain regions, due to dry spells limiting the number of natural predators [12]. As such, mosquito populations are sensitive to both gradual increases in mean temperature [13] predict the global suitability for the development of Ae. aegypti to increase 3.2–4.4% per decade by 2050), and to increased numbers of extreme weather events inducing unpredictable changes to mosquito population dynamics.

Similar relationships and behaviors are observed within other disease vectors. Phlebotomus sandflies have been observed to hatch and metabolize at a faster rate at 28°C compared to 23°C [14], however only some species of the Leishmania parasites that they carry (responsible for leishmaniasis) are shown to multiply faster at such higher temperatures, with some species indeed multiplying faster at lower temperatures [15]. Ticks are also found to have increased egg production and population density at greater temperatures [16], though significantly heterogeneous patterns in tick-borne encephalitis (TBE) in Europe drive hypotheses that other climate change factors beyond temperature, such as flooding and habitat-loss, may be triggering an increase in population density for many rodents and large host-animals for ticks [17], eliciting an increased risk of tick-borne diseases such as encephalitis, Crimean-Congo haemorrhagic fever and Lyme disease.

Increased temperatures will directly increase the rate of food spoilage, and increase the growth rate of common gastroenteritis culprits such as Salmonella and Campylobacter [18], while flooding has been attributed with increased gastroenteritis outbreaks by causing run-off from colonized sources to contaminate drinking water supplies, and livestock at the very start of the food chain [19].

While mechanistic connections between climate change and droplet/airborne diseases have yet to be ascertained, seasonal trends in disease incidence are frequently observed. These trends differ between regions, with some pathogens displaying contradictory patterns. Respiratory syncytial virus (RSV) for example, a common virus transmitted by droplets, will display peaks in the summer at locations with persistently warm weather, but conversely will experience winter peaks in more moderate climates [20]. Influenza transmission famously increases during the colder months for each particular hemisphere, spawning multiple hypotheses as for this climate-driven surge. Host susceptibility may be affected by melatonin levels responding to the day/night cycle [21]. Seasonal changes in human movements such as the opening and closing of schools have been shown to influence the rate of influenza transmission [22]. Alternatively, the survival rate of influenza virus has been shown to be higher in conditions of low vapor pressure (a measure of absolute quantity of moisture in the air) [23], synonymous with the winter months. Unfortunately the conflation of so many potential mechanisms together means that definitive explanations have been difficult to present [24]. Regardless of these seasonal patterns, factors such as an increasing global population, environmental degradation/desertification, rising sea levels, and increased urbanization point towards a future of increased agglomeration and population densities [25]. Perhaps unsurprisingly, population density has been definitively attributed as having greatly increased location-specific transmission rates throughout the COVID-19 pandemic [26].

CLIMATE CHANGE IN THE GCC NATIONS

The Arabian Gulf is one of the most vulnerable regions in the world to the effects of climate change [27]. The GCC nations are forecast to be particularly struck by water stress [28] and severely dangerous heat waves [29], such that limits for human adaptation are brought into question [30]. Many of the most populous regions in the GCC are along the coast of the Gulf, placing them at particular danger of rising sea levels. Under the current worst-case (RCP 8.5) estimations of the Intergovernmental Panel on Climate Change (IPCC) of an approximately 1m rise in sea levels by 2100 [31], 1,215 km^2 of GCC land is projected to be inundated by sea level rise [32]. Already an average 4°C rise in ambient temperature from the 1960s has been recorded, reaching average summer temperatures of approximately 40°C, but with record highs reaching > 50°C [33].

In the face of global temperature increases, Gasparrini et al. (2017) [34] constructed a model to forecast the likely increases in ex- cess mortality to be observed globally by the end of the century, including the associated impacts of increases in communicable diseases. Indeed, an increase in MERS-CoV incidence in Riyadh has previously been associated with increased temperature and UV radiation [35] (1.054 and 1.401 incidence rate ratios respectively). Under the most extreme heating assumptions) [34] predict rises in excess mortality ranging from 3% in Northern Europe to upwards of 15% in South East Asia. Notable however, is that no projections are able to be computed for the entirety of the Middle East due to a lack of any informing

data capturing temperature and mortality linkage. As we display below, this omission of the Arabian Peninsula is a frequent occurrence in the scientific literature. As the GCC population continues to rapidly grow, having doubled from approximately 30 to 60 million in the last twenty years [36], we find ourselves with a considerable, and growing, subset of the global population for whom we know dangerously little of their projected health challenges.

As the population increases, so too does water demand, which is predicted to only become harder to satisfy under projected longer periods of drought [37], and increasing ocean salinity [38]. However, despite these general projections, information on more specific impacts to precipitation trends is unavailable as of yet, making it hard to build meaningful predictions of future agricultural and biodiversity indicators.

VECTOR-BORNE DISEASE FORECASTS

In the last few years several high-profile maps have been published demonstrating the risk posed by, specifically, Aedes-borne disease in the coming century, informed by projected climate and population data [39, 40], an example of which we present below in FIGURE 1.

The general consensus of these maps portrays a minor shift in risk for the GCC nations; however, projections are only as good as the data informing them, and the GCC is woefully under-represented in the relevant data informing these maps. Indeed, less than 1% of the informing data for the map presented in FIGURE 2 represents the entire Eastern Mediterranean Region (EMR) [41]. In attempting to quantify the uncertainty surrounding the predictions for this region, [41] produced suitability maps identifying areas of high risk for vector-establishment throughout all GCC nations that were previously overlooked by the broader global maps. Such models have considerable room for further refinement, as existing mosquito population dynamics are poorly captured in the region [42]. Indeed, the severe temperature increase and decline in precipitation predicted for most of the Middle East [43] will require further research into the assumed impact on all manner of disease vectors. While summer temperatures of greater than 40°C and longer drought periods may suppress many vector populations, current human population increases will require greater urban expansion and water provision - increasing the risk of vector establishment. Substantial water loss may eliminate many sources of infection, or conversely induce greater migration into dense population hubs [44].

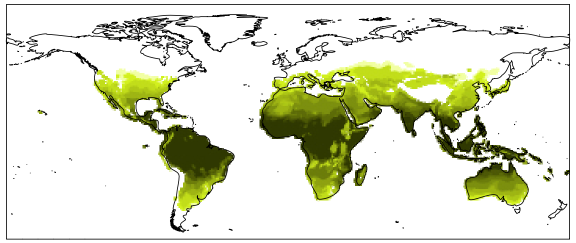
Given the extent of the predicted temperature increases in the GCC nations, climate change will likely introduce a competing selection of factors that both increase and decrease risk. Certain geographic areas will likely become inhospitable for certain vectors, while others will become a more favorable source of pathogen transmission. To investigate the similar scenario of ecological trade-offs predicted in Ecuador, [45] designed a model forecasting the geographic shift in risk posed by 14 different disease vectors across Ecuador up to 2100, revealing a substantial change over time in both the regions of the country most challenged, and the vectors likely to be present there.

FIGURE 1 Projected number of months of climate suitability for Aedes aegypti and albopictus mosquitoes respectively, under the more extreme RCP 8.5 temperature increase forecasts.

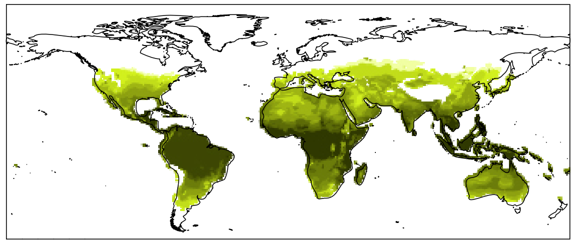
Months of climate suitability

0 12

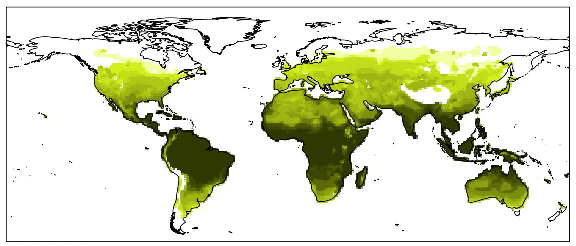
A. AEDES AEGYPTI: CURRENT



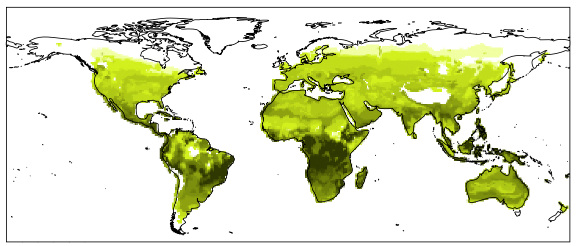
B. AEDES ALBOPICTUS: CURRENT



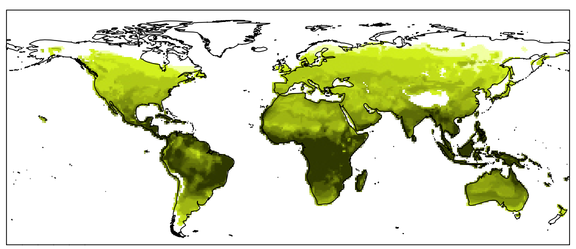
C. AEDES AEGYPTI: RCP 8.5 (2050)



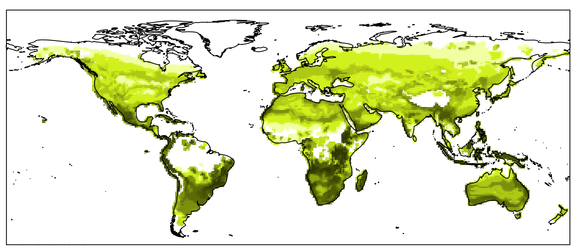
D. AEDES ALBOPICTUS: RCP 8.5 (2050)



E. AEDES AEGYPTI: RCP 8.5 (2080)



F. AEDES ALBOPICTUS: RCP 8.5 (2080)



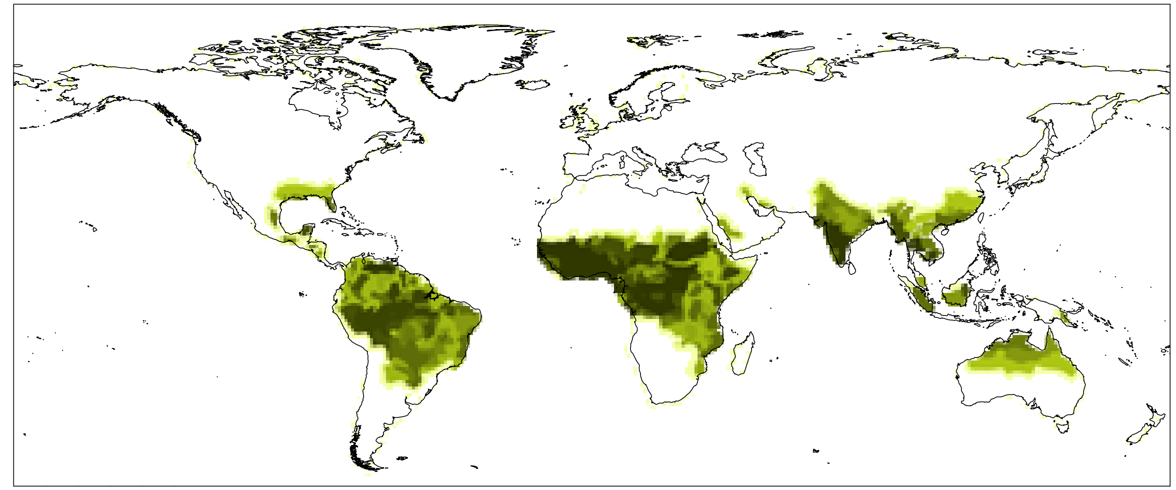
Source: Ryan et al. 2019 [40].

FIGURE 2 The distribution of Aedes aegypti and Aedes albopictus in 2050 under the medium climatic scenario RCP 6.0.

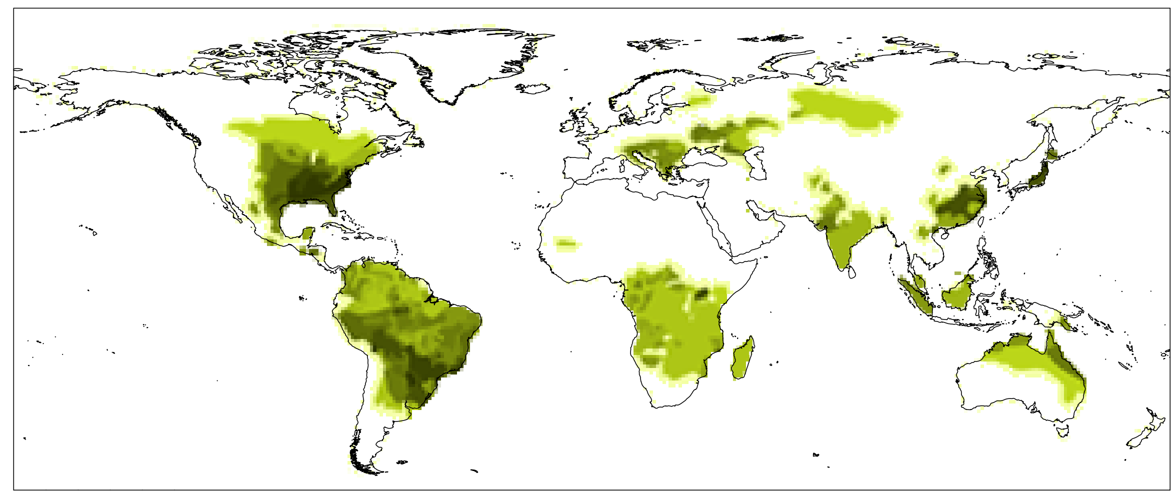
Distribution

0 1

A. AEDES AEGYPTI



B. AEDES ALBOPICTUS



Source: Kraemer et al. 2019 [39].

FURTHER COMMUNICABLE DISEASE FORECASTS

Beyond solely vector-borne communicable diseases, forecasting the spread of diseases via human-to-human interactions in relation to climate change is significantly more challenging. While climate-related factors greatly influence the spread of such diseases, the clear climatic signal is particularly difficult to extract from case data. Since many infections impart acquired immunity for some period of time, each infection will both incite further transmission, but also lessen the available pool of susceptible individuals. These "feedbacks" in transmission will, in some instances, mask the associations with periodic climate patterns, as demonstrated by [46]. This is then further exacerbated once one considers the variation in disease incidence induced by a wide variety of other time-varying factors seen in the last century, such as health-inequality, urbanization, and the increase in international trade and tourism (driving increases in disease importation) [47]. As the number of confounding factors grows, even greater amounts of data are required to begin being able to unpick the correlating patterns.

The COVID-19 pandemic will enable a far greater understanding of these dynamic patterns, providing an immense dataset of incidence and mortality under a wide-reaching system of global covariates. While the quality of disease surveillance has differed substantially across the pandemic from country to country, the sheer scale of the global effort to monitor the spread of distinct COVID-19 lineages across multiple climatic regions and conditions provides greater opportunity to research these climate-disease relationships than has been possible before. Literature investigating the impact of climate on COVID-19 transmission is already emerging, identifying the favorable conditions offered by cold and dry climates [48, 49]. The next decade is likely to yield a vast research output, exploring complex networks of relationships between the spread of COVID-19 and patterns in mobility, behavior, climate, and confounding health factors - greatly improving our understanding and ability to predict how the spread of respiratory diseases will be impacted by changing climates. However, the extent to which such conclusions generalize to a wider array of pathogens remains to be seen.

While improved data gathering in the region will improve the quality of future projections for the challenges facing the GCC nations, modeling unique to the region will be crucial due to the particular demographic dynamics of the area. The countries of the GCC have uniquely large expatriate populations - an average of 53.43% expatriates across the GCC in 2010, compared to the 9.5% expatriate average in the broader Middle East and North Africa (MENA) region [50]. This demographic composition means that while many diseases may not be indigenous to the nation, a far higher number of imported cases are observed than may be seen elsewhere globally. For example, in 2010-2019, 98.5% of the 7,327 reported cases of malaria in the GCC

were imported cases [51]. The majority of this expatriate population is made up of immigration from India, Pakistan, the Philippines, and Bangladesh [52], all of which similarly face substantial climate and disease challenges [53, 54]. Such distinctive transmission dynamics mean that the conclusions of disease modeling efforts may not necessarily directly apply to outbreaks in the GCC population.

[44] Conducted a focused literature review into the existing climate change and health research unique to the EMR region. Of the mere 64 publications that qualified for review at the time, less than 10 could arguably be said to provide meaningful results applicable to the Arabian gulf. They concluded that such information gaps would severely limit the region's ability to prepare for public health challenges and support the adaptability that would be required. Indeed, attempts to quantify the global warming-induced human health risk [55] were hindered by inconsistent forecasts for the Gulf countries due to low data availability.

POLICY ADVICE

Increased investment in cross boarder research and data gathering cannot be stressed enough. Beyond simply increasing the reach of the research output, cross-border initiatives allow deeper conclusions to be drawn from greater data variability. Linking such data to specific local priorities and healthcare capacities will require careful consideration to capture the most appropriate spatial resolution of disease incidence [56]. For example, careful marrying of detailed environmental data pertaining to the Amazon rainforest has been shown to be deeply informative of disease outbreaks in Brazil [57], where deforestation creates ideal conditions for some disease vectors, requiring the targeted use of treatment, intervention, and surveillance. Such systems have succeeded in greatly reducing cases of malaria in Brazil to 130,000 in 2016 - the lowest recorded in 38 years. Likewise, the recently established European Climate and Health Observatory sources a wide array of climate and health data to prepare for the impacts of climate change by developing indicators, early warning systems, and information systems [58, 59]. More specific to the Middle East, the Middle East Consortium for Infectious Disease Surveillance (MECIDS) has recently had great success in monitoring and suppressing outbreaks of both avian influenza and H1N1 influenza in a cross-border collaboration between Jordan, Israel, and the Palestinian Authority [60]. Rapid introduction of cross-border screening, laboratory testing, outbreak communication, and targeted agricultural culling was practiced alongside the shared expertise of experts within both public health and government, as well as representatives from the transportation, education, interior, laboratory, and media sectors.

On this point, it is advised that such research investment must facilitate a "trans-disciplinary approach" [1], requiring the collaboration of specialists covering ecology, climatology, social sciences and biology, beyond just the expertise of mathematical modelers and epidemiologists. Specialists will be required to evaluate and identify weak points in the health systems and surveillance of specific nations, and highlight the specific climate challenges posed to particular regions, to ensure that the most pertinent research outputs are prioritized. An example of such cross-specialization knowledge sharing is seen within MECIDS, where summer schools and virtual events have been hosted to provide training and networking opportunities for epidemiologists and laboratory technicians, within both academia and their respective health ministries [61].

While establishing a strong interdisciplinary surveillance and modeling team is crucial, such expertise can be wasted if findings are not then smoothly translated into public health action. [62] Reference multiple occasions where public health responses have been stymied due to poor linkage between model developers and model users. The addition of monitored climate change factors are likely to further strain this divide. As such they recommended the induction of “outbreak science” specialists fielded to respond to three specific challenges;

→ Establish and communicate model capabilities for decision maker
→ Develop communication pathways between all required parties
→ Promote cross-disciplinary training. [62] Note that while many of these points may be rapidly addressed during specific epidemics, permanent capabilities are rarely supported long-term.

Responding to the various challenges throughout the COVID-19 pandemic has required the consideration of multiple “what-if” scenarios. Such projections depend wholly on robust, efficient, and information-rich data streams. The approaching climate change crisis and its effect on the spread of communicable diseases will require the consideration of substantially more “what-if” scenarios, and likewise will depend on equally vastly expanded data streams. It is vital therefore that such surveillance systems, international partnerships, response systems, and research capacity is developed sooner rather than later.

AREAS FOR FURTHER RESEARCH

→ Targeted gathering of climate and disease data within the GCC will allow better forecasts to be drawn using existing modelling frameworks.
→ Bespoke mechanistic modelling studies of epidemiological systems have yet to be exhaustively specialised to the Middle East. Mathematical modelling of the impact of expatriate movement should be conducted as a first priority.
→ Ecological surveys of disease vectors in the region needed to assess how key vectors are responding to the changing climate.

CLIMATE CHANGE & WOMEN'S HEALTH: A CALL FOR ACTION

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KEY MESSAGES

- → The effect of climate change on women's health has been a rare subject of research.
- → Women are more vulnerable to the effects of climate change than men.
- → Climate change affects maternal, sexual and reproductive health.
- → Countries have not correlated climate data with gender-disaggregated health data.
- → Existing metrics for women's health do not establish connections with climate change.

INTRODUCTION

The third goal of the 17 Sustainable Development Goals (SDGs) established by the United Nations General Assembly in 2015 is "Good Health and Well-Being." Two of the key targets of this goal concern women's health: To lower maternal mortality rates (SDG 3.1) and to guarantee access to services related to sexual and reproductive health (SDG 3.7). "Climate action" is the 13th SDG, and it aims to "Take urgent action to combat climate change and its impacts." Current recognition attests to broad interdependence between environmental and human health [1], yet the effect of climate change on women's health has been a rare subject of research.

Women make up the majority of the world's poor and have unequal access to resources, limited mobility, and limited access to decision making processes, making them more vulnerable to the effects of climate change than men. Women and children are up to 14 times more likely than men to die after extreme-weather disasters like hurricanes, wildfires, and flooding; and females who survive climate-related disasters are more likely to face decreased life expectancy, mental health disorders, gender-based violence, and exploitation [2, 3].

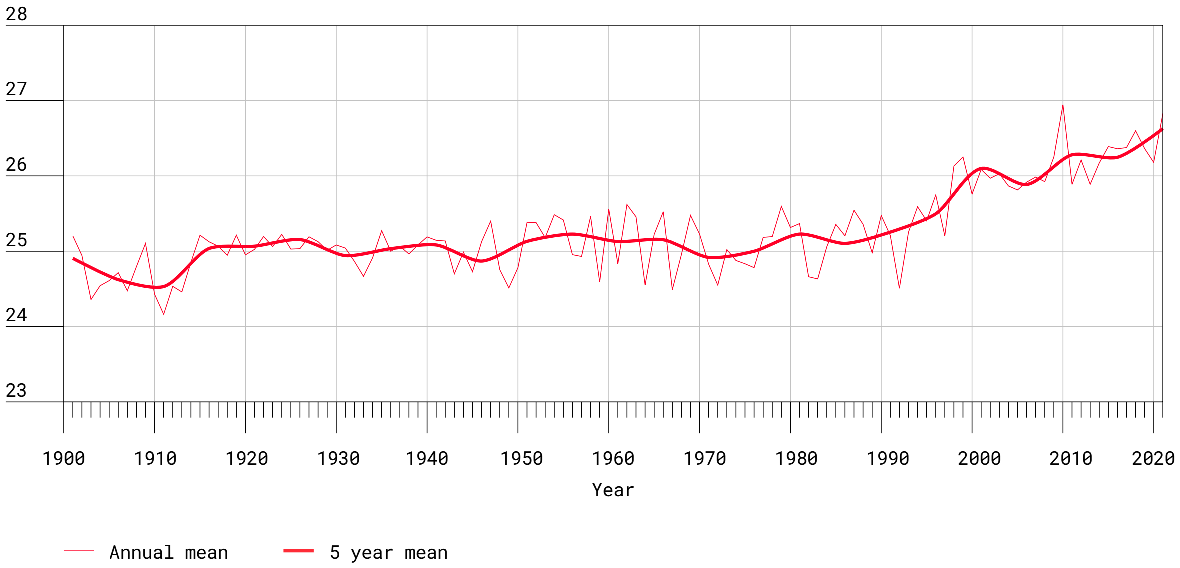
Climate change adversely affects the availability of essential crops like wheat, corn, and rice, which affects production, consumption, and pricing of food [4]. Increased prices of crops raise the price of livestock feed, which in turn raises the price of meat – projecting lower overall consumption of meat and grains by 2050. Such food insecurity may disrupt menstruation in women, where timeliness and regularity of cycles depend on a balanced diet, and where irregularity is associated with a higher risk of major chronic diseases.

Climate change has also been linked to maternal, sexual, and reproductive health [2, 5]. Dehydration during pregnancy, as a result of rising temperatures, heat waves, droughts, rain variability, and restricted access to safe drinking water can have adverse effects on mother and child. Health complications from temperature exposures include compromised ability of pregnant women to thermoregulate, decreased birth weight, release of labor-inducing hormones, preterm births, stillbirth, neonatal stress, heat-related infant mortality, and increased maternal risk of anemia and eclampsia. Undernutrition of pregnant women resulting from climate-related food insecurity can also affect pregnancy and nursing, leading to low-weight births, miscarriages, and perinatal mortality. Vector-borne diseases, such as Malaria, Zika, and dengue, which are associated with climate-related temperature and precipitation fluctuations can increase the risk of spontaneous abortion, premature delivery, stillbirth, and cesarean delivery. Additionally, in areas affected by climate crises, violence, sexual harassment, trafficking, and child and forced marriages increase, making girls who become pregnant before the age of 15 at risk of placental tears, obstructed delivery, and maternal mortality. Even after climate-related disasters have passed, disruptions occur to health services, impeding women's access to contraceptives, counselling, maternal and child care, and treatments and testing for HIV and other sexually transmitted infections. Sexually transmitted infections, if left untreated in affected mothers, could result in infertility, tubal or ectopic pregnancy, cervical cancer, and perinatal or congenital infections in infants.

Additionally, maintenance of a healthy lifestyle is challenged by rising temperatures. Women have been found to respond differently to exertion in the heat than men, as a result of typically higher percentage of body fat and lower aerobic power. Specifically, women are 3.7 times more likely to be heat intolerant than men [6], making women participation in sports outdoors in high temperatures very difficult.

In spite of the risks that climate change poses to women's health, many countries still do not systematically correlate climate data with gender-disaggregated health data. In the case of the Kingdom of Saudi Arabia, for example, the climate has been warming at an accelerated pace [FIGURE 1]. Temperatures have been increasing at a rate of 0.63°C per decade [7]. The geographical terrain of the country makes its inhabitants more susceptible to the effects of climate change. More than a third of the land is desert, and the topography varies from vast stretches of sand to rugged mountains. This makes the country prone to heatwaves, water scarcity, and air pollution [FIGURE 2]. Future temperature in the region is projected to continue to increase and to "exceed the threshold deemed unsuitable for human adaptability" [8], affecting the sustainment of healthy lifestyle habits like outdoor exercise and affecting the country's production of fresh fruits and vegetables, causing micronutrient deficiencies like vitamin D.

FIGURE 1 Rise in average annual mean temperature in Saudi Arabia since 1901.

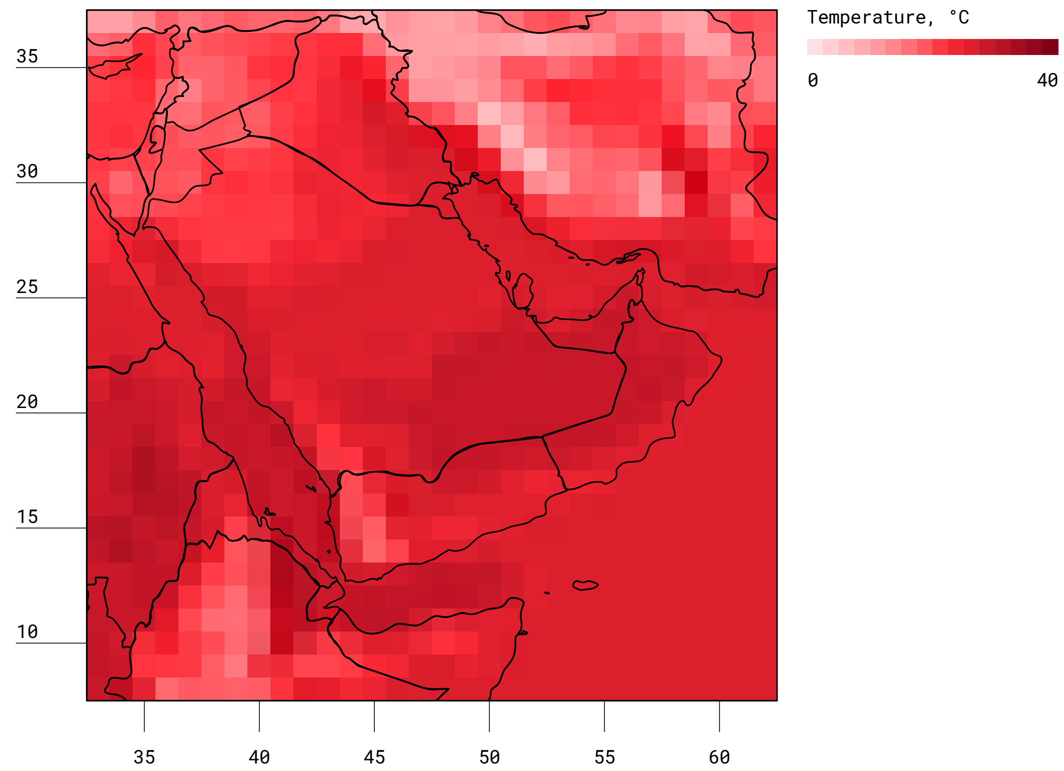


Source: Climate Change Knowledge Portal [9].

According to the World Health Survey Saudi Arabia 2019 Final Report [10], 81.6% of female respondents had insufficient physical activity, 92.9% of female respondents had insufficient intake of fruit and vegetables, 32.7% of female respondents were overweight, and 21.4% were obese. Moreover, the percentage of anemia among pregnant women was 53%. The Saudi Healthcare Responsiveness study (2019) [11] also found that women had relatively higher blood pressure than men (16.1% and 11.5% respectively), suffered relatively more strokes than men (0.50% and 0.40% respectively), had slightly more heart disorders than men (2.40% and 2.20% respectively), and higher mental illness than men (1.50% and 0.70% respectively).

Gulf Corporation Countries (GCC), which are close to one another in climate conditions, report health statistics related to SDGs. Saudi Arabia reduced the maternal mortality rate (SDG 3.1) from 17 per 100,000 live births in 2015 to 12 in 2018, and reported a contraceptive prevalence rate (SDG 3.7) of 24% using modern methods [12]. In 2015, Bahrain decreased the maternal mortality rate from 26 to 13, Qatar from 29 to 4, and UAE reached 6 per 100,000 live births. [1] Noted, however, that the GCC reports have not included environmental challenges, nor plans to preserve sustainability of these health improvements

FIGURE 2 Observed annual mean temperature 1991-2020 in Saudi Arabia.



Source: Natalia Odnoletkova and Tadeusz W. Patzek, KAUST.
Based on ERA5 dataset.

in the case of unexpected events like natural disasters. The reports did not make links between SDG 3 “Good Health and Well-being” and other SDGs (e.g., “Climate Action” or “Responsible Consumption and Production”), did not make connections among targets within SDG 3 itself (e.g., reducing communicable and non-communicable diseases), or describe any environmental regulations to enhance the health and well-being of pregnant women and babies.

Existing metrics for the gender gap in health also do not make direct connections with climate change. The Global Gender Gap Index issued by the World Economic Forum [13], for instance, gives Saudi Arabia in 2021 a result of 0.964 (where 1.00 is a full score) in the dimension of Health and Survival, with high scores on the variables of sex ratio at birth (0.944) and healthy life expectancy (1.009). The Saudi

Women Participation in Development Index [14] locally issued by the National Observatory for Women in 2019 similarly gives the country a high score of 0.98 in the Health Pillar (where 1.00 is a full score), with scores of 0.99 in births not ending in mortality, 1.00 in births under the supervision of health professionals, 1.00 in healthy life expectancy, and 0.57 in percentage of women exercising regularly.

CONCLUSION

It is thus imperative that collaboration platforms that have come into being to address climate change at the national, regional, and global scale consider implementing a system for the correlation of climate data with gender-disaggregated health data. Endeavors such as the Saudi Green Initiative and the Middle East Green Initiative among other projects could provide opportunities to better and more directly assess the impact of climate change on health and well-being. This would not only identify gaps in knowledge and policies, but would also pave the way to evidence-based planning and public awareness of how to best confront effects of climate change on women's health.

AREAS OF FURTHER RESEARCH

→ The impact of climate change on women's health.
→ The need for environmental policies and regulations to enhance the health and well-being of women.
→ A knowledge base for public awareness on how to best confront effects of climate change on women's health.

2.4

IMPLICATIONS ON FOOD SECURITY IN HIGH FOOD IMPORTING COUNTRIES: FOOD IMPORT VULNERABILITY IN THE GULF COOPERATION COUNCIL

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KEY MESSAGES

→ Domestic food production cannot meet most of food demand in the GCC.
→ Imports are the key to Food Security in the GCC.
→ Future climate and demographic changes will impact world market prices and food supply from traditional trading partners of the GCC.
→ GCCs food imports for some commodities are limited to a few supplying nations making the GCC vulnerable geo-political events and supply chain issues.
→ It is crucial that the GCC maintains it fossil fuel driven export economy or diversify by 2050 to absorb the food impact price shocks from climate change to maintain Food Security.

INTRODUCTION
FOOD SECURITY, CLIMATE CHANGE, AND HEALTH

Food security and human health are inextricably linked. The 2009 Declaration of the World Food Summit defines food security as, "when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life"[1]. Food security is built on four pillars: availability (sufficient supply of food), access (sufficient resources and market availability), utilization (sufficient knowledge of food preparation and dietary diversity do achieve healthy nutritional status), and stability in achieving the other three dimensions over time [1-3]. Integral to the concept of food security is the achievement of positive nutritional outcomes[1].

TABLE 1 Global average of percent change in yield due to Climate Change (CC).

Commodity	% Change in yield
Grains	-8.6%
Oilseeds	-7.9%
Rice	-5.9%
Fruits and Veg.	-8.2%
Meat and Milk	-3.5%
Pr. Foods	Not available

-100% 0%

Source: IFPRI, 2019.

The effects of climate change pose a long-term threat to all four pillars of food security. The impacts relative to technological advances over the next 30 years will occur in multiple, interconnected ways, key among them: crop yields are predicted to decline for all major crops due to changes in precipitation patterns, extreme weather events, and increasing competition from weeds and pests on crops [(TABLE 1) 4, 5] pests, disease, heat stress, reduced quality of animal feed, and changes in water temperature will affect livestock and fishery production[5, 6]; climate change-induced geopolitical instability and infrastructure damage could disrupt food distribution systems[5, 7]; the nutrient quality of many crops will decrease with elevated atmospheric CO_2[5] and yield loss and supply chain disruption, in addition to population and economic growth, will drive increases in world market food prices [TABLE 2]. Additionally, in conditions of price-driven food insecurity, people cope by shifting their diets to calorie-rich but nutrient-poor foods and/or they endure hunger, leading to health related consequences ranging from micronutrient malnutrition to obesity[5].

TABLE 2 Changes in real world market prices from 2020-2050.
→ NO CC: Not factoring in Climate Change;
→ CC: Factoring in Climate Change impacts to world.

Commodity	Worldmarket prices (US$)			% Difference between NO CC and CC Worldmarket prices (US$)[4]
	2020	2050 NO CC	2050 CC	
Oilseeds	485	511	669	+31%
Grains	230	259	336	+30%
Rice	396	457	567	+24%
Pr. Foods	640	743	851	+14%
Fruits and Veg.	952	1,145	1,311	+14%
Meat and Milk	2,713	2,832	2,955	+4%

0 – 2,955 (colour scale); 0 – +100%

Source: IFPRI, 2019.

It is widely recognized that a country's food security increases with economic development. However, as the ripple effects of climate change accelerate through the complex and interdependent global food system, the future food security of even some wealthy nations is at risk. This threat is particularly relevant for countries with limited capacity for domestic food production and vulnerable non-agricultural export markets that rely heavily on imports to meet demand for food, such as the rich Arab Gulf countries. There is an imminent need for these countries to assess food-related risk factors in order to guide domestic and foreign policy towards decisions that will ensure future food security. Here we look at the potential threats to food security in the Gulf Cooperation council (GCC) in the context of global food supply chains, with a particular focus on trade and geopolitical dynamics in the broader West Asian region. This analysis forms a foundation for analyzing the relationship between food security and climate change in other high net food importing nations.

METHODS
STUDY AREA: GULF COOPERATION COUNCIL (GCC) COUNTRIES

The GCC is a group of six Arab Middle Eastern countries (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates) bordering the Gulf [FIGURE 1]. The countries cover a geographic area of 2.6 million km^2, have a total population of approximately 56 million people, and a combined GDP of approximately US$ 1.5 trn [8]. Their vast oil and gas reserves (30% of the proven oil and 22% of the proven natural gas reserves in the world) and relatively small populations have made the region one of the wealthiest in the world [3].

The GCC countries are ranked as the most food secure in the Arab world and are among the highest-ranking in the world for both food security and food affordability [9]. Their fiscal strength allows them to bridge limited capacity for domestic food production with food imports and provides them high buying power in international food markets, making them less vulnerable to price risk than other food importers [3,10]. However, the current situation masks a fragility in the long-term food security for the nations of the GCC.

The Council on Foreign Relations reports that countries at the greatest risk for food insecurity are those that rely heavily on food imports, lack diversity in food suppliers, and/or are already facing risks from climate change, conflict, or economic troubles [147]. The GCC states meet most of these conditions: domestic food production is capable of meeting only a small portion of food needs, a situation that will intensify with climate change; they are some of the most food import-dependent countries in the world, leaving them vulnerable to import price volatility and supply disruption; regional instability and geopolitical tensions increase the price and supply risk and have the potential to cause domestic unrest; and the ability of governments to continue to mitigate price risk is dependent on successful economic diversification away from oil and gas [12,14].

Capacity for domestic food production in the GCC is highly constrained by absolute water scarcity[2] (the region is the most water-stressed in the world), high temperatures, and poor soils [3,15].

[FIGURE 2] Presents the historical climatic conditions that relate to water stress and limited agricultural potential.

[2] *Absolute water scarcity is defined as less than $500m^3$ per capita per year of renewable freshwater resources (https:// www.un.org/ waterforlifedecade/scarcity.shtml)*

FIGURE 1 GCC countries and the broader West Asia region.

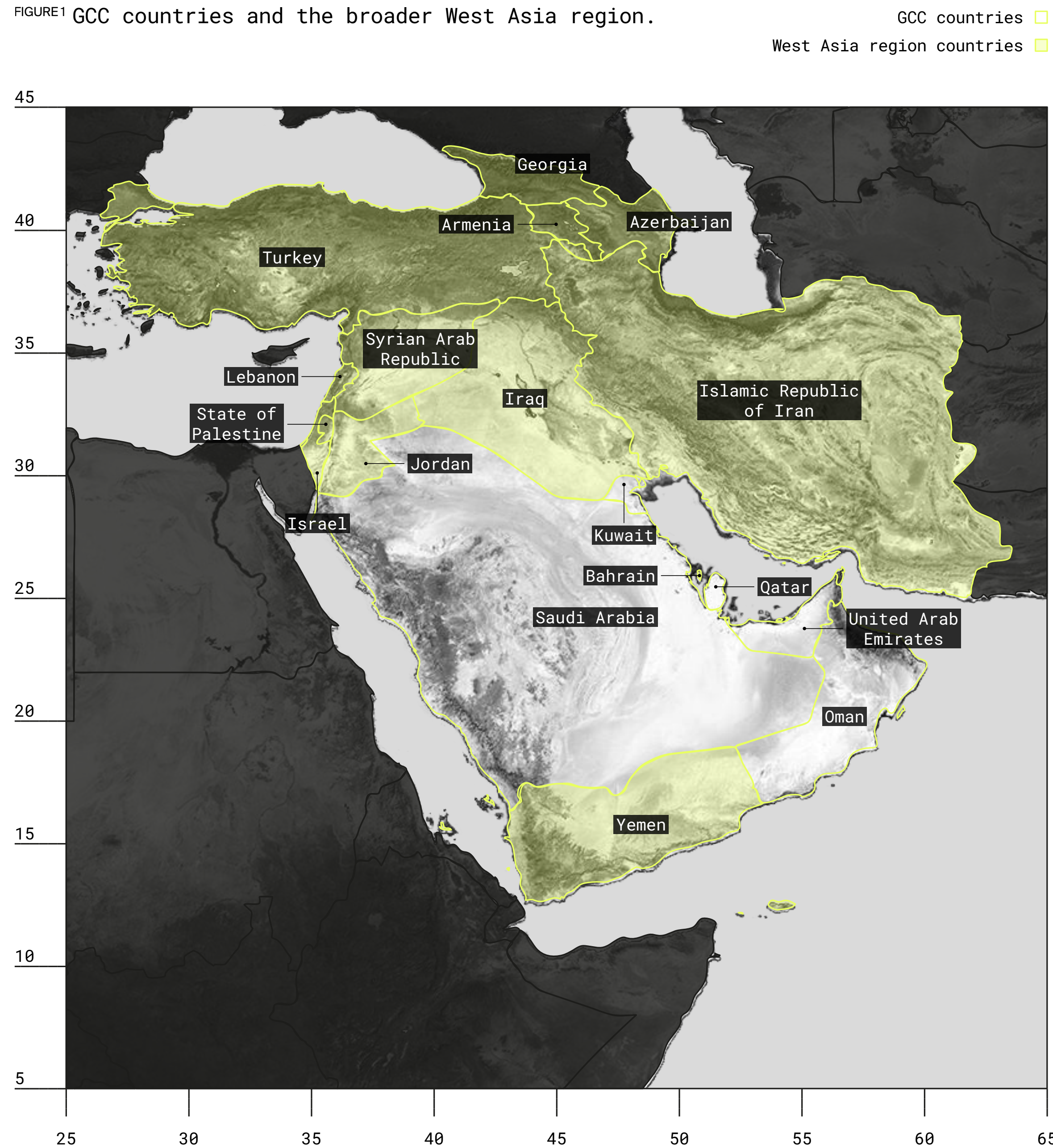
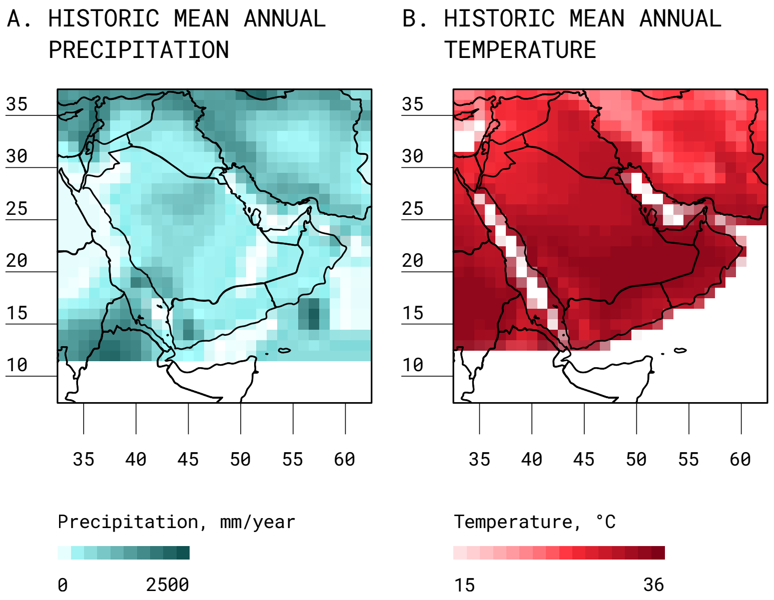


FIGURE 2 Historical Climate of the GCC Region.



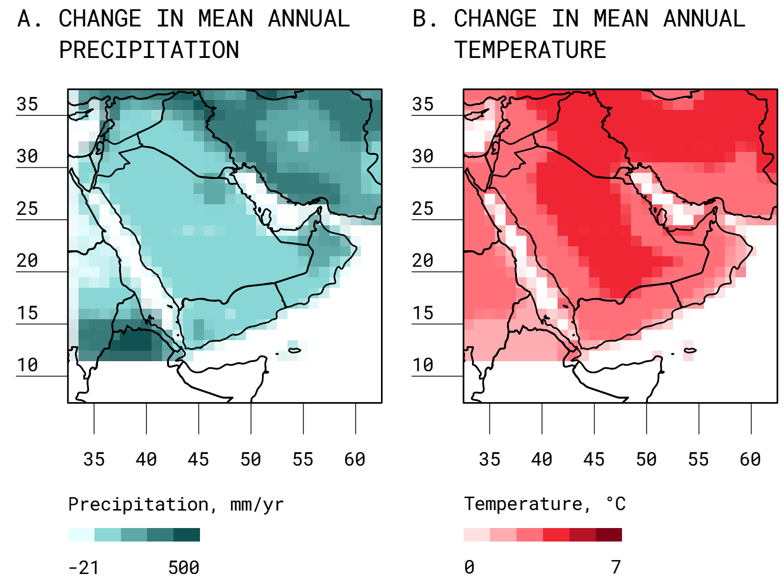
Source: WorldClim, 2020[16].

Only 1% of the land area of the GCC is arable land suitable for crops, and only 19.5% of the land area of the GCC is considered agricultural land [3] [15]. There is limited potential to expand the area for agricultural production in the region. Fertile cropland and renewable water resources are nearly exhausted, and climate change impacts in the form of temperature rise, sea level rise, and drought is likely to tighten these constraints [9, 12]. The GCC countries also have relatively low irrigation efficiency ratios – 40% less efficient than Egypt for example [3].

Any expansion of agricultural production in the GCC will depend on innovation for sustainable intensification on existing agricultural land and continued adoption of technological solutions. Approaches such as greenhouse vegetable production, indoor vertical farming, desalinated water irrigation for horticulture crops, treated wastewater irrigation, and drought and salt tolerant crop varieties can help increase domestic production. However, their potential remains marginal, and due to the higher cost of many of them, their economic viability is largely limited to higher value horticulture crops. Additionally, domestic production of some food products, especially meat and dairy, rely heavily on imports for animal feed, and thus does little to reduce market price risk [10]. Furthermore, gains in domestic production

[3] Arable land consists of the total area under temporary crops, temporary meadows and pastures, kitchen gardens, and land temporarily fallow. Agricultural land includes arable land, land under permanent crops, and land under permanent meadows and pastures [15, 17].

FIGURE 3 Climate Change in 2050 from CanESM5 Climate Model for the RCP 8.5 scenario.



Source: WorldClim, 2020[16].

are likely to be offset by population growth, rising income levels, and changes in dietary consumption, all but ensuring continued reliance on food imports to meet most of the demand [9].

Despite their wealth, the GCC countries' reliance on imports leaves them vulnerable to availability risk. This arises when an import-dependent country is not able to purchase food, even if it has the resources to do so. A number of factors may lead to availability risk including, climate shocks and natural disasters in exporting nations; export restrictions imposed by multiple food producers at once, such as what happened in the 2007-2008 food crisis; and political factors such as war, social unrest, or blockade [10].

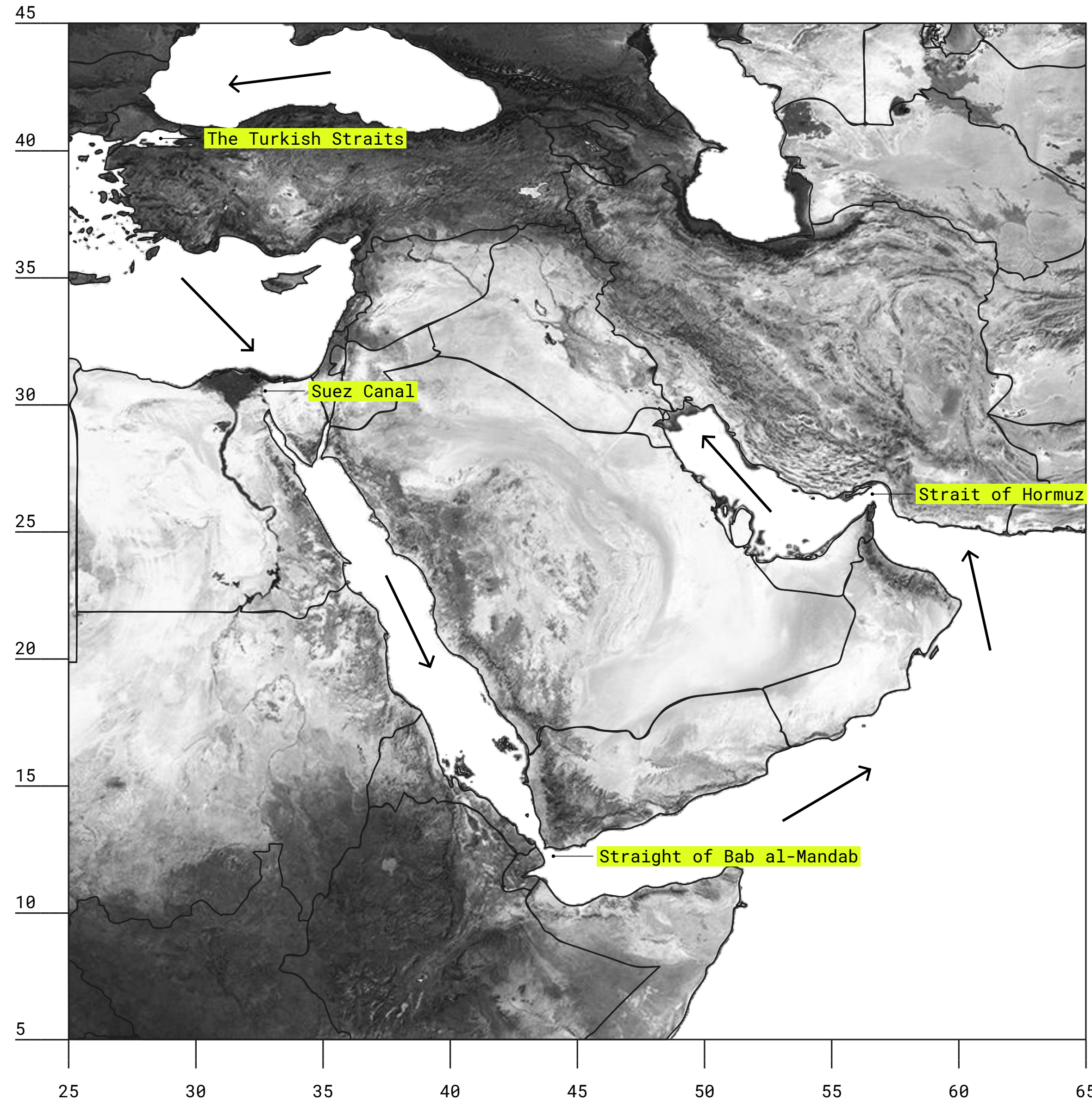
Another important factor to consider is that populations of the GCC countries are not universally wealthy. Across the region, the poorest 10% of the population spend between 30-50% of their income on food [12]. Immigrants also make up a significant portion of the population in the region. Many of them are poor workers from East and Southeast Asia and other Arab countries who do not have access to the social safety nets available to GCC citizens, making them vulnerable to food price spikes [18]. This is particularly relevant when considering that rice, which is the main staple for most immigrant workers, is more vulnerable to price fluctuations than other commodities [12,18]. If maritime shipping through the Gulf were to be disrupted for a prolonged period of time, this could cause a global price spike in rice, eroding food security for low-income immigrants and risking civil unrest – if trade disruptions exceed the capacity of strategic food reserves [18].

The situation in the previous paragraph describes a chokepoint disruption. The nations of the GCC are some of the most exposed in the world to potential food security risks from maritime chokepoints [3]. Over a third of all GCC food imports pass through at least one of four West Asia maritime chokepoints, for which no alternative routes exists (see FIGURE 4) [13]. The greatest threat to food security in the GCC is some form of regional conflict, instability, or disaster that disrupts two or three of the maritime chokepoints to the Arabian peninsula [19].

Over 80% of wheat must pass through at least one of these chokepoints for five of the six countries – the exception being Oman, for whom over 50% must pass through at least one [10]. This risk is particularly high for the Gulf countries of Kuwait, Bahrain, the UAE, and Qatar, for whom there is no alternative maritime route to the Strait of Hormuz. With its access to the Arabian Sea, only Oman has direct access to alternative shipping routes for food supplies from Asia, but closure of the Turkish Straits, the Suez Canal, or Bab Al Mandab, would still close off access to Oman's principal sources of wheat (See supplementary material) [10]. Some of the risk to the Persian Gulf countries has been ameliorated with the recent opening of a grain import and re-export hub on UAE's Gulf of Oman coast, but the recent diplomatic crisis between Qatar and other GCC countries and the associated closure of maritime and land borders demonstrates that overland transport routes may not prove a reliable alternative to maritime ones [19].

The focus of this paper is on the threats that climate change poses to food security in the region and does not fully address economic reforms currently underway or planned for the future. Thus, this analysis can be distilled down into two principal threats to: climate change impacts to yields and the resultant price increases to food imports. The remainder of this paper will focus on these factors.

FIGURE 4 Maritime chokepoints that could impact food security in the GCC.



Source: [149].

METHODS OF ANALYSIS:
There were three components used in the framework for this analysis:
→ International trade analysis.
→ Economic modeling of agricultural markets.
→ Modeling of climate change impact on crop yields and water resource supply and demand.

INTERNATIONAL TRADE ANALYSIS — The core of this analysis was the understanding of the current food self-sufficiency of the GCC nations. This was undertaken using the latest Global Trade, Assistance, and Production (GTAP) Data Base, version 10 (also referred to as GTAP 10) developed at Purdue University. The Data Base describes the world economy for four reference years (2004, 2007, 2011, and 2014) and distinguishes 65 sectors, in each of 141 countries/regions. For each country/region, the Data Base reports production, intermediate and final uses, international trade and transport margins, and taxes/subsidies[20].

To understand food security, it was decided to focus on six main food commodity groups: Grains, Rice, Fruits and Vegetables, Oil Seeds, Meat and Milk, and Processed Foods. GTAP 10 provides data for 65 commodity sectors and a subset of 16 sectors were aggregated to the six food security categories for this analysis. TABLE 3 Lists food commodity sectors categories.

The aggregation of the 16 GTAP sectors to the six-food security categories used in this analysis is listed below:
→ Grains: wht and gro
→ Rice: pdr
→ Fruits and Veg: vuf and ocr
→ Oil Seeds: osd
→ Meat and Milk: cmt, omt and mlk
→ Proceed Food: pcr, sgr,ofd,bot, and vol

After aggregating the sectoral data, analytical tools were developed that processed the GTAP data to provide a set of data for each GCC country. These data included:
→ The exporting countries to each GCC country for each food security
→ The volume of exports from each exporting country
→ The volume of exports from each GCC country to other regional and global countries
→ The total demand for each food security sector for the GCC nations
→ The data used was from 2014 and provides the background data for understanding the current food security situation for the GCC nations.

TABLE 3 Key GTAP Food Commodity Sectors.

GTAP Food	Detailed makeup of GTAP Sector
pdr	Rice: seed, paddy (not husked)
wht	Wheat: seed, other
gro	Other Grains: maize(corn), sorghum, barley, rye, oats, millets, other cereals
v_f	Veg & Fruit: vegetables, fruit and nuts, edible roots and tubers, pulses
osd	Oil Seeds: oil seeds and oleaginous fruit
ocr	Other Crops
ctl	Cattle: bovine animals, live, other ruminants, horses and other equines, bovine semen
oap	Other Animal Products
smt	Cattle Meat: meat of: cattle, buffalo, sheep, goat, camels and horses
omt	Other Meat: meat of pigs, of poultry, fresh or chilled;
vol	Vegetable Oils: margarine and similar preparations; cotton linters; oil-cake, other residues
mil	Milk: dairy products
pcr	Processed Rice: semi- or wholly milled, or husked
sgr	Sugar and molasses
ofd	Other Food: prepared and preserved fish, vegetables, pulses and potatoes; fruits and nuts; wheat and meslin flour; other cereal flours; groats, mixes and doughs for the preparation of bakers' wares; starches and starch products; sugars and sugar syrups; bakery products; cocoa, chocolate and sugar confectionery; macaroni, noodles, couscous and similar farinaceous products;
ofd	Beverages and Tobacco products

Source: Aguiar et al. 2019[20].

ECONOMIC MODELING OF AGRICULTURAL MARKETS — The International Food Policy Research Institute's (IFPRI) IMPACT model is an integrated system of linked economic, climate, water, and crop models that allows for the exploration of policies to reduce hunger and improve food security in a sustainable way. Using IMPACT to model alternative future scenarios and assessing their outcomes can help inform policy choices.

At IMPACT's core is a partial equilibrium, the multi-market economic model that simulates national and international agricultural markets. Links to climate, water, and crop models support the integrated study of changing environmental, biophysical, and socioeconomic trends, allowing for in-depth analysis of a variety of critical issues of interest to policy makers at national, regional, and global levels. [FIGURE 5, 157]

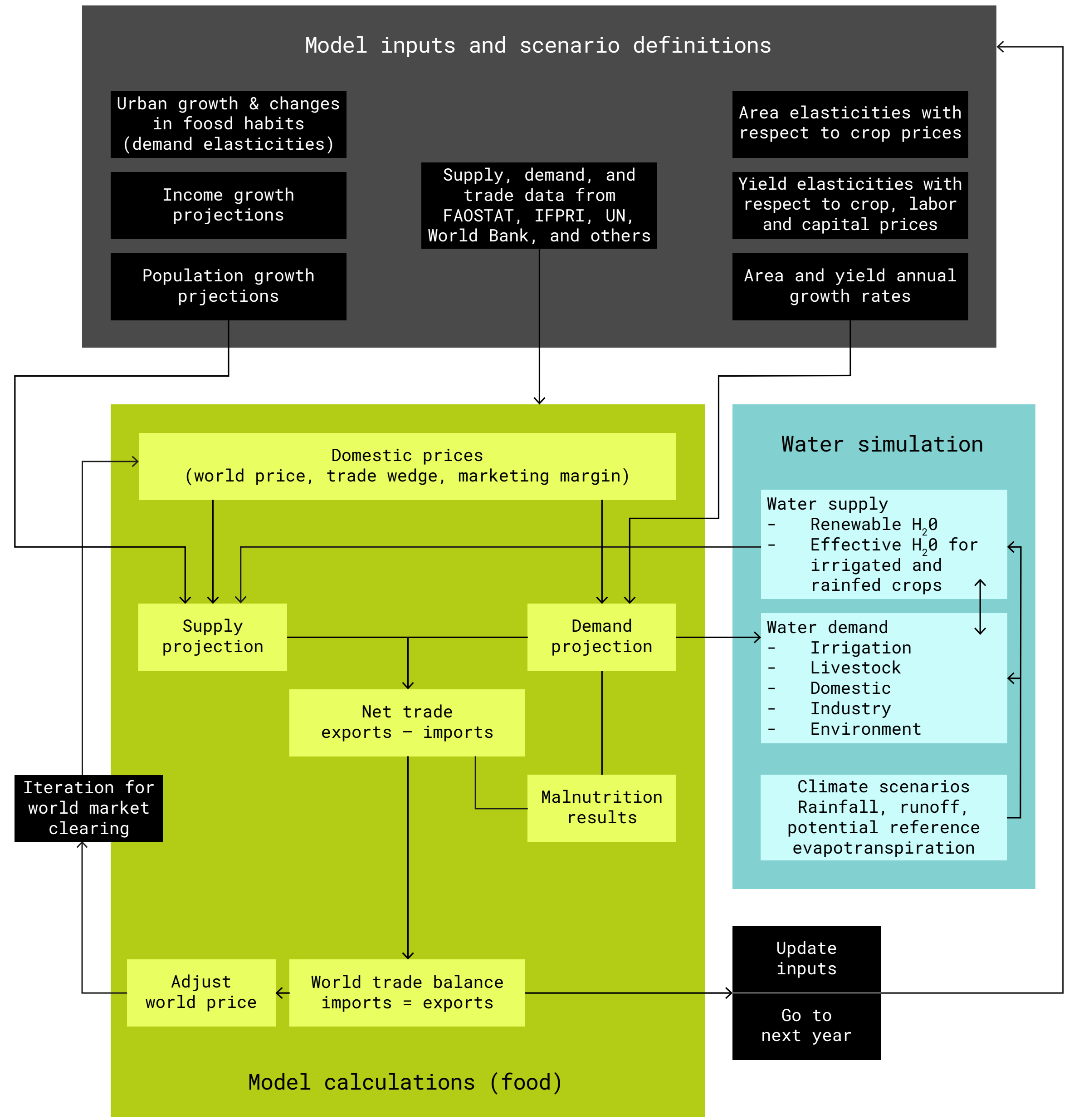
The global model runs at a monthly time step for crop and water modeling and at an annual time step for economic modeling. The spatial scale of the model has 320 Food Producing Units(FPU), which is the inspection of 154 River Basins with 159 Political/Economic policy regions [FIGURE 6].

For this analysis dataset results for 2050 from IFPRI's IMPACT Projections of Food Production, Consumption, and Hunger to 2050, With and Without Climate Change: Extended Country-level Results for 2019 are used. Results are included for yields, production, and consumption for selected countries. The projections are for two "baseline scenarios" – one considers the impacts of climate change, while the other assumes no climate change (for comparison).

The IMPACT outputs used in this analysis include:

→ World market prices of 60+ food commodities
→ Trade of 60+ food commodities between 159 economic units
→ National Demand for 60+ Food Commodities
→ Feed demand of Food commodities for Livestock

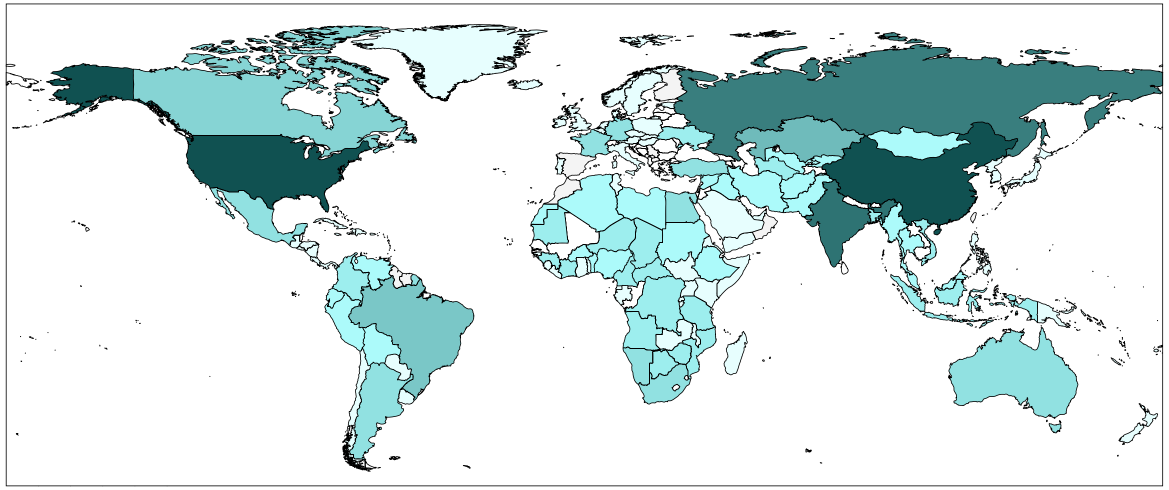
FIGURE 5 Schematic of IMPACT Modeling Framework.



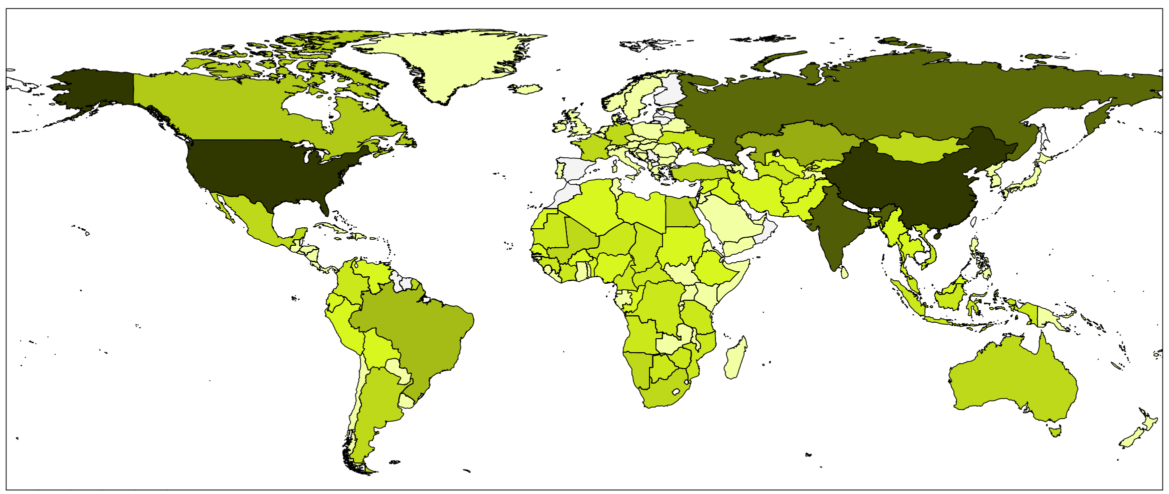
Source: From [22], IFPRI 2012.

FIGURE 6 Spatial resolution of the IMPACT Modeling Framework.

A. WATER BASINS



B. FOOD PRODUCTION UNITS



Source: From [22], IFPRI 2012.

MODELING OF CLIMATE CHANGE IMPACT ON CROP YIELDS AND WATER FOR IRRIGATION — Key elements of the IMPACT Modeling Framework [FIGURE 5] are detailed biophysical models of crop yield (rainfed and irrigated) and water supply for irrigation driven by historic and climate change projections of monthly climate data. For crop yield modeling, IFPRI uses the DSSAT crop modeling systems for nine major crops, and this is linked to the IFPRI global water model that has a monthly hydrologic model and a monthly river basin water balance model for each of the 320 FPU. The 320 FPU follow the hydrologic topology into 126 river basins to assure regional hydrologic water balance.

The water and crop models within the IMPACT Modeling Framework provided the following data for this analysis for GCC countries and the exporting countries that they import from on Climate Change Impacts on:

→ Irrigation and rainfed crop yields
→ Irrigation water availability
→ Economically drive crop production
→ Feed demand for livestock.

These results are used directly in this analysis as well as indirectly through the economic modeling results (e.g. world market prices, per capita consumption).

RESULTS AND ANALYSIS

GCC SUMMARY — All GCC countries are severely water stressed (See "key demographic, agriculture, and water statistics" tables for each country in following sections). With negligible surface freshwater resources, nearly all water withdrawals from natural sources come from groundwater at rates far exceeding natural recharge or from fossil aquifers that have virtually no natural recharge. Additionally, the problem of seawater intrusion into coastal aquifers due to over pumping is a common problem in the GCC, a situation that sea level rise will further exacerbate [3, 23]. The region is effectively mining it's groundwater.

All of the GCC countries have high import vulnerability index scores or greater for two or more food commodity groups [TABLE 4]. Even foods (excluding fresh fruits and vegetables) produced domestically do little to increase food security because they are highly reliant on foreign imports as inputs.

TABLE 4 Imports for key food commodities by GCC and West Asian Countries.

A. PERCENT OF DEMAND FOR KEY COMMODITIES

Region	Country	Grains	Rice	Fruits and Veg	Oilseeds	Meat and Milk	Pr. Foods
GCC	Bahrain	46	0	71	98	44	49
	Kuwait	99	89	77	99	78	65
	Oman	83	0	46	97	53	36
	Qatar	44	0	54	98	50	47
	Saudi Arabia	60	95	46	100	48	39
	United Arab Emirates	93	47	34	98	53	1
Rest of West Asia	Armenia	3	2	0	12	3	0
	Azerbaijan	10	1	0	3	9	7
	Georgia	20	34	0	58	17	0
	IM	32	0	0	15	1	14
	Israel	79	34	0	65	2	14
	Jordan	80	25	1	99	25	33
	Turkey	16	18	0	57	0	0
	Rest of West Asia	17	1	6	13	11	24

0 100

Source: [20] Aguiar et al. 2019. Author calculations for rice from: [24, 25] United Nations 2022; FAO 2022.

Note: Rest of West Asia includes Iraq, Lebanon, Palestinian Territory, Syria and Yemen.

TABLE 4 Imports for key food commodities by GCC and West Asian Countries.

B. NUMBER OF EXPORTING COUNTRIES PROVING ~80% OF IMPORTS

Region	Country	Grains	Rice	Fruits and Veg	Oilseeds	Meat and Milk	Pr. Foods
GCC	Bahrain	4	2	14	7	8	17
	Kuwait	3	5	13	4	11	18
	Oman	4	3	8	2	8	12
	Qatar	4	3	15	8	8	17
	Saudi Arabia	8	3	18	4	10	20
	United Arab Emirates	5	4	18	4	10	22
Rest of West Asia	Armenia	1	7	13	3	8	14
	Azerbaijan	2	4	8	3	9	6
	Georgia	1	3	9	2	11	11
	IM	6	2	5	6	3	7
	Israel	4	7	13	5	8	20
	Jordan	4	6	15	5	10	17
	Turkey	4	3	16	8	15	18
	Rest of West Asia	8	5	12	8	16	20

Max value is 22 (United Arab Emirates, Pr. Foods)

Source: [20] Aguiar et al. 2019. Author calculations for rice from: [24, 25] United Nations 2022; FAO 2022.

Note: The number of countries it takes to pass the 80% threshold (e.g. if 4 countries supply a total of 60% of imports and 5 countries supply a total of 82%, the number of countries will be 5). Rest of West Asia includes Iraq, Lebanon, Palestinian Territory, Syria and Yemen.

TABLE 4 Imports for key food commodities by GCC and West Asian Countries.

C. VULNERABILITY INDEX

Region	Country	Grains	Rice	Fruits and Veg	Oilseeds	Meat and Milk	Pr. Foods
GCC	Bahrain	12	0	5	14	6	3
GCC	Kuwait	33	18	6	25	7	4
GCC	Oman	21	0	6	49	7	3
GCC	Qatar	11	0	4	12	6	3
GCC	Saudi Arabia	8	32	3	25	5	2
GCC	United Arab Emirates	19	12	2	25	5	0
Rest of West Asia	Armenia	3	0	0	4	0	0
Rest of West Asia	Azerbaijan	5	0	0	1	1	1
Rest of West Asia	Georgia	20	11	0	29	2	0
Rest of West Asia	IM	5	0	0	3	0	2
Rest of West Asia	Israel	20	5	0	13	0	1
Rest of West Asia	Jordan	20	4	0	20	3	2
Rest of West Asia	Turkey	4	6	0	7	0	0
Rest of West Asia	Rest of West Asia	2	0	1	2	1	1

Low Vulnerability (0-5) Medium Vulnerability (6-10)
High Vulnerability (11-15) Severe Vulnerability (>15)

Source: [20] Aguiar et al. 2019. Author calculations for rice from: [24, 25] United Nations 2022; FAO 2022.

Note: Vulnerability Index is created by dividing the percent of total demand for food commodity met from imports by the number of countries suppling ~80% of imports. Rest of West Asia includes Iraq, Lebanon, Palestinian Territory, Syria and Yemen.

For example, Saudi Arabia has a growing domestic meat and milk industry whose products it exports to the other countries in the GCC [FIGURE 7, 8]. It is reliant on imports to meet 60% of total demand for grain [TABLE 4], but fully 68% of its grain is used to feed livestock [FIGURE 8]. The UAE is the largest food processor and re-exporter in the GCC [FIGURE 7], for which it is highly dependent on foreign food imports.

Intra-GCC trade also means that food security in the region is layered. For example, Oman is heavily reliant on the UAE as a trade intermediary. The country imports 62% of its rice, 28% of its fruits and vegetables, 67% of its meat and milk, and 31% of its processed foods via the UAE. Thus, if the UAE experiences trade restrictions, Oman's food security is at risk. [TABLE 5] shows. The Export to Import percentage for GCC and the rest of West Asia.

The IMPACT model estimates national food demand as function of population, economic wellbeing (GDP), and local and world market prices. For this analysis, a standard IPCC Shared Socio-economic Pathway was used to forecast population and GDP/capita to 2050, and food demand was estimate for historic climate and for climate change conditions to crop yields.

[TABLE 6] Presents the results for 2050 without Climate Change and with Climate Change. The results show in 2050 a significant increase in per capita fruit and vegetable, oilseed, and meat consumption, while showing a slight decrease in cereal consumption compared to 2010. This is due to how the income effect on diet choices combines with price effects. Due to this demand shift, the increase in population, and the fact that the region imports cereals for livestock feed to produce local meat, the results show dramatic increases in cereal imports (200%) and significant imports of fruit and vegetable, oilseeds, and meat to the region.

The IPFRI analysis projects significant impacts of climate change on the global yields and production of the major commodities imported by the GCC [TABLE 1]. These production impacts result in major changes in world market prices [TABLE 2]. The potential increase in world market prices coupled with local GCC yield reductions from climate change suggests moderate decreases in per capita consumption of all food commodities. The reduced demand results in a mixed impact on imports, as the strong demand for meats results in increases of demand for cereals for feed and also meat as local production is impacted. There are significant decreases in fruits and vegetable and oil seed imports due to the world market price effects. The IFPRI reports significantly greater impacts on consumption for regions with lower economic wealth. For example the rest of West Asia Region neighboring the GCC shows a 16% and 9% decrease in cereal and meat imports, respectively due to climate change.

The projected increases in commodity food prices by 2050 highlights a key vulnerability of the GCC states: in a region with

FIGURE 7 Intra-GCC trade of key food commodities metric tonnes.

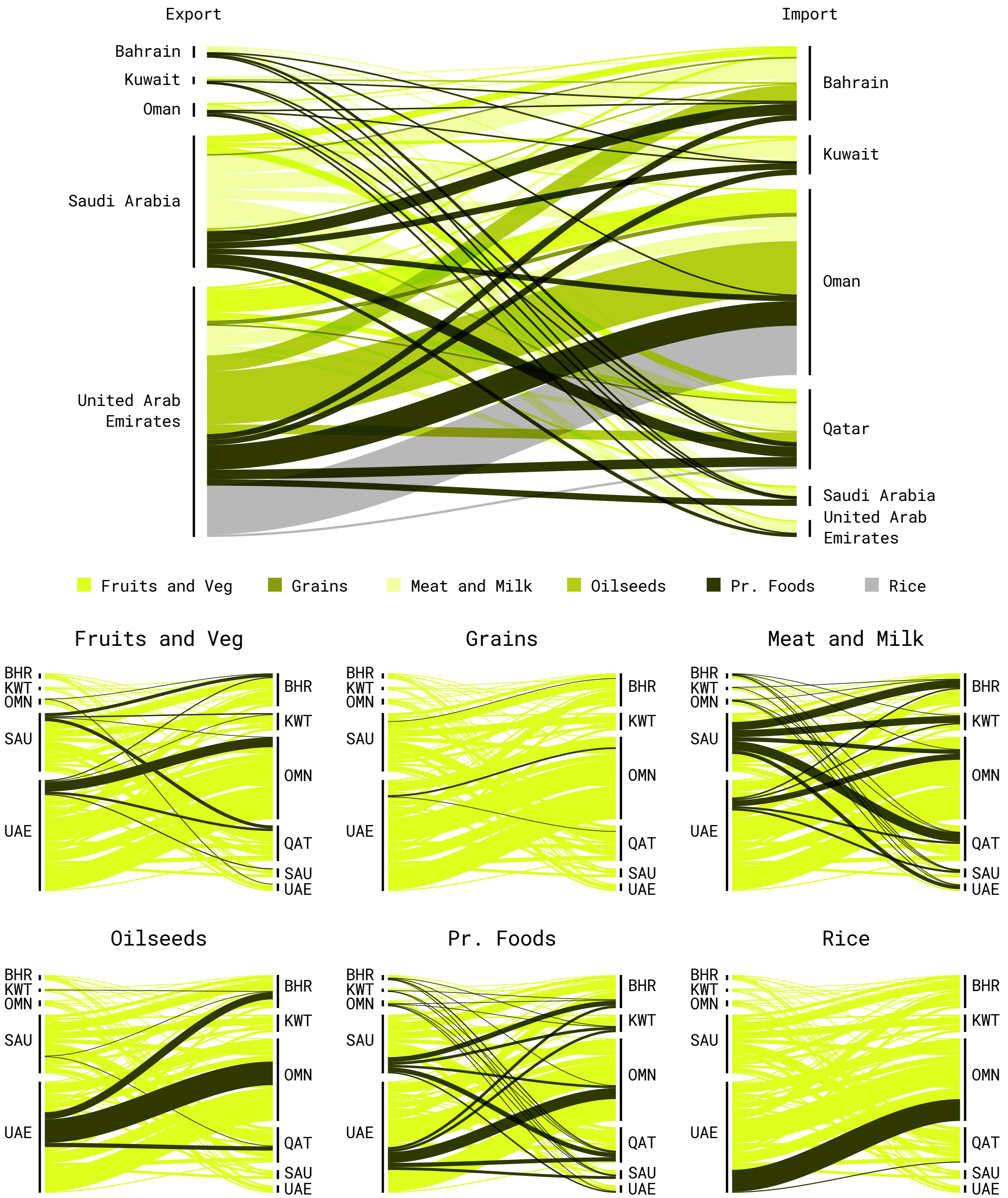
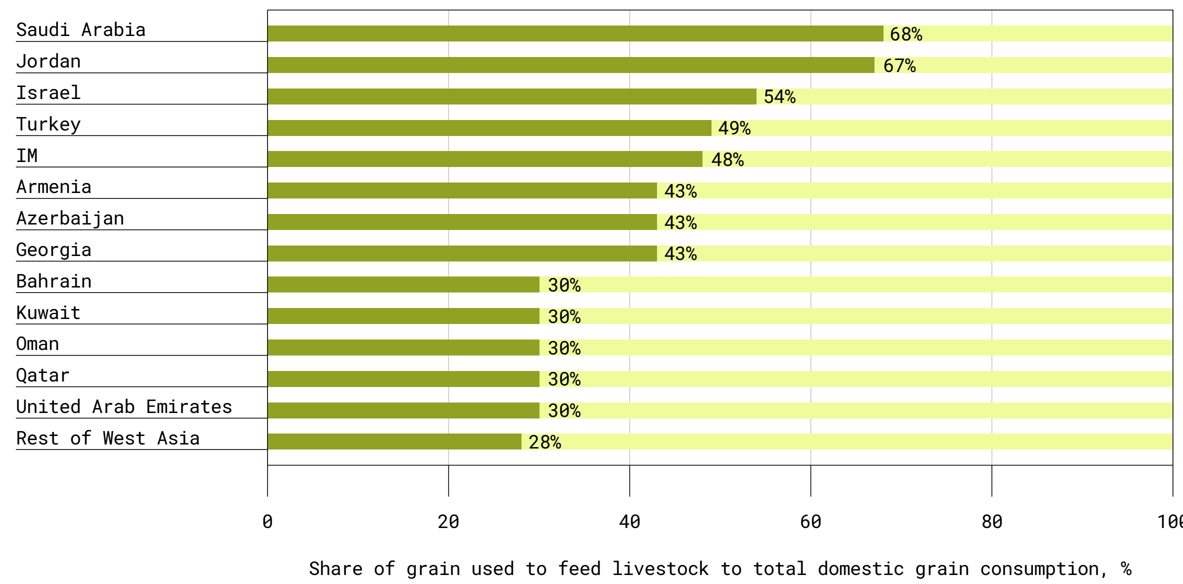


FIGURE 8 Ratio of grain used to feed livestock to total domestic grain consumption for GCC and other West Asian countries.



Source: [20] Aguiar et Al., 2019.

Note: Average for 5 GCC countries due to data aggregation from Aguiar et Al., 2019. Rest of West Asia includes Iraq, Lebanon, Palestinian Territory, Syria and Yemen.

extremely limited capacity for domestic food production, the current high levels of food security are wholly dependent on the countries being able to maintain their wealth. If current efforts to diversify the oil and gas economies of the GCC are not successful, and if the prices of oil and gas remain low (which they are expected to do as renewables continue to grow), then food security and social stability are threatened. A demonstrative case for this is that of rice. Half of the GCC countries rank high on the import vulnerability index for rice [TABLE 4C], and demand for rice in the Gulf region is expected to increase due to consumption from immigrants from Asia [15]. An inability to meet demand for rice could cause social unrest that could have ripple effects throughout the region.

TABLE 5 Export-Import Ratio: the ratio of exports to imports.

Region	Country	Grains	Rice	Fruits and Veg	Oilseeds	Meat and Milk	Pr. Foods
GCC	Bahrain	1	1	1	2	31	30
	Kuwait	0	0	1	1	11	10
	Oman	0	0	27	0	27	43
	Qatar	1	0	1	1	2	1
	Saudi Arabia	0	0	10	0	25	19
	United Arab Emirates	7	40	13	3	28	63
Rest of West Asia	Armenia	11	10	78	8	28	97
	Azerbaijan	1	1	127	0	5	29
	Georgia	3	0	127	2	5	54
	IM	1	127	127	2	44	9
	Israel	15	0	127	17	32	42
	Jordan	1	1	94	1	15	21
	Turkey	9	0	127	14	127	127
	Rest of West Asia	2	8	47	3	11	127

0 127

Note: Rest of West Asia includes Iraq, Lebanon, Palestinian Territory, Syria and Yemen.

TABLE 6 Changes in GCC per capita consumption and net imports from 2010-2050.
→ NO CC: Not factoring in Climate Change;
→ CC: Factoring in Climate Change impacts to world.

A. PER CAPITA CONSUMPTION

Commodity	Per Capita Consumption (Kg/year)			% Difference between NO CC and CC per Capita Consumption (Kg/year)
	2010	2050 NO CC	2050 CC	
Cereals	327	323	313	-3.3%
Fruits and Veg.	442	521	508	-2.4%
Oilseeds	8	9	9	-6.4%
Meats	116	143	142	-0.6%

0 521 -10% 0 +10%

Source: [4] IFPRI, 2019.

B. IMPORTS

Commodity	Imports (Million Metric Tons)			% Difference between NO CC and CC Imports (Million Metric Tons)
	2010	2050 NO CC	2050 CC	
Cereals	13.7	35.2	35.8	+1.6%
Fruits and Veg.	6.2	8.1	7.4	-8.3%
Oilseeds	1.2	2.2	2.1	-7.4%
Meats	1.4	2.6	2.6	+1.5%

0 40 -10% 0 +10%

Source: [4] IFPRI, 2019.

BAHRAIN

The island nation of Bahrain is severely water stressed, withdrawing 134% more freshwater than available sources. However, it is able to meet 61% of its demand for water withdrawal with desalinated seawater [TABLE: BHR 130]. While agriculture only accounts for 0.3% of GDP, it is responsible for over 30% of water withdrawals in the country. It has the second lowest irrigation efficiency ration in the GCC [3]. Bahrain reuses 10-15% of its treated wastewater for irrigation [10]. This imbalance is highly economically inefficient, and as table 8 shows, it is unsustainable in the long term for meeting domestic food demand.

With only 46,000km^2 of cultivated land (5.9% of total area), agricultural production in Bahrain is minimal and is primarily focused on high-productivity, high-value horticultural crops and livestock [8, 9] [4]. Climate change impacts to these agricultural products shown in [TABLE BHR] Indicate a 7% yield increase to fruit and vegetable horticulture crops and a 5% yield decrease for meat and milk. Yields for the limited grains grown in the country are expected to decrease by 13% and remain neutral for rice (see note) and the negligible amount of domestic oilseed production. Climate change yield impacts for processed foods are not applicable, as they are value added products that use agricultural products as inputs.

Bahrain exports (% of exports to imports in [TABLE BHR]) a net of 1% of its grain imports, 1% of rice, 1% of fruit and vegetables, 2% of oilseeds, 31% of meat and milk, and 30% of processed foods. Net exports are a measure of import passthrough activity and/or export of a different type of crop in a commodity category (e.g. importing grapes but exporting domestically produced dates). Bahrain is a moderate export intermediary for milk and meat and processed foods.

On the import vulnerability index (see methods section for description of metric), Bahrain ranks as low vulnerability for fruits and vegetables and processed foods, indicating either sufficient domestic production or sufficient diversity of import supplying nations. It ranks as medium vulnerability for meat and milk, high vulnerability for grains and oilseeds, and severe vulnerability for rice.

KUWAIT

Kuwait is the most water stressed country in the GCC, withdrawing 3,850% more freshwater than available resources [TABLE: KWT 131]. It only meets 35% of demand with seawater desalination. Kuwait does, however, reuse about 50% of its treated wastewater for irrigation [10]. Agriculture accounts for only about half a percent of GDP, while being responsible for over 60% of total withdrawals. This water use paradigm is the least sustainable of the GCC countries.

Only 0.9% of Kuwait's 18 million sq.km area is cultivated, and agriculture only accounts for half a percent of GDP [8]. The economically inefficient use of water is even more dramatic when considering that Kuwaiti agriculture produces four times less USD per hectare than Bahrain's [15], meaning that it is producing lower value crops or producing higher value crops less efficiently under conditions of extreme water stress. Kuwait also has the lowest irrigation efficiency ratio in the GCC [3].

Kuwait is the most import dependent of the GCC countries for meeting food demand [TABLE 4]. It produces very little food domestically, relying on imports to meet 99% of demand for grains, 95% for rice, 77% for fruits and vegetables, 99% for oilseeds, 78% for meat and milk, and 65% for processed foods [TABLE KWT]. Despite being one of the most food secure countries in the world, price risk could pose a serious threat to food security because the majority of the population consists of immigrant labor from low-income countries [3, 27].

On the import vulnerability index [TABLE KWT], Kuwait has a low vulnerability score for only processed foods, and medium vulnerability for fruits and vegetables and meat and milk, largely as a result of its diversified supply chains for these food commodities. It is severely import vulnerable for grains (having just three suppliers for 81% of demand), rice (five suppliers for 89% of demand), and oilseeds (four suppliers for 84% of demand). Kuwait is a still a net exporter of 11% of meat and milk and 10% of processed foods, two of its least import vulnerable food commodities.

OMAN

Oman has the highest per capita renewable water resources in the GCC [10], but it is still withdrawing 117% of renewable resources [TABLE: OMN P132]. It meets 18% of demand with desalination, but the Omani government is planning to increase desalination capacity by 66% in the near future [TABLE OMN AND 10]. Oman is also the only GCC country for whom the majority of their water does not come from nonrenewable groundwater resources [29].

Only 0.3% of Oman's 310 million km^2 area is cultivated, and agriculture accounts for only 2.2% of GDP but is responsible for over 85% of water withdrawals [8]. Oman has the highest irrigation efficiency ratio in the GCC [3]. While Omani agriculture accounts for only 8% of total GCC food production, it is sufficient to meet over one third of domestic demand [TABLE OMN AND 26]. Oman is reliant on imports to meet 83% of its demand for grains, 90% for rice, 46% for fruits and vegetables, 97% for oilseeds, 53% for meat and milk, and 36% for processed foods [TABLE OMN].

To improve food self-sufficiency, government policies have focused on increasing local agricultural production and domestic production of processed foods [26]. Some climate change models also project an increase rainfall for the country, which may increase yields for some crops [15]. However, temperature increases will likely offset any gains from additional resources, which may explain why [4] and GTAP database [20] data indicate yield decreases in the country for all major

[4] The data from rice from the GTAP database [20] (Aguiar et al. 2019) used for [TABLE BHR] indicates that Bahrain is 94% self-sufficient for rice. It is unclear how much, rice production occurs in the country, and this potential discrepancy could be due to a lack of available data for Bahrain and data aggregation in the GTAP database. The Bahrain import vulnerability index number for rice is likely sufficiently higher than indicated in the table.

crop categories except fruits and vegetables.

On the import vulnerability index [TABLE OMN], Oman has low vulnerability scores for processed foods and medium vulnerability for fruits and vegetables and milk and meat, largely due to its domestic production. It has severe vulnerability for grains, rice, and oilseeds, due to its high reliance on imports and limited number of suppliers. The UAE is its principal exporter for rice, fruits and vegetables, oilseeds, meat and milk, and processed foods (See supplemental materials). It has net exports of 27% for fruits and vegetables and meat and milk, and 43% for processed foods.

QATAR

Qatar is severely water stressed, withdrawing over 432% more freshwater than available resources [TABLE: QAT P133]. It is able to meet 71% of demand with desalination and reuses only 10-15% of treated wastewater for irrigation [8, 10]. Agriculture contributes only 0.2% to GDP but is responsible for 32% of water withdrawals [TABLE QAT]. Qatar's irrigation efficiency ratio is nearly 50% lower than the GCC average [3]. Only 1.5% of Qatar's total area of 11.5 million sq. km is cultivated [8].

Qatar is ranked as the most food secure country in the GCC and the thirteenth in the world [9]. However, much like Kuwait, its food security is susceptible to price because the majority of its population consists of immigrant labor from low-income countries [3, 28]. Qatar is reliant on imports to meet 44% of demand for grains, 99% for rice, 54% for fruits and vegetables, 98% for oilseeds, 50% for meat and milk, and 47% for processed foods [TABLE QAT].

Despite being one of the most food secure countries in the world, Qatar's vulnerability to food insecurity became very clear during the diplomactic crisis between Qatar, Saudi Arabia, UAE, Bahrain, and Egypt and the closure of maritime and land borders from 2017 to early 2021. Diplomatic ties have been restored, but the event is demonstrative of the long-term challenges to food supply chains to the regions.

On the import vulnerability index [TABLE QAT], Qatar has low vulnerability for fruits and vegetables and processed foods. It has medium vulnerability for meat and milk, high vulnerability for grains and oilseeds, and severe vulnerability for rice. It has negligible net exports for every food commodity category except rice.

SAUDI ARABIA

Saudi Arabia is the third most water stressed country in the GCC, withdrawing almost 900% more freshwater than available resources [TABLE: SAU P134]. It meets only about 9% of its demand with desalinated water, but like Kuwait, reuses about 50% of its treated wastewater for irrigation [TABLE SAU AND KWT]. Agriculture accounts for only 2.5% of GDP but is responsible for over 80% of withdrawals. Only 1.7% of Saudi Arabia's 2.1 billion sq. km area is cultivated [8]. Saudi Arabia has the second highest irrigation efficiency ratio in the GCC [3].

Saudi Arabia is reliant on imports to meet 60% of demand for grain, 95% for rice, 46% for fruits and vegetables, 100% for oilseeds, 48% for meat and milk, and 39% for processed foods [TABLE SAU]. The country has a growing meat and milk industry and is the largest producer and exporter of these goods in the GCC [FIGURE 7]. It is the principal exporter of meat and milk to Bahrain, Kuwait, and Qatar and a major exporter to other West Asian countries (See supplementary materials).

Saudi Arabia is the second largest food processing and food re-exporter in the GCC [26]. It is the principal exporter of processed food for Bahrain and a top exporter for Kuwait and Qatar (See supplementary materials). Despite being a major producer of these foods, their domestic production does not do much to reduce the county's reliance on food imports. As [FIGURE 8] shows, fully 68% of Saudi Arabia's grain is used to feed livestock. As a result, domestic meat and milk production actually increases the demand for imports of strategic grain commodities, leaving the country vulnerable to global price increases in grain. In fact, Saudi Arabia consumes nearly two-thirds of global barley exports just to feed its sheep [12].

On the import vulnerability index [TABLE SAU], Saudi Arabia has low vulnerability for fruits and vegetables, meat and milk, and processed foods. It has medium vulnerability for grains, and high vulnerability for rice and oilseeds. The low vulnerability scores for meat and milk and for processed foods are somewhat misleading, as the domestic production for these relies on continued access to and purchasing power for other import markets, such as grain.

UNITED ARAB EMIRATES

The UAE is second only to Kuwait in its degree of water stress and in the unstainable use of its water resources for agriculture. It withdraws approximately 1,700% more freshwater than available resources [TABLE: UAE P135]. It meets 44% of freshwater demand with desalination. Agriculture only contributes 0.8% to GDP but accounts for approximately 83% of water withdrawals.

Only 1.2% of its 71.2 million sq. km area is cultivated land [8]. The UAE's irrigation efficiency ratio is in line with the mean for the GCC. Intensive use of groundwater, mainly for irrigation, over the past 30 years caused severe saltwater intrusion into coastal aquifers and has led to extensive salinization of agricultural lands irrigated with this groundwater.

The UAE has the highest per capita food consumption in the GCC and accounts for 20% of total food consumption (largely driven by tourism), yet it only accounts for approximately 12% of total food production in the region [26]. The country is reliant on imports to meet 93% of demand for grains, 95% for rice, 34% for fruits and veget-

Wables, 98% for oilseeds, 53% for meat and milk, and 22% for processed foods [TABLE UAE].

The UAE is the top food processing and re-exporting country in the GCC[12, 26]. It is the top supplier of processed foods to Oman, and is a major exporter to Bahrain, Kuwait, Qatar, and Saudi Arabia. It is also the principal supplier of rice, fruits and vegetables, and meat and milk to Oman, and of oilseeds to both Oman and Bahrain ([FIGURE 7] and Supplementary materials). [TABLE UAE] Shows that much of this is through the UAE's role as a re-exporting intermediary.

On the import vulnerability index [TABLE UAE], the UAE has a low vulnerability for fruits and vegetables, meat and milk, and processed foods. It has a severe vulnerability for rice, grains, and oilseeds. As with most of the other GCC countries, its low vulnerability score for processed foods and meat and milk in particular masks the reality that it is highly dependent on imports as inputs for production. It is, however, able to hedge this risk through its diversified supply chains, which demonstrates that food security can be achieved for some food commodities even under conditions of high imports.

BAHRAIN

BHR

KEY DEMOGRAPHIC, AGRICULTURE, AND WATER STATISTICS

Total population 1M inhabitants	1.5
Percentage of population immigrants, est. %	48.0
Population growth %	0.9
GDP per capita current US$/inhab	23,739.0
Agriculture, value added % GDP	0.3
Water Stress %	134.0
Agricultural water withdrawal as % of total renewable water resources %	125.0
Agricultural water withdrawal as % of total water withdrawal %	33.3
Percentage of withdrawls that are from desalination %	61.0

KEY FOOD SECURITY INDICATORS RELATED TO FOOD IMPORTS

Indicator, %	Grains	Rice	Fruits and Veg	Oilseeds	Meat and Milk	Pr. Foods
Imports of Total Demand	46	98	71	98	44	49
Imported from major exporters	83	80	81	80	81	81
Exports to Imports	1	1	1	2	31	30
Domestic 2050 CC Yield Impact	-13	ND	7	0	-5	NA
Grain to Feed	30	–	–	–	–	–
CC Impact on WM Prices	30	24	14	31	4	15

-100% 0% 100%

Number of Major Exporters	4	2	14	7	8	17

Max value is 22

Import Vulnerability Index	12	49	5	14	6	3

Low Vulnerability (0-5)
Medium Vulnerability (6-10)
High Vulnerability (11-15)
Severe Vulnerability (>15)

Source: Population Reference Board, 2020; FAO, 2021a; CIA World Factbook, 2021;
Note: Grain to feed data is an average across all GCC countries due to data aggregation from GTAP Database[4, 20].

KUWAIT

KWT

KEY DEMOGRAPHIC, AGRICULTURE, AND WATER STATISTICS

Total population 1M inhabitants	4.7
Percentage of population immigrants, est. %	70.0
Population growth %	1.2
GDP per capita current US$/inhab	28,897.0
Agriculture, value added % GDP	0.5
Water Stress %	3.8
Agricultural water withdrawal as % of total renewable water resources %	3.9
Agricultural water withdrawal as % of total water withdrawal %	62.3
Percentage of withdrawls that are from desalination %	35.0

KEY FOOD SECURITY INDICATORS RELATED TO FOOD IMPORTS

Indicator, %	Grains	Rice	Fruits and Veg	Oilseeds	Meat and Milk	Pr. Foods
Imports of Total Demand	99	95	77	99	78	65
Imported from major exporters	81	80	81	84	81	82
Exports to Imports	1	0	1	1	31	10
Domestic 2050 CC Yield Impact	-13	ND	7	0	-5	NA
Grain to Feed	30	–	–	–	–	–
CC Impact on WM Prices	30	24	14	31	4	15

-100% 0% 100%

Number of Major Exporters	3	5	13	4	11	18

Max value is 22

Import Vulnerability Index	33	19	6	25	7	4

Low Vulnerability (0-5) Medium Vulnerability (6-10)
High Vulnerability (11-15) Severe Vulnerability (>15)

Source: Population Reference Board, 2020; FAO, 2021a; CIA World Factbook, 2021;
Note: Grain to feed data is an average across all GCC countries due to data aggregation from GTAP Database[4, 20].

OMAN

OMN

KEY DEMOGRAPHIC, AGRICULTURE, AND WATER STATISTICS

Total population 1M inhabitants	4.7
Percentage of population immigrants, est. %	46.0
Population growth %	1.9
GDP per capita current US$/inhab	17,099.0
Agriculture, value added % GDP	2.2
Water Stress %	117.0
Agricultural water withdrawal as % of total renewable water resources %	115.0
Agricultural water withdrawal as % of total water withdrawal %	85.8
Percentage of withdrawls that are from desalination %	18.0

KEY FOOD SECURITY INDICATORS RELATED TO FOOD IMPORTS

Indicator, %	Grains	Rice	Fruits and Veg	Oilseeds	Meat and Milk	Pr. Foods
Imports of Total Demand	83	90	46	97	53	36
Imported from major exporters	82	83	80	82	84	81
Exports to Imports	0	0	27	0	27	43
Domestic 2050 CC Yield Impact	-13	ND	7	0	-5	NA
Grain to Feed	30	–	–	–	–	–
CC Impact on WM Prices	30	24	14	31	4	15

-100% 0% 100%

Number of Major Exporters	4	3	8	2	8	12

Max value is 22

Import Vulnerability Index	21	30	6	49	7	3

Low Vulnerability (0-5) Medium Vulnerability (6-10)
High Vulnerability (11-15) Severe Vulnerability (>15)

Source: Population Reference Board, 2020; FAO, 2021a; CIA World Factbook, 2021;
Note: Grain to feed data is an average across all GCC countries due to data aggregation from GTAP Database[4, 20].

QATAR

QAT

KEY DEMOGRAPHIC, AGRICULTURE, AND WATER STATISTICS

Total population 1M inhabitants	2.8
Percentage of population immigrants, est. %	88.0
Population growth %	1.2
GDP per capita current US$/inhab	63,249.0
Agriculture, value added % GDP	0.2
Water Stress %	432.0
Agricultural water withdrawal as % of total renewable water resources %	503.0
Agricultural water withdrawal as % of total water withdrawal %	32.0
Percentage of withdrawls that are from desalination %	71.0

KEY FOOD SECURITY INDICATORS RELATED TO FOOD IMPORTS

Indicator, %	Grains	Rice	Fruits and Veg	Oilseeds	Meat and Milk	Pr. Foods
Imports of Total Demand	44	99	54	98	50	47
Imported from major exporters	83	84	81	81	80	81
Exports to Imports	1	0	1	1	2	1
Domestic 2050 CC Yield Impact	-13	ND	7	0	-5	NA
Grain to Feed	30	–	–	–	–	–
CC Impact on WM Prices	30	24	14	31	4	15

-100% 0% 100%

Indicator	Grains	Rice	Fruits and Veg	Oilseeds	Meat and Milk	Pr. Foods
Number of Major Exporters	4	3	15	8	8	17

Max value is 22

Indicator	Grains	Rice	Fruits and Veg	Oilseeds	Meat and Milk	Pr. Foods
Import Vulnerability Index	12	49	5	14	6	3

Low Vulnerability (0-5) Medium Vulnerability (6-10)
High Vulnerability (11-15) Severe Vulnerability (>15)

Source: Population Reference Board, 2020; FAO, 2021a; CIA World Factbook, 2021;
Note: Grain to feed data is an average across all GCC countries due to data aggregation from GTAP Database [4, 20].

SAUDI ARABIA

SAU

KEY DEMOGRAPHIC, AGRICULTURE, AND WATER STATISTICS

Total population 1M inhabitants	35.0
Percentage of population immigrants, est. %	38.0
Population growth %	1.6
GDP per capita current US$/inhab	20,905.0
Agriculture, value added % GDP	2.5
Water Stress %	883.0
Agricultural water withdrawal as % of total renewable water resources %	800.0
Agricultural water withdrawal as % of total water withdrawal %	82.2
Percentage of withdrawls that are from desalination %	9.0

KEY FOOD SECURITY INDICATORS RELATED TO FOOD IMPORTS

Indicator, %	Grains	Rice	Fruits and Veg	Oilseeds	Meat and Milk	Pr. Foods
Imports of Total Demand	60	95	46	100	48	39
Imported from major exporters	82	82	82	84	80	81
Exports to Imports	0	0	10	0	25	19
Domestic 2050 CC Yield Impact	-10	ND	-8	0	-7	NA
Grain to Feed	30	–	–	–	–	–
CC Impact on WM Prices	30	24	14	31	4	15

-100% 0% 100%

Indicator	Grains	Rice	Fruits and Veg	Oilseeds	Meat and Milk	Pr. Foods
Number of Major Exporters	8	3	18	4	10	20

Max value is 22

Indicator	Grains	Rice	Fruits and Veg	Oilseeds	Meat and Milk	Pr. Foods
Import Vulnerability Index	8	32	3	25	5	2

Low Vulnerability (0-5) Medium Vulnerability (6-10)
High Vulnerability (11-15) Severe Vulnerability (>15)

Source: Population Reference Board, 2020; FAO, 2021a; CIA World Factbook, 2021;
Note: Grain to feed data is an average across all GCC countries due to data aggregation from GTAP Database [4, 20].

UNITED ARAB EMIRATES

KEY DEMOGRAPHIC, AGRICULTURE, AND WATER STATISTICS

Total population 1M inhabitants	9.8
Percentage of population immigrants, est. %	88.0
Population growth %	0.6
GDP per capita current US$/inhab	40.18
Agriculture, value added % GDP	0.8
Water Stress %	1.7
Agricultural water withdrawal as % of total renewable water resources %	2.2
Agricultural water withdrawal as % of total water withdrawal %	82.8
Percentage of withdrawls that are from desalination %	44.0

KEY FOOD SECURITY INDICATORS RELATED TO FOOD IMPORTS

Indicator, %	Grains	Rice	Fruits and Veg	Oilseeds	Meat and Milk	Pr. Foods
Imports of Total Demand	93	5	34	98	53	22
Imported from major exporters	84	88	81	81	81	81
Exports to Imports	7	40	13	3	28	63
Domestic 2050 CC Yield Impact	-13	ND	7	0	-5	NA
Grain to Feed	30	–	–	–	–	–
CC Impact on WM Prices	30	24	14	31	4	15

-100% 0% 100%

Number of Major Exporters	5	4	18	4	10	22

Max value is 22

Import Vulnerability Index	19	24	2	25	5	0

Low Vulnerability (0-5) Medium Vulnerability (6-10)
High Vulnerability (11-15) Severe Vulnerability (>15)

Source: Population Reference Board, 2020; FAO, 2021a; CIA World Factbook, 2021;
Note: Grain to feed data is an average across all GCC countries due to data aggregation from GTAP Database [4, 20].

SUMMARY & CONCLUSION

It is clear that domestic food production cannot currently meet most of demand in the GCC and that climate and demographic changes will further challenge the ability of these countries to achieve food self-sufficiency with domestic production. Climate change will make this more challenging, as it is projected to cause a slightly negative net impact on agricultural production in the GCC. The changing climate is also projected to push average global yields down for the food commodity categories discussed in this paper [TABLE 1]. Yield decreases are also projected in many of the countries that export food to the GCC (see supplementary material). Even absent climate change, world population growth and changing diets are likely to cause food price increases. Models suggest that the impacts of climate change will further drive-up food prices significantly – by an average of 20% across the major food commodity categories [TABLE 2].

This analysis demonstrated that sufficient diversification of food import suppliers–and increasing food storage capacity and improving supply chain security–can hedge the risk of relying on imports for achieving food security (see e.g. analysis for Bahrain and UAE above). Food consumption in the GCC is projected to remain relatively flat. So theoretically, the GCC countries should be able to maintain their high levels of food security, even with their high reliance on imports, if they sufficiently diversify their food import supply chains.

A key assumption to this analysis is that SSP scenario assumes the GCC maintains it fossil fuel drive export economy and has the income to pay for the dramatic increase in imports by 2050 and can also absorb the price shocks from climate change. The model results show that food prices will continue to increase through 2050, and if the countries of the GCC are not successful in diversifying their economies away from oil and gas, their food security will be at risk. Under current economic conditions, GCC food security is directly tied to world hydrocarbon prices.

Additionally, most food imports to the GCC must pass through four politically tenuous maritime chokepoints, and regional instability and geopolitics are constraining factors on land-based food import routes. Recent political tensions between Qatar and other GCC members further demonstrates that maintaining good relations within the block of nations has important implications for food security. Further political unrest in the broader West Asia region could place additional strain on supply routes and lead to influxes of refugees that could cause internal sociopolitical tensions. The current war between Ukraine and Russia, principal sources of wheat to many West Asian countries, clearly demonstrates the food security risks from conflict in major food exporting countries.

Related to this is the growing practice of acquisition of agricultural land in foreign countries to produce food for the GCC. This topic is largely outside the scope of this paper, but it is worthwhile to note that land acquisition may not produce the food security that is intended. Many countries where this agricultural land is purchased are developing countries with weak political institutions and where climate change could have negative impacts on food production. If climate change leads to food insecurity in these countries, social unrest could staunch the flow of food exports to the GCC, even if the land is legally owned. Some of these arrangements are also still vulnerable to the maritime chokepoints.

All GCC countries include expanding the desalination of seawater and saline groundwater to reduce water stress. Increasing desalination capacity could help meet urban water demand and, in some cases, could provide a source of irrigation water for highly efficient production of high value horticulture crops. This may moderately reduce the demand for imports, but horticulture crops are not the foundation of diets in the region. The crops that are most in demand are grains, rice, and animal products, which due to the agroecology of the region will continue to be imported.

There are some implications to the expansion of desalination. Higher water temperatures, a likely outcome of climate change, can promote algal blooms that are problematic for desalination plants and can reduce the ability of certain types of plants to function. The potential conflict with Iran poses a physical security risk to desalination plants, and cyber security threats to plant computer systems is a large and growing issue.

Finally, one area that holds promise for reducing the demand of imports is reducing food waste which is beyond the scope of this analysis. However, about one-third of all food is wasted globally, and the GCC countries stand out as among the highest per capita food wasters in the world [39, 40]. In higher income countries, food waste occurs on the consumer side of the food system, and wealthier countries generally consume more food per capita, generating more waste per capita. Reducing food waste could reduce the pressure on food imports. However, the GCC countries are not homogenous in the makeup of their populations, and thus strategies for addressing food waste will need to be tailored differently based on the country. In the UAE for example, addressing food waste may be more challenging due to the large tourism sector and that industry's reluctance to change the guest experience in any way [29]. We point the reader towards other studies focused on food waste in the GCC for more in-depth analysis of this issue [29, 39, 40].

AREAS OF FURTHER RESEARCH

- → Address the uncertainty in climate change and socio-economic projections.
- → Develop a global linked economic modeling system to allow for addressing balance of payments for food importing nations.
- → Develop a global bi-lateral trade model focused on food and agriculture.
- → Extension of the Food Security and Trade Vulnerability Index to Global coverage and actionable for policy.
- → Develop a framework to provide for the projection of the index for future global change scenarios.

NATURAL AND ANTHROPOGENIC AIR POLLUTION IN THE GCC – IMPACTS ON AIR QUALITY & PUBLIC HEALTH

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KEY MESSAGES

→ Air pollution is the fourth leading risk factor for early death worldwide after high blood pressure, tobacco use, and poor diet. The evidence is mounting that much lower air pollution levels than previously thought can cause harm to health.

→ Air pollution is a multiscale problem that requires advanced knowledge of atmospheric dynamics, aerosol microphysics, and atmospheric chemistry. Air quality assessments at global, regional, and local scales require blending observations with model calculations.

→ The health effect of particulate matter air pollution is the leading environmental health concern of the World Health Organization (WHO) worldwide. This is especially important in the Middle East, where natural dust causes high PM pollution in rural and urban areas.

→ Anthropogenic aerosols form in the atmosphere due to the oxidation of industrial, traffic, and household emissions. Their contribution to air pollution compared with natural sources is essential on the west and east coasts of Saudi Arabia and over the Arabian Gulf. In these areas, e.g., sulfate aerosols surface concentration reaches 8-11 μg/m³, while the "clean" background level is 2-4 μg/m³.

This chapter comprises three parts.

→ Part 1 is written from the global perspective. It introduces air pollution modeling and observations and quantifies the effect of air pollution on human health using data-informed global modeling. It also discusses the regional processes over the Middle East (ME) and shows the significant impact of natural dust aerosol pollution in this region.

→ Part 2 evaluates fine spatial regional aerosol air pollution distributions considering both natural and anthropogenic aerosols. It tests model data against optical and air quality observations and quantifies particulate matter (PM) air pollution in the major Middle East cities.

→ Part 3 discusses air pollution and its health outcomes at city and street levels, describes the health effect evaluation methodology and estimates the air pollution impacts on human health in the major cities in KSA.

GLOBAL AND REGIONAL AIR POLLUTION: MIDDLE EAST

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INTRODUCTION

Air pollution is a main public health hazard, at the same level as high blood pressure, tobacco smoking, dietary risks and diabetes, leading to morbidity and excess mortality [1-3]. The World Health Organization (WHO) has identified gaseous and particulate pollutants as significant risk factors of respiratory infections, chronic obstructive pulmonary disease (COPD), lung cancer, as well as cardiovascular and cerebrovascular diseases, leading to heart attacks and strokes, respectively. Worldwide, diseases due to air pollution cause greater loss of life than HIV/AIDS, tuberculosis and malaria together, and an order of magnitude more than by all forms of violence; and they are responsible for trillions of US dollars in welfare losses each year [2, 4]. Global estimates of excess mortality from air pollutants such as fine particulate matter and photochemical oxidants range between about four and ten million per year, depending on the compounds and disease categories that are considered [1, 5, 6].

The last update of air quality guidelines by the WHO was in 2005, recommending upper threshold values for fine particulate matter with an aerodynamic diameter smaller than 10 µm and 2.5 µm (PM_{10} and $PM_{2.5}$), ozone (O_3), nitrogen dioxide (NO_2) and sulfur dioxide (SO_2). Some countries have adopted the guideline for annual mean NO_2 of 40 µg/m^3, and a few countries that for $PM_{2.5}$ of 10 µg/m^3, whereas many countries have defined higher threshold levels or do not manage air quality at all [TABLE 1]. This is worrisome, especially because recent studies have indicated significant health impacts at levels below the current air quality guidelines [7, 8], and it may be expected that the WHO will update its recommendations accordingly in the near future [9, 10]. In the Middle East, few countries apply controls on emissions (e.g., Israel) and only Saudi Arabia has defined air quality standards following the ArRiyadh Air Quality Management, while pollution levels are generally high and increasing [11, 13]. In this chapter we evaluate air pollution levels and health impacts in the Middle East and compare to other regions, following the Global Burden of Disease approach, based on publicly available data and the recent literature.

TABLE 1 Daily and annual air quality standards for NO_2 and $PM_{2.5}$.

Countries	Limits for NO_2 in µg/m³		Limits for $PM_{2.5}$ in µg/m³	
	Daily mean	Annual mean	Daily mean	Annual mean
European Union	NA	40	NA	25
Australia	NA	60	25	8
Brazil	NA	100	NA	NA
Canada	NA	NA	28	10
China	80	40	75	35
India	80	40	60	40
Indonesia	150	100	NA	NA
Japan	113	NA	35	15
Mexico	NA	100	45	12
Russia	NA	40	35	25
Saudi Arabia	NA	100	35	15
South Africa	NA	40	65	25
South Korea	115	57	50	25
Turkey	NA	NA	100	64
United States	NA	100	35	12

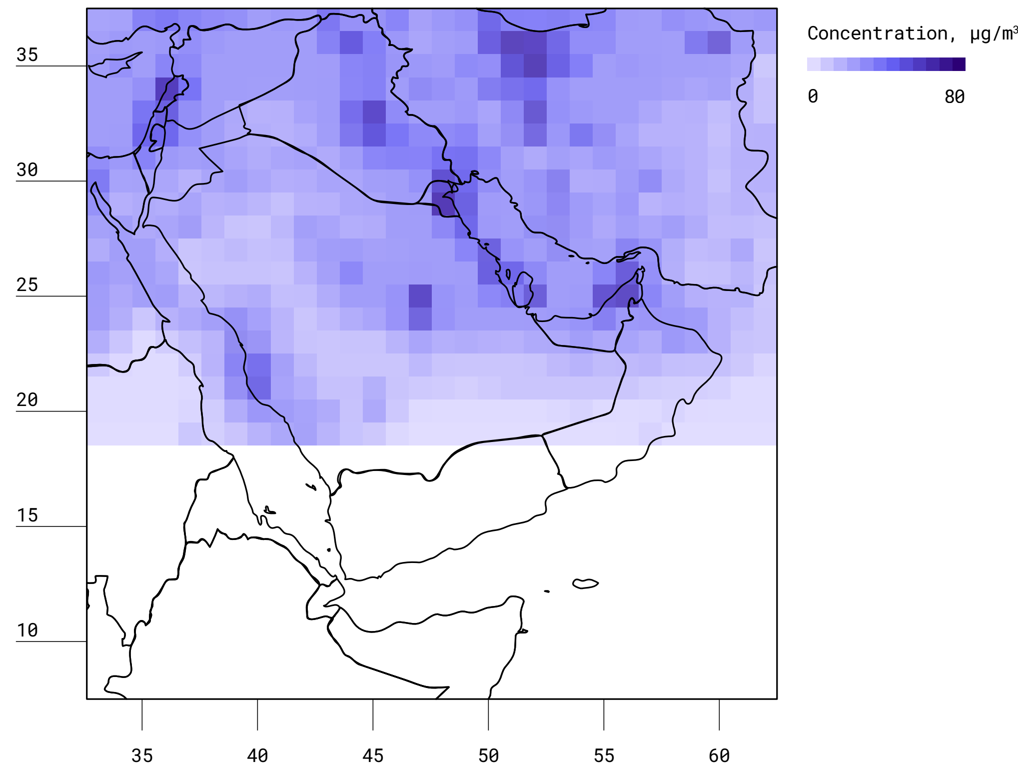
Concentration, µg/m³

0 150

Source: [14] Kutlar et. al., 2017.

Note: The annual WHO guidelines for NO_2 and $PM_{2.5}$ are 40 µg/m³ and 10 µg/m³, respectively.

FIGURE 1 Annual mean tropospheric NO_2 column concentrations in the Middle East, observed by the TROPOMI satellite instrument.



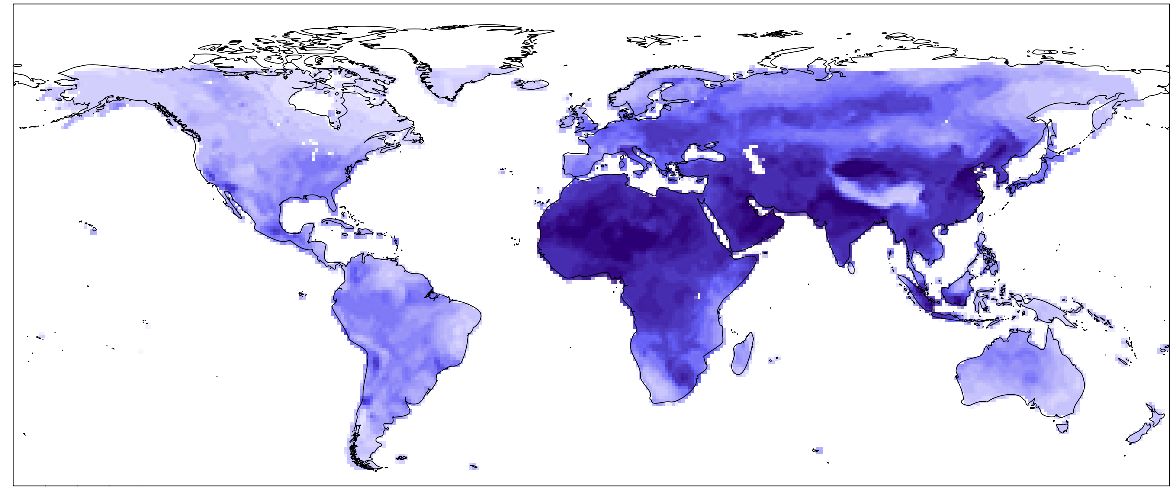
AIR POLLUTANTS

Nitrogen monoxide (NO) and nitrogen dioxide (NO_2), together defined as NOx, are gases that are formed during high-temperature combustion, in particular by the use of fossil fuels in energy generation and transportation. At the high temperatures generated in efficient combustion engines, molecular nitrogen and oxygen (the major gaseous components of the atmosphere) are decomposed, and subsequently NO is formed from O- and N-atoms through the so-called Zeldovich mechanism. After release into the ambient air NO is rapidly converted into NO_2. Furthermore, the burning of nitrogen containing fuels, also by less efficient combustion, e.g., of firewood and vegetation, can lead to NOx emissions through oxidation processes in the exhaust plumes. In the atmosphere, NOx interacts chemically with other pollutants under the influence of sunlight, forming particulate nitrate and ozone (O_3), the latter being known for its central role in photochemical smog [15]. FIGURE 1 Presents a regional map of annual average NO_2 concentrations from satellite observations, which underscores the role of emissions from urban and industrial locations in the spatial distribution of atmospheric NO_2 in the Middle East.

Fine particulate matter suspended in the air, referred to as aerosol, is composed of a mixture of dust, black carbon (including soot), inorganic acids, salts and low-volatile organic compounds. Direct releases of particulate matter into the atmosphere are defined as primary emissions, and can be natural, such as sea spray and aeolian dust, as well as anthropogenic. The latter include combustion products (e.g., fly ash, black carbon, primary organic carbon), break and tire wear, and products from waste incineration and industrial furnaces. Secondary particles are chemically formed within the atmosphere from precursor gases such as SO_2 and NO_2, largely associated with fossil fuel use, which are oxidized into acids that form salts with ammonia (NH_3) released from agricultural practices. Organic gases, emitted by traffic, domestic energy use, petrochemical industry and the volatilization of solvents, can be oxidized into products with lower volatility and higher solubility, and form secondary organic aerosols. The mixture of primary and secondary aerosols constitutes fine particulate matter ($PM_{2.5}$), being particularly relevant for public health as it can deeply penetrate the respiratory tract and impair lung function. FIGURE 2 Shows global, annual average $PM_{2.5}$ concentrations near the earth's surface, both with and without sea salt and desert dust. FIGURE 3 Presents the same data on a regional scale for the Middle East.

FIGURE 2 Annual mean distribution of $PM_{2.5}$, derived from satellite observations.

A. $PM_{2.5}$



B. $PM_{2.5}$, SEA SALT AND AEOLIAN DUST REMOVED

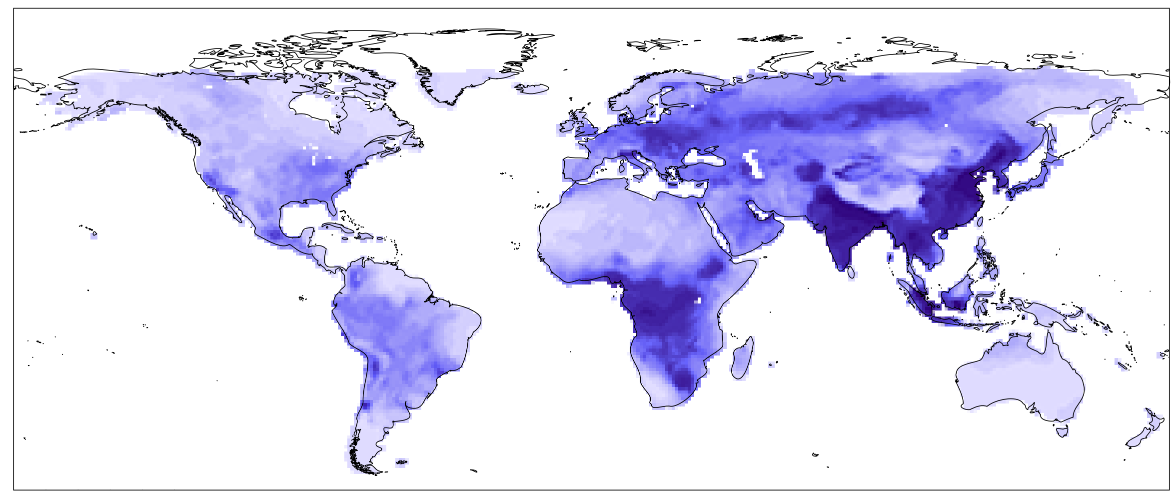
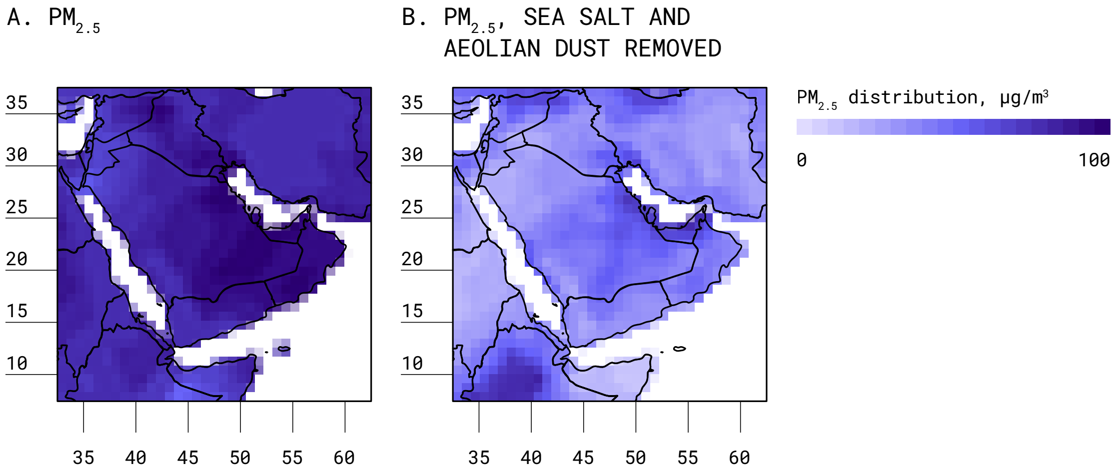


FIGURE 3 Annual mean distribution of $PM_{2.5}$ over the Middle East, derived from satellite observations[283].



PUBLIC HEALTH RISKS

Upon inhalation, NO_2 interacts with mucous membranes in the upper and lower respiratory tract, where it is converted into NO, nitrous acid (HONO) and nitric acid (HNO_3), which irritate the bronchi and can trigger asthma attacks [16,17]. In the lungs, NO_2 and its reaction products can cause tissue damage and inflammation. The exposure to $PM_{2.5}$ can result in a chronic oxidant/antioxidant imbalance in the respiratory system, with inflammatory responses, and implications for the etiology of respiratory and cardiovascular diseases [18-20]. Oxidative stress can occur directly by the inhalation of reactive oxygen species in $PM_{2.5}$, or indirectly from their catalytic generation within the epithelial lining fluid upon inhalation of toxic aerosol compounds, e.g., co-emitted by combustion sources [21,22]. The long-term impacts of inflammation within the respiratory tract can have local consequences, e.g., asthma and emphysema, as well as chronic outcomes such as circulatory and cardiovascular diseases [23,24]. Further, ozone is a strong oxidant that leads to respiratory and circulatory diseases through oxidative stress and airway damage, with immune-inflammatory responses within and beyond the lungs [25,26].

The harmfulness of fine particulates ($PM_{2.5}$) only partly relates to their chemical composition, as they trigger chronic irritation in the respiratory system, while the ultrafine size fraction (particles smaller than 0.1 μm) can translocate into the blood stream, affecting the circulatory system and other organs [27]. Bio-persistent particles including mineral

dust grains, not broken down by the organism, contribute to systemic stress and excess mortality [28,29]. As a result of chronic exposure, the viability of alveolar macrophages, responsible for the detection and removal of bacteria and other harmful organisms, can decrease significantly [18]. The physical and oxidative stress due to $PM_{2.5}$ deposition in the lungs and the resulting inflammations particularly affect people with pre-existing illness, and increase the risk of lung cancer. Inflammation of the lower respiratory tract releases messenger substances that carry inflammatory responses throughout the body, reducing the elasticity of blood vessels and contributing to blood clothing, atherosclerosis, and diseases that lead to heart attacks and strokes [19]. The inflammatory responses have also been linked to type 2 diabetes and neurological disorders [30-32].

PEDIATRIC ASTHMA FROM NO_2

Asthma is a chronic inflammatory disease of the lungs that is strongly influenced by environmental factors, with a strong upward trend of nearly 10% per decade globally, giving rise to a total of about 330 million cases, which leads to a number of excess deaths of about half a million each year [33,34]. Air pollution, notably NO_2, exacerbates asthma and also causes new cases, especially among children up to an age of about 18-20 years [16,35]. The biomedical mechanisms of asthma development from the exposure to NO_2 have been well established, and the US Environmental Protection Agency has concluded that there is ample evidence that documents a causal relationship [36]. The annual guideline concentration for NO_2 proposed by the WHO is 40 μg/m^3, however, it was formulated nearly two decades ago when the scientific evidence was still limited. Recently, the global exposure of the population to NO_2 has been estimated by using satellite observations and land use regression (LUR) models, assuming that land traffic is the major emission source that influences asthma incidence [37,38].

We have extended these analyses by using a global atmospheric chemistry – circulation model, combined with a LUR model, and satellite and ground-based air quality measurements, which corroborates that land transportation is an important source of NO_2 but that other sectors contribute as well [39]. The global NO_2 dataset established in [39] with a horizontal grid-spacing of 1km was aggregated to 5km, i.e., at the same resolution as that of global population data. It was found that the global mean, population-weighted exposure to NO_2 is between 18 and 19 μg/m^3. We derived an exposure-response function based on a meta-analysis of 41 epidemiological studies to relate exposure to NO_2-related asthma incidence in children and adolescents (NINC) [40]. The results indicate a global NINC of about 3.5 (2.1–6.0) million per year (numbers between parentheses represent the 95% confidence interval). The country with the highest incidence is China with 0.57 (0.33–0.96) million per year, and India has the second highest with 0.3 (0.17–0.52) million per year, while in western Europe the NINC is about 0.11 (0.06–0.17) million per year.

The estimated NINC in the Middle East (17 countries including 7 GCC countries)[1] is about 0.44 (0.28– 0.76) million per year, which is very high if we consider that the total population (nearly 600 million) is less than half that of China and India. In addition to significantly elevated NO_2 levels, the urban population fraction in the Middle East is comparatively large (>70%), which bears upon the exposure to traffic emissions. For Saudi Arabia we estimate an NINC of about 27 (16–44) thousand per year [39]. Globally, land transportation is the leading sector that contributes to NINC (about 44%), followed by the domestic burning of solid biofuels (about 10%) and energy generation from fossil fuels (about 9%). In Saudi Arabia land traffic is the major source of NO_2 and NINC, followed by fossil fuel use in energy generation and industry, and international shipping, which affects air quality in coastal areas. [39] found that about 90% of the NINC occurs in countries that meet the annual guideline of the WHO for NO_2 (40 μg/m³), which suggests a need to revisit this guideline to improve the health of children and adolescents.

[1] 17 countries are Bahrain, Cyprus, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine Territories, Qatar, Saudi Arabia, Syria, Turkey, UAE Yemen.

HEALTH OUTCOMES FROM $PM_{2.5}$ AND O_3

Exposure of the population to $PM_{2.5}$ has been estimated through a data-informed global atmospheric modelling approach, which also distinguishes exposure by a number of emission categories [4]. Data sources include satellites and ground-based remote sensing stations and about 4,500 air quality monitoring sites worldwide – note that stations are predominantly located in Europe, North America and East Asia. To estimate excess mortality the recent MR-BRT (meta-regression – Bayesian, regularized, trimmed) exposure-response functions of the Global Burden of Disease [3] were applied to derive age-dependent hazard ratios from exposure to $PM_{2.5}$. The MR-BRT functions include specific expressions for ischemic heart disease, stroke (ischemic and hemorrhagic), chronic obstructive pulmonary disease, lung cancer and type-II diabetes among adults (population >25 years of age), acute lower respiratory tract infection among children (population under 5 years of age), and low-birth weight and short gestation among neonates (age 0-27 days) [41]. As an example, FIGURE 4 shows the fractions of excess mortality attributed to $PM_{2.5}$ through different disease categories for four countries. It illustrates that in middle- to high-income countries cardiovascular diseases are predominant (IHD, stroke), while in low-income countries e.g. in Africa child mortality is of particular importance.

While local concentrations of air pollutants often vary greatly due to meteorological processes (e.g. wind direction, turbulent flows), such variability has limited weight in the mortality calculations. These involve time-integrated, annual concentrations of $PM_{2.5}$ and O_3 (to assess long-term exposure) computed by an atmospheric model and derived from satellite observations. Ozone and a large fraction of the $PM_{2.5}$ compounds are secondary pollutants, which means that they are chemically formed in the atmosphere on a time scale of hours to days. Therefore, their concentrations are not controlled locally but rather on a larger scale, which is also true for aeolian dust downwind of deserts. Therefore, urban concentrations and those in the areas that surround cities are typically not very different. FIGURE 5 Shows data from

FIGURE 4 Percentage contributions of disease categories that contribute to excess mortality from $PM_{2.5}$ in the Kingdom of Saudi Arabia, the United States, China and Nigeria.

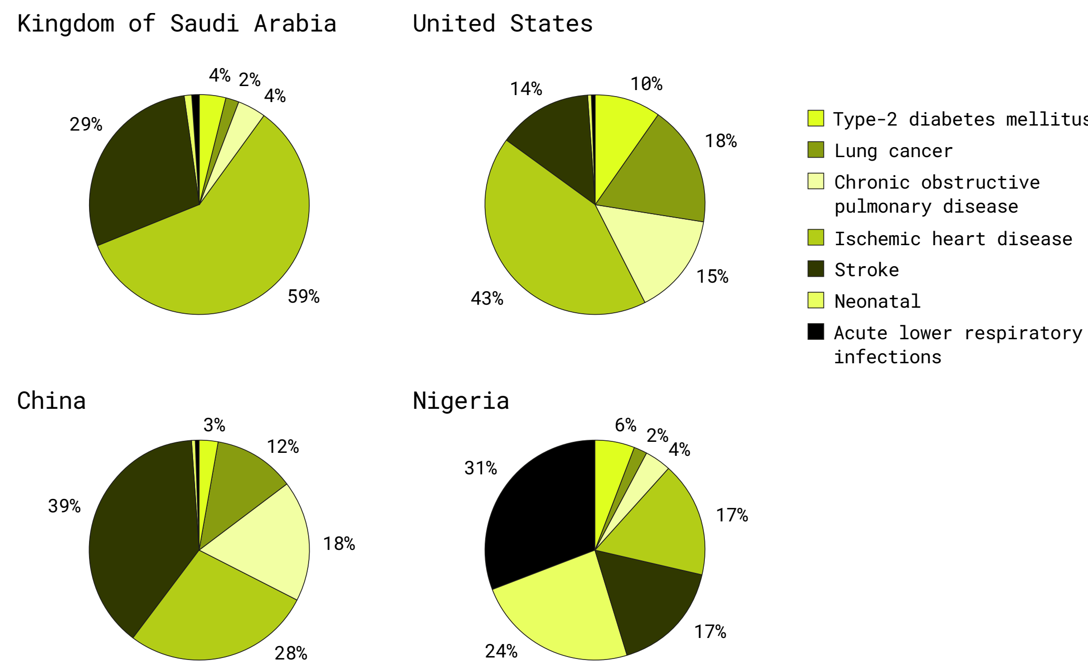
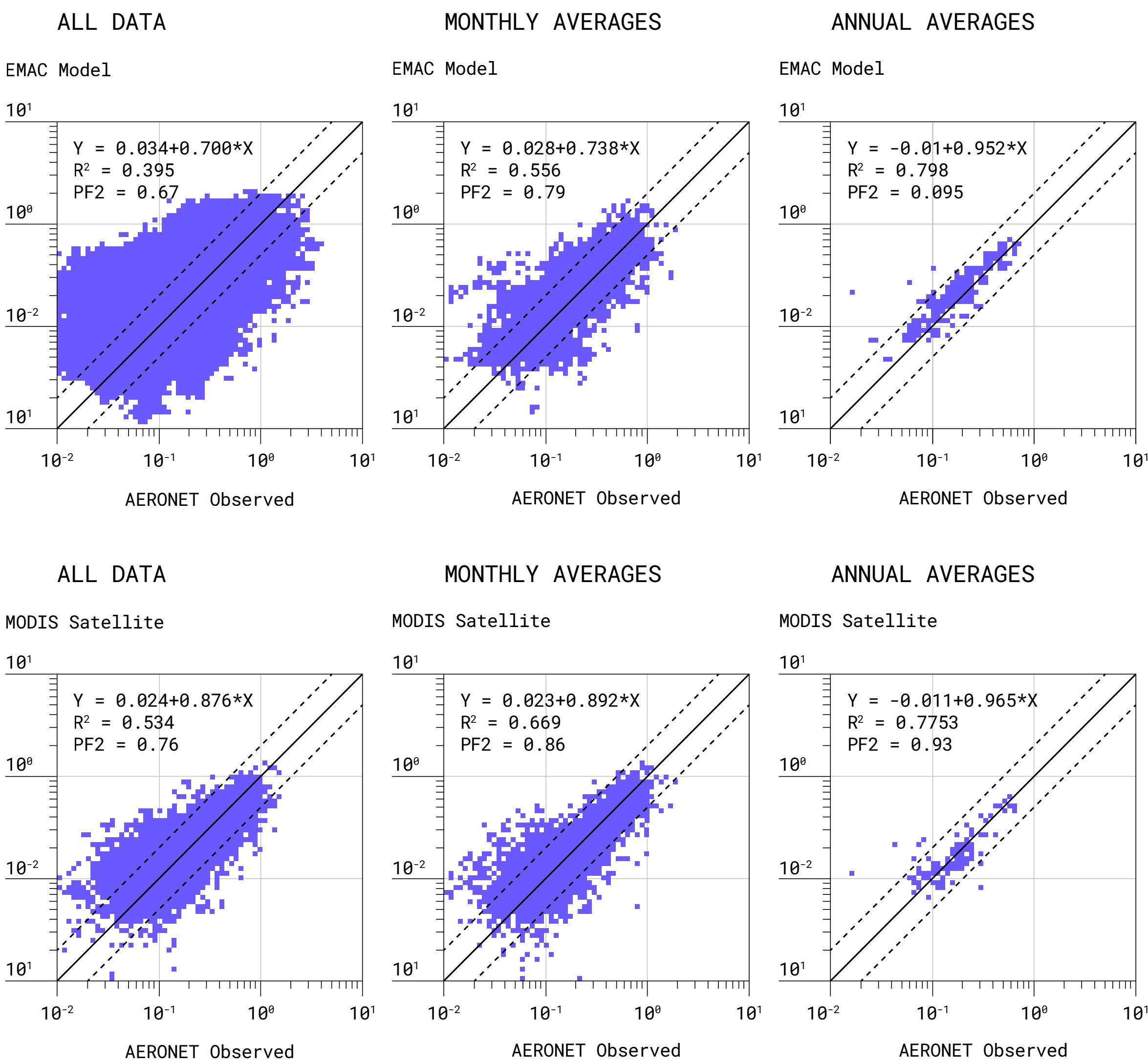


FIGURE 5 Comparison of aerosol optical depth (AOD) from ground-based (AERONET) measurements with (EMAC) model calculations and with MODIS satellite data.



ground-based AERONET stations, compared to results from our global atmospheric chemistry model EMAC (upper panels), and to MODIS satellite measurements (lower panels) of aerosol optical depth (AOD). The large spread in the left panels illustrates the local variability, which is not captured well by the model nor by the satellite observations – however, is not needed to represent the chronic exposure to $PM_{2.5}$, which depends on annual average concentrations, for which the correlations (R^2) are very high (right panels).

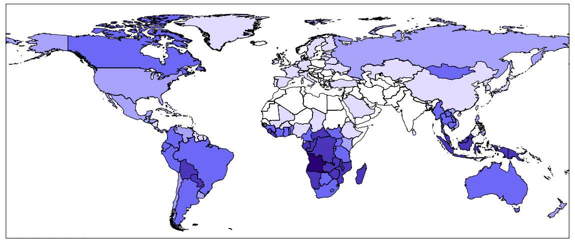
The global atmospheric model – AERONET comparison includes more data points (N=110,468) than of MODIS – AERONET (N=4,488) as the satellite view is limited by fixed daily overpass times and by clouds. By combining the global data of annual mean exposure to ambient $PM_{2.5}$ with the MR-BRT functions of the [3], we estimate 4.23 (95% confidence interval 3.0-6.14) million excess deaths annually [41]. We find that globally, 91 (66-126) adults per 100,000 and 49 (23-111) neonates and children per 100,000 die prematurely each year from $PM_{2.5}$. Ischemic (coronary) heart disease (38%) and stroke (32%) are the most prevalent causes of mortality in adults followed by COPD (15%), lung cancer (8%) and type 2 diabetes (7%). The excess mortality by age category can vary greatly per region, with a high proportion of neonatal and child mortality in low-income countries in Africa and South Asia [FIGURE 4]. [FIGURE 6] Presents the sector contributions to excess mortality from air pollution. It demonstrates the health benefits that could be achieved by replacing each of these activities by non-polluting alternatives. The countries with highest excess mortality from $PM_{2.5}$ are China, India, Pakistan, Indonesia, Bangladesh and Japan in South and East Asia, while Russia, the USA, Nigeria and Egypt are also among the top ten.

FIGURE 6 Percentage contribution to excess mortality from ambient $PM_{2.5}$ by source sectors and country.

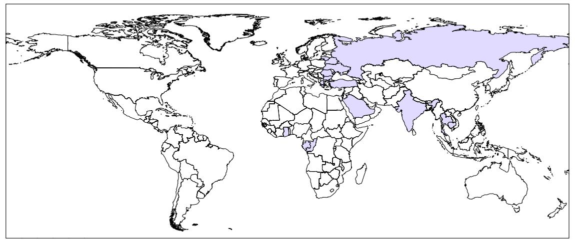
Contribution to excess mortality, %

0-7.5 | 7.5-15 | 15-30 | 30-65 | 65-100

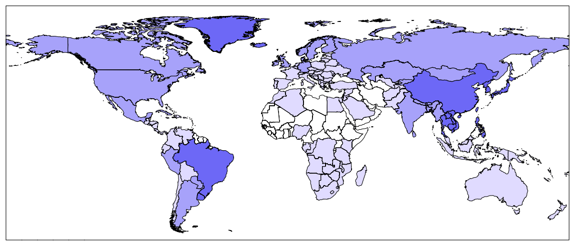
A. BIOMASS BURNING



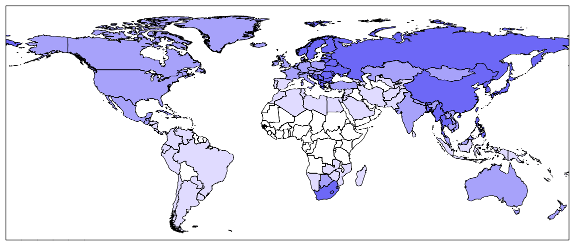
B. AGRICULTURAL WASTE BURNING



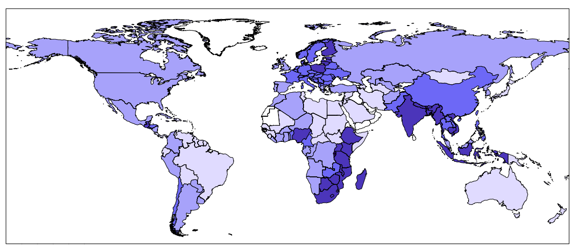
C. INDUSTRY



D. ENERGY GENERATION



E. DOMESTIC ENERGY USE



F. SHIPPING

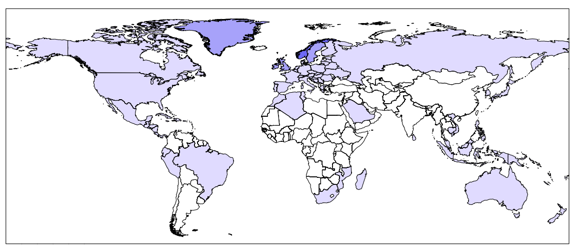
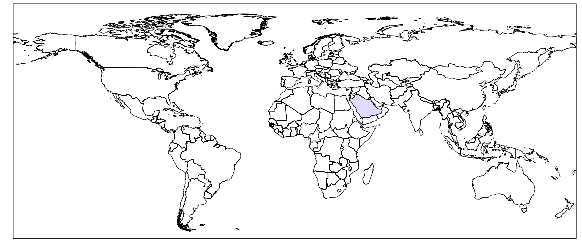


FIGURE 6 Percentage contribution to excess mortality from ambient $PM_{2.5}$ by source sectors and country.

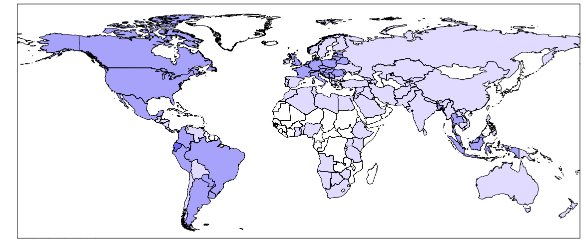
Contribution to excess mortality, %

0-7.5 | 7.5-15 | 15-30 | 30-65 | 65-100

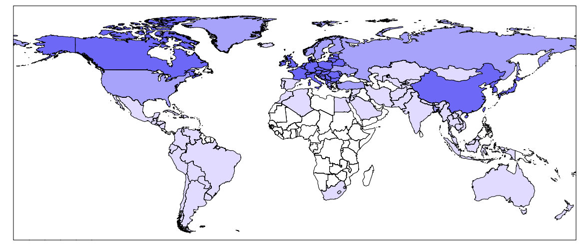
G. WASTE INCINERATION



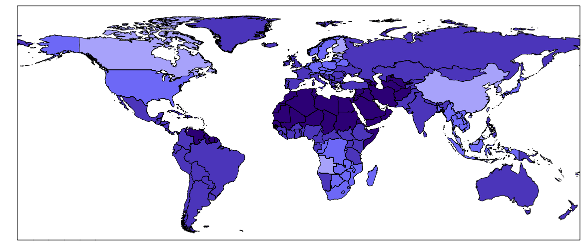
H. LAND TRANSPORTATION



I. BIOMASS BURNING



J. AGRICULTURAL WASTE BURNING



DISCUSSION

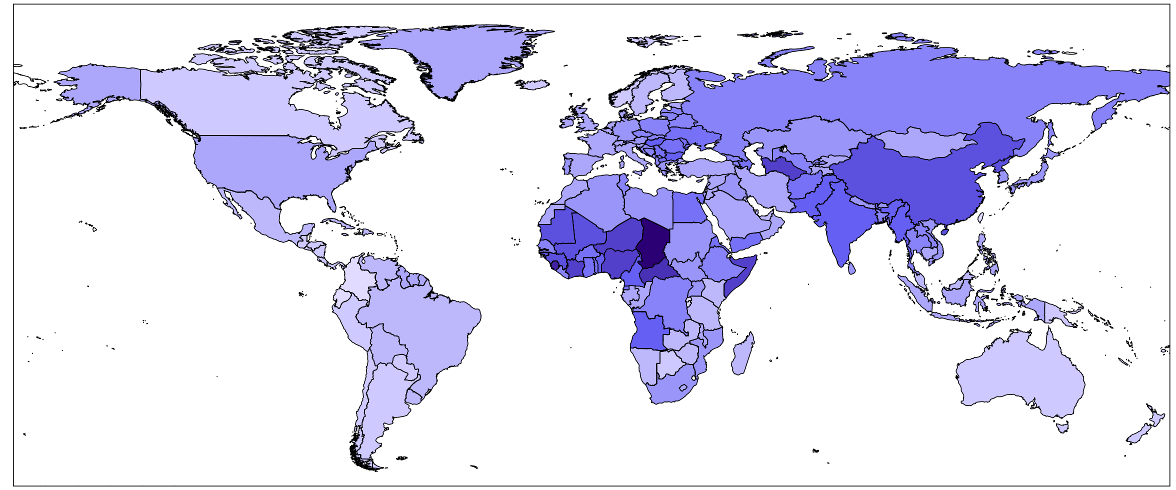
Based on nearly five decades of epidemiological, toxicological and biomedical research, it has been convincingly shown that air pollution is a major public health risk factor. The WHO has formulated guideline concentrations, recommended for legislation in the members states. However, not all countries have adopted the guidelines, while most apply less strict air pollution concentration standards or have not implemented air quality legislation at all (most of the Middle East, except Saudi Arabia). Moreover, the WHO guidelines date from 2005, and are currently being reconsidered on the basis of recent meta-studies, showing that health impacts occur at relatively low pollution levels below the current guideline concentrations. Public health outcomes have been well-documented for a large (and growing) number of disease categories, including respiratory infections, also in children, COPD, lung cancer, cardiovascular and cerebrovascular diseases.

A recent estimate of global excess mortality attributed to the exposure to $PM_{2.5}$ is about 4.23 (3.0– 6.14) million per year, accounting for specific disease categories [3, 41]. By also including other non-communicable diseases for which explicit exposure-response functions are not available, as well as ozone (in addition to $PM_{2.5}$), the global excess mortality was estimated to be about twice as high [4, 5], and a new estimate by [6] even exceeds 10 million per year for the fossil fuel component of $PM_{2.5}$ only. By adopting the method of the [3] for the health outcomes from the exposure to $PM_{2.5}$, and adding that of ozone, we estimate an excess mortality for the ME countries (17 countries including 7 GCC countries) of 274 (193–391) thousand per year, and 18,6 (13,7–25,6) thousand per year for Saudi Arabia. [4] evaluated the loss of life expectancy from air pollution, and contrasted it with other health risk factors (using the GEMM of [5]. FIGURE 7 Shows results of these calculations, comparing ambient air pollution to tobacco smoking. Since about two thirds of ambient air pollution are of anthropogenic origin and "avoidable", it can be concluded that the global mean loss of life expectancy from smoking and avoidable air pollution are quite similar.

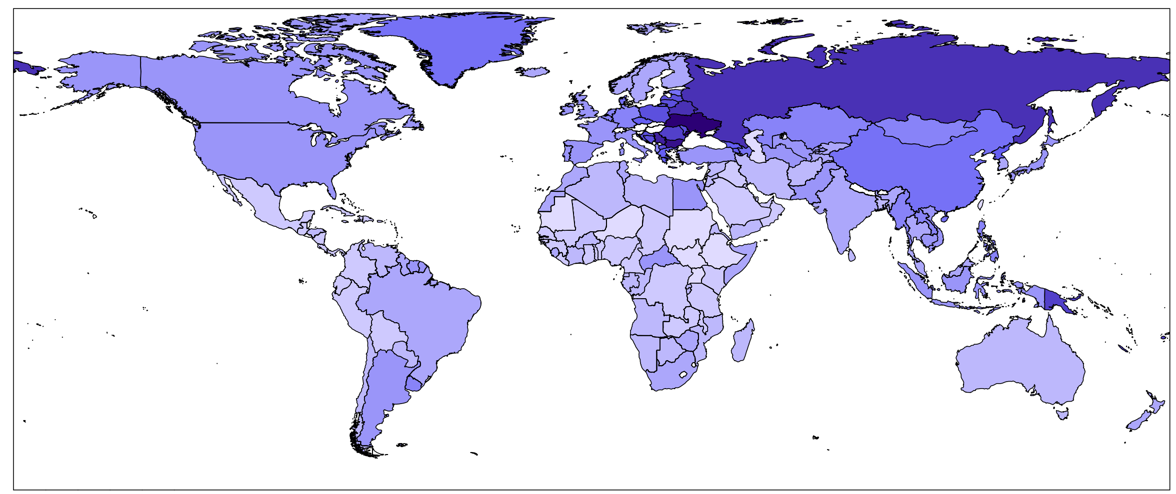
FIGURE 7 Mean global and country-level loss of life expectancy from the exposure to all ambient air pollution (including natural) and from tobacco smoking.

Loss of life expectancy (years)
0 7

A. ALL AMBIENT AIR POLLUTION (2.9 YEAR)



B. TOBACCO SMOKING (2.2 YEAR)



The estimated mean loss of life expectancy from air pollution for the Middle East is about 2.3 years, and about 2.0 years in Saudi Arabia. Furthermore, the NO_2-related asthma incidence (NINC) under children and adolescents is remarkably high. The estimated NINC in the Middle East is 0.44 (0.28–0.76) million per year, and 27 (16–44) thousand per year in Saudi Arabia. Due to the high levels of photochemical air pollution, the health outcomes of O_3 are also well above-average. It should be emphasized that air pollution data for the Middle East have been derived from satellite observations and modeling only, and that exposure-response functions and uncertainty analyses relied on epidemiological studies in North America, Europe and East Asia; such data and studies are not yet available for the region. To do justice to the specific conditions in the Middle East, with a high fraction of city dwellers, high levels of aeolian dust and prevalent petrochemical industry, it is recommended to initiate dedicated studies in the region.

REGIONAL NATURAL AND ANTHROPOGENIC AEROSOL AIR POLLUTION IN THE MIDDLE EAST

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King Abdullah University of Science and Technology, Thuwal, Saudi Arabia

INTRODUCTION

The previous part addresses the air quality and its health effect from the global perspective based on satellite observations and global model (EMAC) simulations. A regional-to-local spatial resolutions are needed to focus on the national scales and impact on the urban population. This part deals with the analysis of the regional scale PM pollution in the Middle East using available aerosol reanalysis products and high-resolution model simulations calibrated with satellite observations and in-situ air quality data sets. In the Middle East, the natural dust contribution to PM pollution is high and has to be specifically addressed.

PM is a complex mixture of sea salt, sulfate, black carbon, organic matter, and mineral dust, suspended in the air. The dramatic increase in the level of air pollution in developing countries over the last decades is forced by rapid economic and population growth, burning of fossil fuels, construction, and agricultural activities [1]. However, the primary cause of air pollution in the ME is mineral dust, and it is on the rise [2]. Along with Asia and Africa, the ME significantly contributes to global dust emissions, which are in the range of 1000-2000 Mt [3]. According to [4], the Middle East and North Africa (MENA) regions account for about half of global dust emissions. By integrating surface emissions in MERRA-2 reanalysis, we found that the total global dust emission averaged over the 2015-2016 period is about 1600 Mt, right in the middle of the [3] estimate. The dust emission from our simulation domain (see [FIGURE 8]) that covers the ME and nearby areas is about 500 Mt, contributing ≈30% to the global dust emission budget. Also, frequent inflows of pollutants from Europe and Africa worsen the air quality over the Arabian Peninsula [5-11]. Because of the large amount of dust, the ME is one of the most polluted areas in the world.

Located in the center of the northern subtropical dust belt, the Arabian Desert is the third-largest (after the Sahara and the East Asian deserts) region of dust generation, where dust plays a significant role in controlling regional climate [12-21].

In addition to natural dust aerosols, the ME receives high concentrations of anthropogenic PM [22-25]. The most important anthropogenic aerosol in ME is sulfate with SO_2 as a precursor, the contributions of other types of aerosols in PM, sea salt, organic matter, and black carbon are of lesser importance [26]. ME emits about 10% of the total global anthropogenic SO_2 [27] generated in energy production, water desalination, and oil recovery operations [28]. SO_2 is converted photochemically into sulfate aerosol [29]. [30, 31] simulated transport and distribution of SO_2 over the Middle east using the high-resolution WRF-CHEM (i.e., the Weather Research and Forecasting) model and demonstrated high surface concentrations of SO_2 along the west and east coasts of Arabian Peninsula.

The impact of aerosols on air-quality is characterized by near-surface concentrations of PM, which comprise both PM_{10} and $PM_{2.5}$ (particles with aerodynamic diameters less than 10 µm and 2.5 µm, correspondingly). Extended exposure to PM may cause cardiovascular and respiratory disease, lung cancer, and cause premature mortality on a global scale [29]. According to the WHO, outdoor air pollution caused 4.2 million premature deaths worldwide in 2016 [32]. To protect human health and the environment, WHO [33], and the National Agencies, e.g., the United States Environmental Protection Agency (US-EPA) [34], European Commission (EC) [35], and the Kingdom Saudi Arabia Presidency of Meteorology and Environment (KSA-PME) [36] issued the air quality regulations for PM that are presented in TABLE 2. The WHO guidelines are the strictest, while KSA-PME regulations are the softest.

FIGURE 8 Simulation domain with marked locations of the AQMS and AERONET sites.

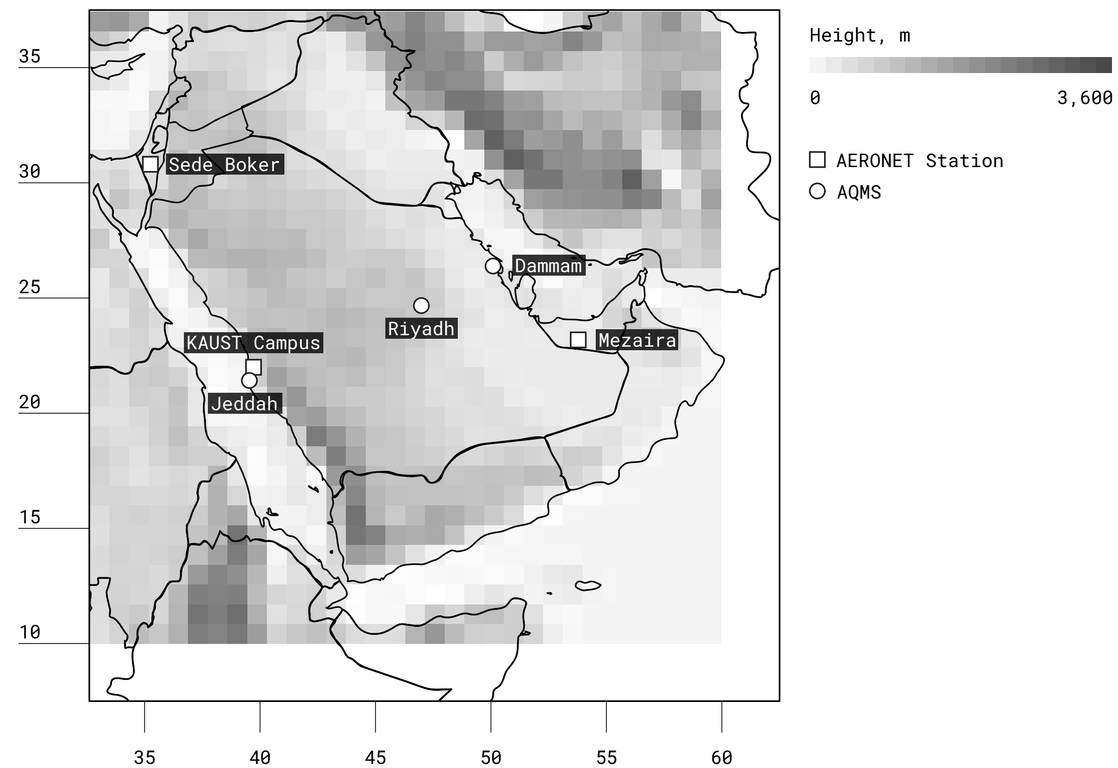


TABLE 2 Air quality regulations for $PM_{2.5}$ and PM_{10} prescribed by WHO, US-EPA, EC, and KSA-PME.

Particulate Matter (PM)	Average period	WHO	US EPA	EC	KSA-PME
$PM_{2.5}$	24 h	25	35[1]	NA	35
	1 yr	10	15[2]	25	15
PM_{10}	24 h	50	150[3]	50[4]	340
	1 yr	20	NA	40	80

Concentration, μg/m³

0 340

Note
[1] 98th percentile, averaged over 3 years.
[2] Annual mean, averaged over 3 years.
[3] Not to be exceeded more than once per year on average over 3 years.
[4] 35 permitted exceedances per year.

DATA

Satellite-based sensors can observe aerosols globally. NASA MODIS provides the most reliable aerosol dataset [37]. MODIS data has been processed by different algorithms, such as MODIS- DB&DT [38], or MAIAC [39]. Global satellite observations of aerosol optical depth (AOD) inform about vertically-integrated aerosol loading in an entire atmospheric column. However, the near-surface PM concentration cannot be observed from space. These measurements could be conducted only in situ in a limited number of locations. Along with instrumental observations, modern data assimilation products provide valuable information about AOD and near-surface PM concentration even in areas where satellite sensors are unreliable due to factors such as the high reflectivity of land surfaces [40]. Assimilation products improve the aerosol total column loadings through the assimilation of observed AOD but are incapable of assimilating the aerosol vertical structure and chemical composition. There are two well-known data assimilation products that assimilate atmospheric constituents: MERRA-2 [26, 41] from the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) and CAMS-OA [42-44] from European Centre for Medium-range Weather Forecast (ECMWF). These data assimilation products adequately reproduce AOD and PM concentrations in different regions of the world [41, 45-47].

MODELING

To calculate fine-resolution PM and sulfate fields, we use the Weather Research and Forecasting (WRF) model [48] coupled with chemistry [49, 50]. The WRF- Chem is used for the prediction and simulation of weather, air quality, and dust storms, accounting for the aerosol effect on radiation. WRF-Chem has been widely used for air quality simulations in different parts of the globe: East Asia [51], North America [52, 53], Europe [54, 55], South America [56] and Middle East [11]. We conducted simulations for the 2015-2016 period. The simulation domain, shown in FIGURE 8, is centered at 28°N, 42°E, and a 10×10 km² horizontal grid (450×450 grid nodes) is employed. The vertical grid comprises 50 vertical levels with enhanced resolution closer to the ground comprising 11 model levels within the near-surface 1-km layer.

The aerosol/chemistry initial and boundary conditions (IC&BC) are calculated using MERRA-2 output using the newly developed Merra2BC interpolation utility [57]. To be consistent with aerosol/chemistry IC&BC, we also define the meteorological IC&BC using MERRA-2 output. We configure WRF-Chem in our simulations with the Unified Noah land surface model. The Revised MM5 Monin-Obukhov scheme is chosen to represent land surface processes and surface layer physics. The Yonsei University scheme is chosen for PBL parameterization. The WRF single-moment microphysics scheme is used for the treatment of cloud microphysics. The New Grell's scheme is used for cumulus parameterization. The Rapid Radiative Transfer Model (RRTMG) for both short-wave and long-wave radiation is used for radiative transfer calculations. Only the aerosol direct radiative effect is accounted for. More details on the physical parameterizations used can be found at http://www2.mmm.ucar.edu/wrf/users/phys_references.html.

To calculate anthropogenic emissions, we use the novel OMI-HTAP emission dataset [58] based on the combination of distributed emissions from residential and transportation sectors taken from the HTAP-2.2 inventory [1] with the catalog of the strong (>30 kt yr-1) point emissions [59] built using satellite observations by Ozone Monitoring Instrument (OMI) [60, 61]. The catalog contains more than 500 point sources of industrial origin, some of which are not present in the widely used EDGAR-4.2 and HTAP-2.2 emission datasets. For example, 14 previously unaccounted point emissions located in the ME (mostly in the Arabian Gulf) were detected, and most of them are related to the oil and gas industry. OMI-HTAP emissions are provided on a 0.1° x 0.1° grid [58].

To calculate aerosols, we employ the GOCART [62] aerosol model. Dust emission from the surface is calculated using the GOCART emission scheme [63]. We use the U.S. Geological Survey (USGS) 24-category land-use mapping [64] to turn off natural dust emissions in urban areas. As in our previous studies [5, 6, 20], we tune dust emissions to fit the AOD from the AERONET stations located within the domain.

MODEL VALIDATION

First, we evaluate the ability of WRF-Chem, CAMS-OA, and MERRA-2 to reproduce the aerosol content in the atmosphere accurately. This content is characterized by AOD. In the ME, mineral dust contribution to the total AOD is dominant (≈87%) [16, 65]. The treatment of optically active dust within the model is therefore vitally important.

The comparison of the daily averaged AOD time series and corresponding scatter plots calculated using WRF-Chem, MERRA-2, CAMS-OA with MODIS (MODIS-DB&DT, and MAIAC) and AERONET AOD observations conducted at KAUST Campus, Mezaira and Sede Boker during 2015-2016 period is presented in FIGURE 9.

The scatter plots show that the model and assimilation products are capable of reproducing the magnitude and temporal evolution of the observed AERONET AOD at all sites. To quantify the capability of the WRF-Chem, MERRA-2, and CAMS-OA models, and the MODIS-DB&DT and MAIAC products to reproduce the AERONET AOD, we calculate Pearson correlation coefficient *R* and mean bias with respect to the AERONET AOD observations for the 2015-2016 period. The correlation coefficients are the highest for MERRA-2 and MAIAC. MAIAC shows better correlation than MERRA-2 during 2015 (0.88- 0.96), but MERRA-2 is better correlated with AERONET (0.85-0.91) than MAIAC in 2016. CAMS-OA, despite it does not assimilate AERONET, shows better correlations (0.65-0.87) than MODIS-DB&DT (0.56-0.84). However, CAMS-OA overestimates AOD, particularly during acute dust events, and has a relatively high positive mean bias. The correlation coefficient for the WRF-Chem AOD is (0.43-0.85). MERRA-2 and WRF-Chem have the lowest mean bias in comparison with the other models and products.

FIGURE 9 Daily averaged AOD at three AERONET sites (KAUST Campus, Mezaira, Sede Boker) and corresponding scatter plots computed for WRF-Chem, AERONET, MERRA-2, CAMS-OA, MODIS-DB&DT, and MAIAC.

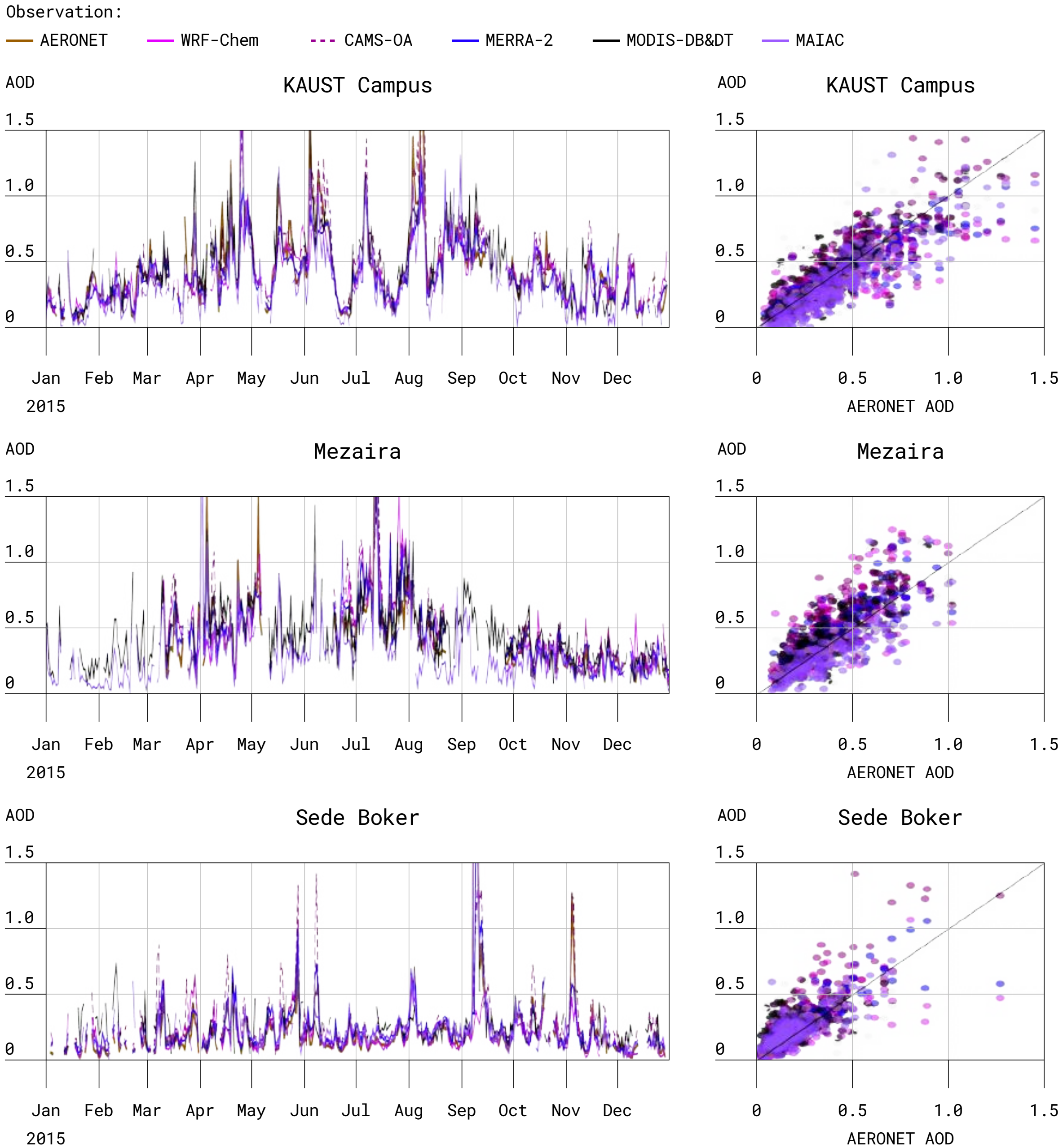
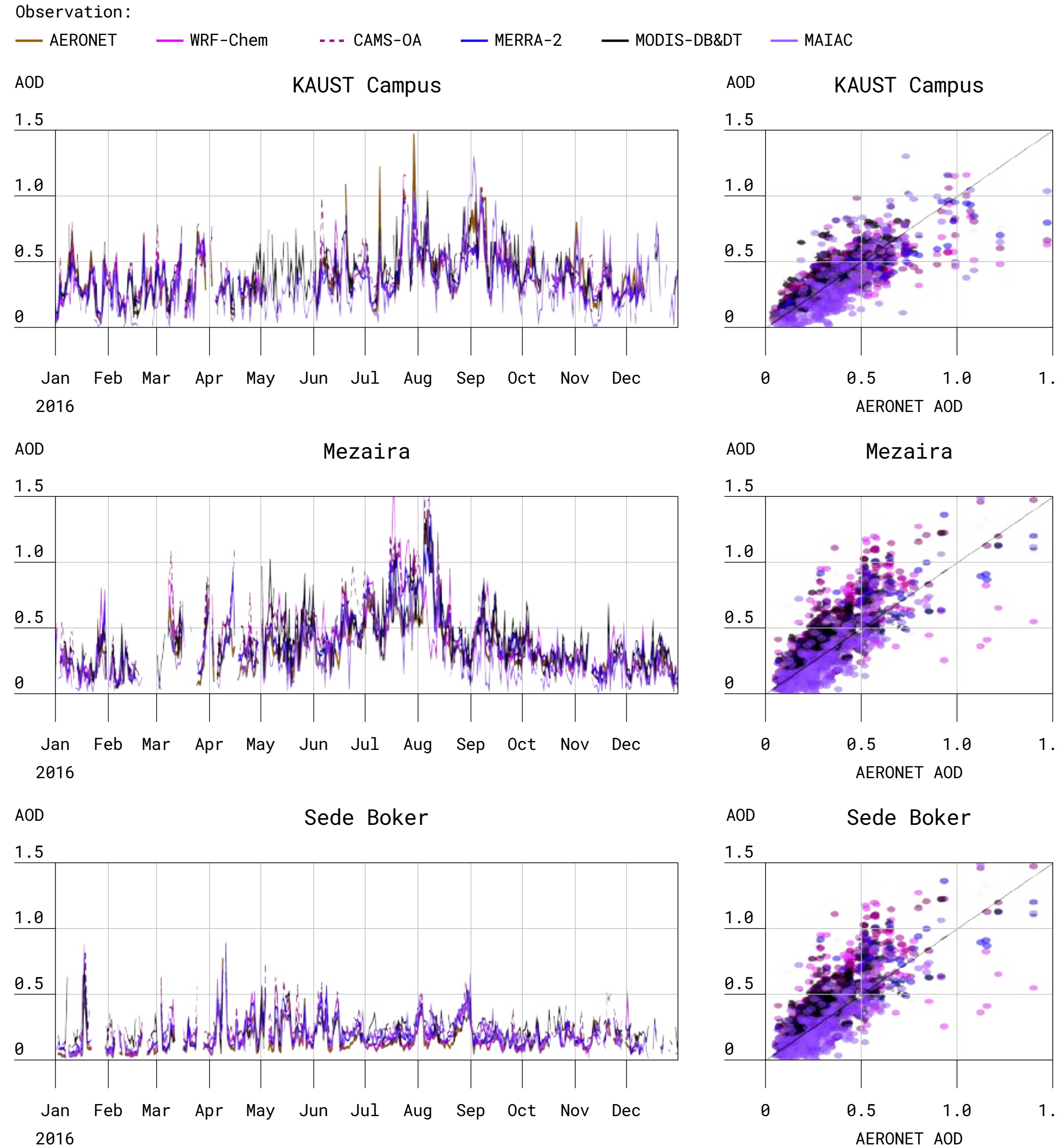


FIGURE 9 Daily averaged AOD at three AERONET sites (KAUST Campus, Mezaira, Sede Boker) and corresponding scatter plots computed for WRF-Chem, AERONET, MERRA-2, CAMS-OA, MODIS-DB&DT, and MAIAC.



PM AIR POLLUTION

To test the simulated PM concentrations, we use observations conducted by the air quality monitoring stations (AQMS) that measure surface concentrations of $PM_{2.5}$ and PM_{10} in Riyadh, Jeddah, and Dammam (megacities of Saudi Arabia), see FIGURE 8. Observations are available starting from 2016. The measurements were conducted by the Saudi Authority for Industrial Cities and Technology Zones (MODON). The PM measurements are conducted every 15 minutes.

The modeled $PM_{2.5}$ and PM_{10} concentrations were sampled from the model fields at the exact AQMS locations. The histograms at the right-side panels in FIGURE 10, 11 show the annual mean PM concentrations from WRF-Chem, MERRA-2, and CAMS-OA split into the dust and non-dust components. The dashed and dash-dotted horizontal lines correspond to KSA-PME limits and WHO air quality guidelines for daily (on the left-side panels) and annual mean (on the right-side panels) PM concentrations.

FIGURE 10 Shows that the daily averaged $PM_{2.5}$ concentrations observed by MODON AQMS at all locations never drop below the WHO limit of 25 μg/m³. During the severe dust events, this limit is exceeded in 2016 10-15 times. The less restrictive KSA-PME limit of 35 μg/m³ is exceeded 7-11 times during the dust outbreaks. Annually averaged MODON measurements are 8-18 times higher than the 10 μg m⁻³ WHO limit and 5-12 times higher than the 15 μg/m³ KSA-PME limit for annual mean $PM_{2.5}$ concentrations. Annual mean $PM_{2.5}$ concentrations from WRF-Chem and MERRA-2 exceed the 10 μg/m³ WHO limit by≈4-7 and ≈6-10 times, respectively, in alllocations. The KSA-PME limit of 15 μg m⁻³ for annual average $PM_{2.5}$ concentrations is exceeded ≈2.5-4.5 and ≈4-6.5 times, respectively, for WRF-Chem and MERRA-2.

In Jeddah and Dammam, WRF-Chem and MERRA-2 show similar relative contributions of non-dust components to $PM_{2.5}$ (30-34% in Jeddah and 12-14% in Dammam), but in MERRA-2 sea salt is a major contributor into non-dust $PM_{2.5}$, while in WRF-Chem it is sulfate. This difference between WRF-Chem and MERRA-2 is mainly because MERRA-2 generates more sea salt, but also because MERRA-2 underestimates SO_2 emissions located in the Arabian Gulf and along the west coast of Saudi Arabia [31], and hence underestimates sulfate concentrations. In Riyadh, the contribution of the non-dust component to $PM_{2.5}$ is ≈9-12% for both MERRA-2 and WRF-Chem. In CAMS-OA, the contribution of non-dust particulates to $PM_{2.5}$ in Jeddah and Dammam is ≈7-10%, and the contribution of sea salt is little.

According to model simulations, the contribution of dust to $PM_{2.5}$ in Jeddah is 65-90%, while in Riyadh and Dammam, this contribution is 85-95%. Daily averaged PM10 MODON measurements almost continuously exceed the WHO guideline of 50 μg/m³ at all locations, see FIGURE 11. In Riyadh and Dammam, PM_{10} concentration is higher than in Jeddah, where the KSA-PME limit of 340 μg/m³ for daily averaged PM_{10} is exceeded in 2016 about a dozen times. In Dammam, this limit is more frequently exceeded, especially during the summer period. During acute dust events in Dammam, daily averaged PM_{10} concentrations can exceed the WHO guideline limit by more than 10-20 times. Annually averaged MODON measurements are 7-11 times higher than the 20 μg/m³ WHO guideline and in 2-3 times higher than the 80 KSA-PME limits for annual mean PM_{10} concentrations.

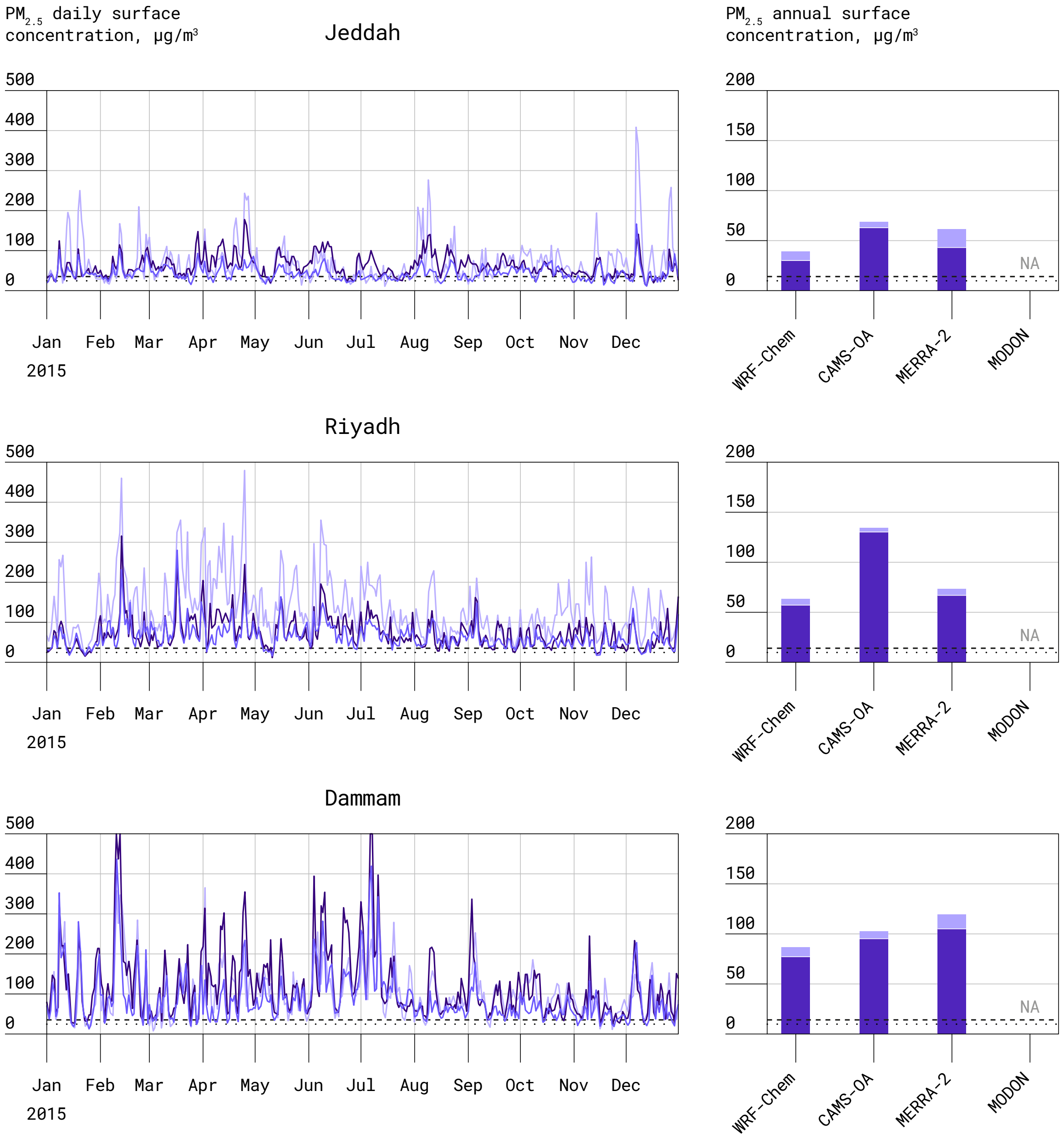
WRF-Chem compares better with PM_{10} observations by MODON than MERRA-2 and CAMS-OA in all locations because of its higher spatial resolution. Annual mean PM_{10} concentrations from WRF-Chem and MERRA-2 exceed the WHO limit of 20 μg m⁻³ ≈6-15 and ≈10-20 times, respectively, in alllocations.

Contribution of dust to PM_{10} in Jeddah is 70-90%, while in Riyadh and Dammam this contribution is 90-96%. Minimal contribution (≈3.5-4%) of non-dust components to PM_{10} is observed among all models in Riyadh.

FIGURE 10 Daily averaged $PM_{2.5}$ surface concentrations and decomposition of the $PM_{2.5}$ annual mean surface concentrations into dust and non-dust components.

A. DAILY AVERAGED $PM_{2.5}$ SURFACE CONCENTRATIONS

B. DECOMPOSITION OF $PM_{2.5}$ ANNUAL MEAN SURFACE COCENTRATIONS



Observation:
- MODON
- MERRA-2
- WRF-Chem
- CAMS-OA

Guideline references:
- WHO
- KSA-PME

Dust components:
- Dust $PM_{2.5}$
- Non-dust $PM_{2.5}$
- MODON

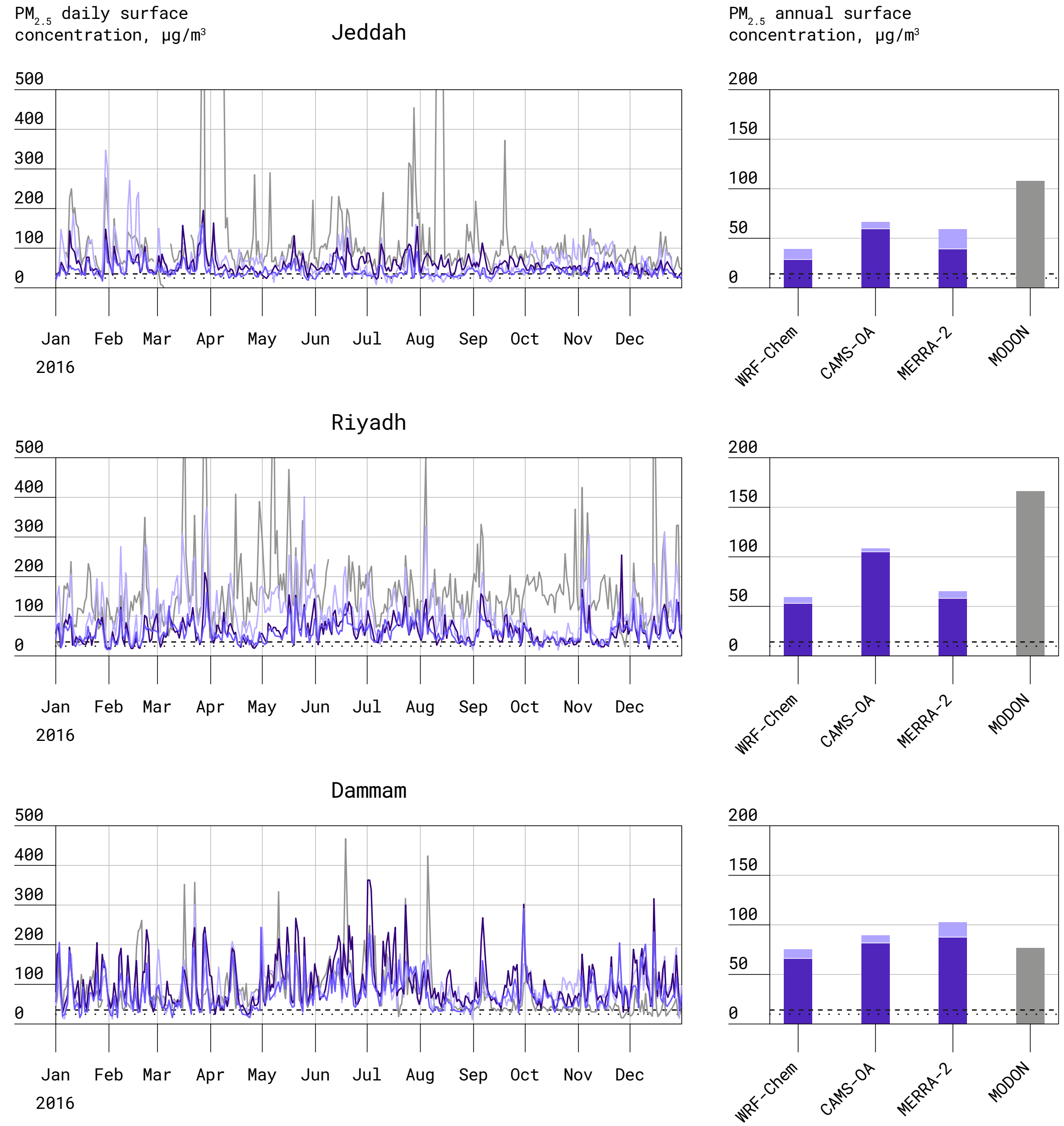
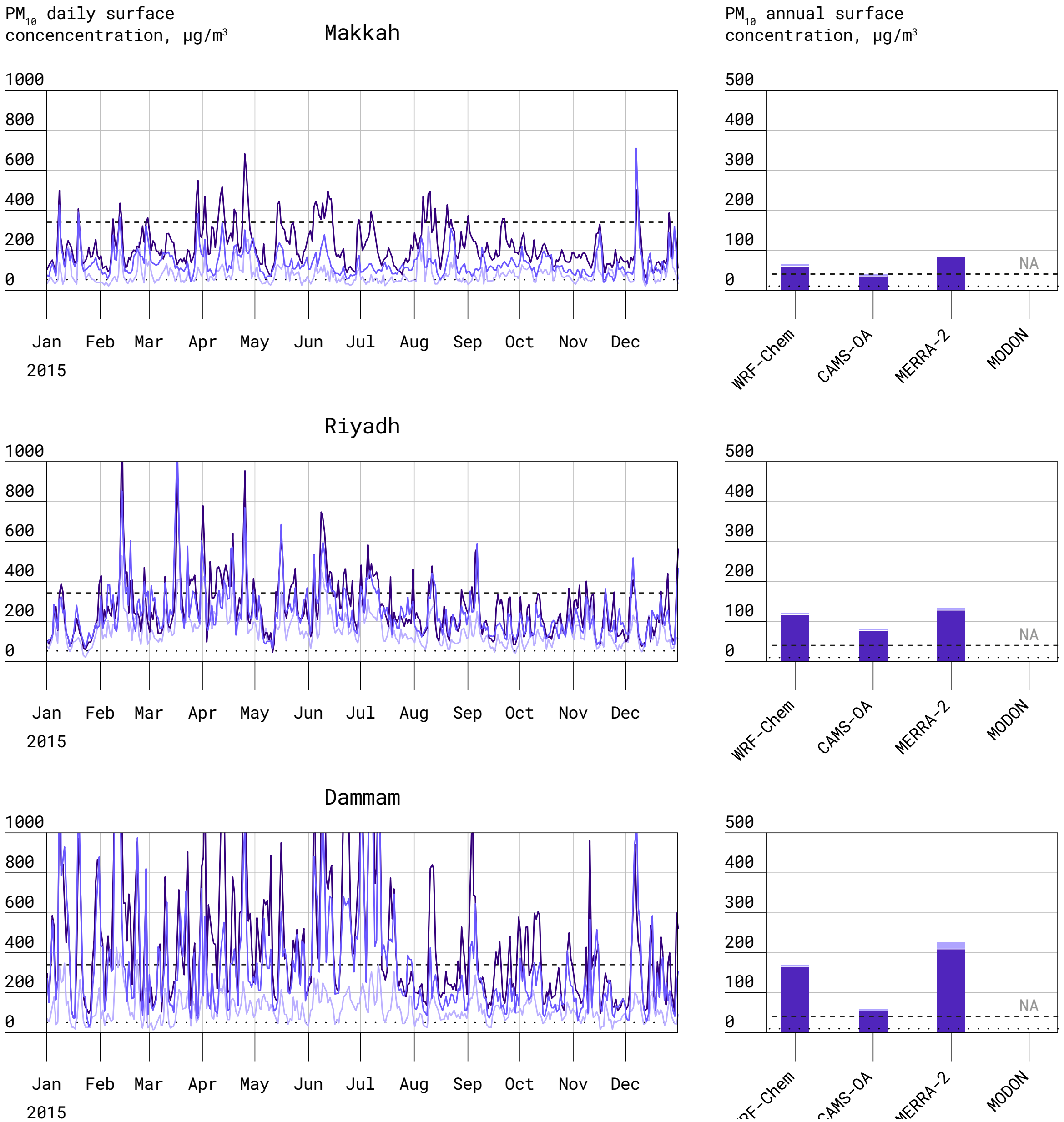


FIGURE 11 Daily averaged $PM_{2.5}$ surface concentrations and decomposition of the PM_{10} annual mean surface concentrations into dust and non-dust components.

A. DAILY AVERAGED PM_{10} SURFACE CONCENTRATIONS

B. DECOMPOSITION OF PM_{10} ANNUAL MEAN SURFACE COCENTRATIONS



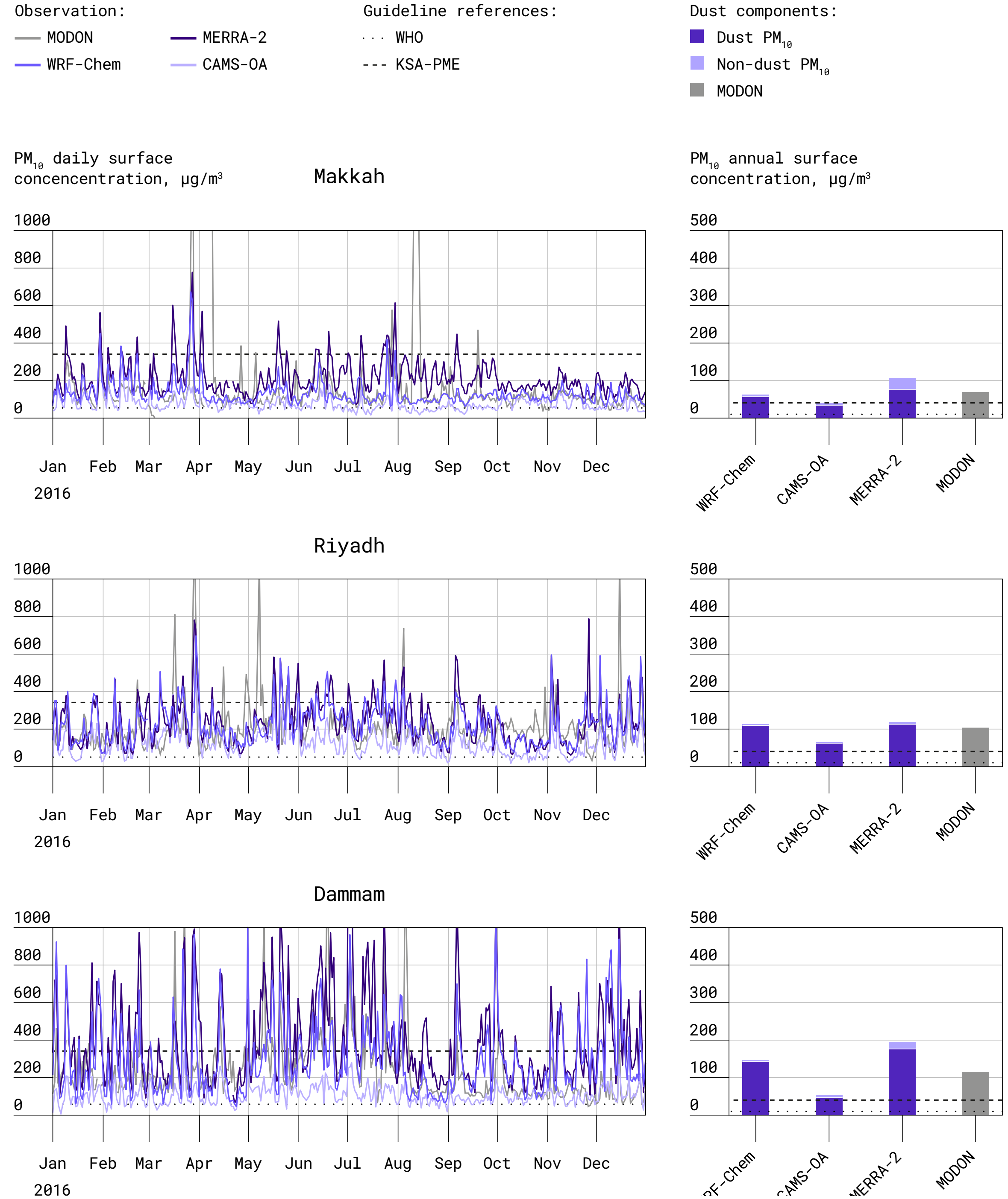
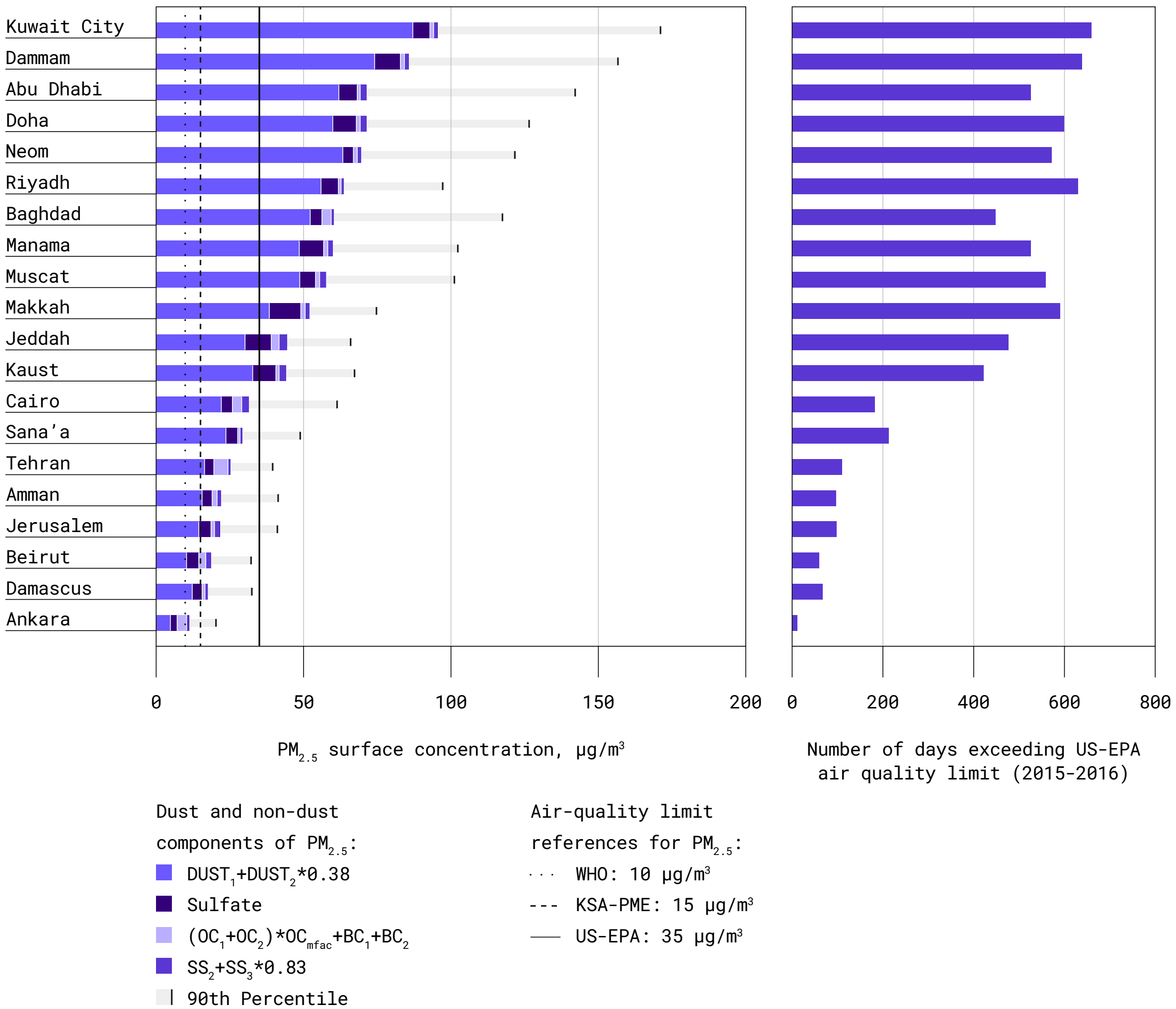


FIGURE 12 Annual mean 2015-2016 PM surface concentrations calculated for the ME major cities and PM decomposition into dust and non-dust components.

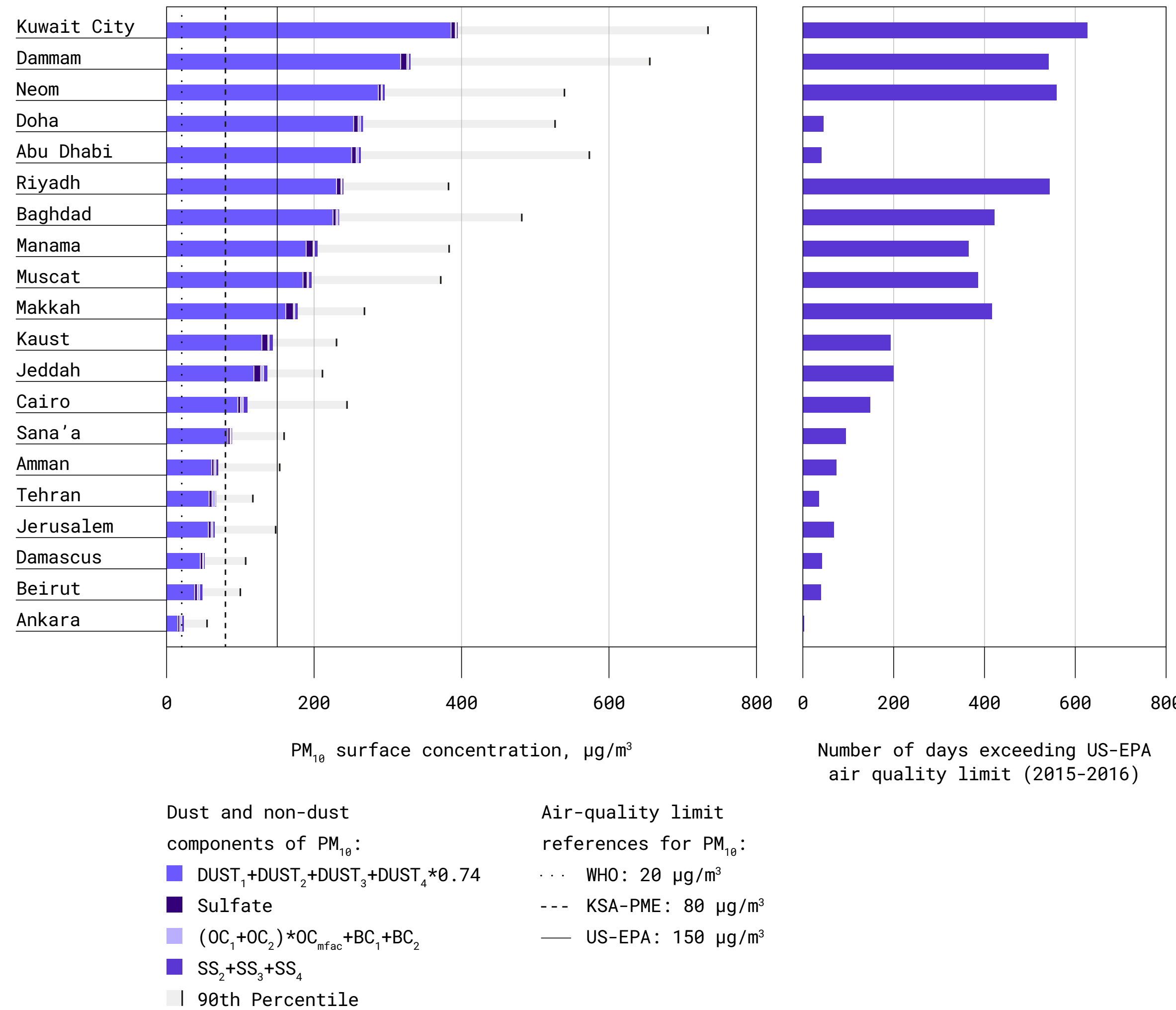
FIGURE 12 Annual mean 2015-2016 PM surface concentrations calculated for the ME major cities and PM decomposition into dust and non-dust components.

A. $PM_{2.5}$ SURFACE CONCENTRATION



Note: 90th percentiles calculated using daily mean PM concentrations.

B. PM_{10} SURFACE CONCENTRATION



Note: 90th percentiles calculated using daily mean PM concentrations.

PM AIR POLLUTION IN THE ME MAJOR CITIES

To evaluate the air-quality in the ME's major cities, we calculate for their locations the average for 2015-2016 daily $PM_{2.5}$ and PM_{10} surface concentrations, their 90th percentiles, and we also calculate the contribution of the dust and non-dust components into PM (see FIGURE 12). We also calculate the number of days during the 2015-2016 period when the daily $PM_{2.5}$ and PM_{10} surface concentrations exceed the US-EPA air-quality limit of 35 μg/m³ and 150 μg/m³, respectively.

FIGURE 12 Shows that the annually-averaged $PM_{2.5}$ and PM_{10} exceed the WHO air-quality guidelines 2-9 and 3-20 times, respectively, in all major cities of the ME. The KSA-PME air-quality limit for annual mean $PM_{2.5}$ is exceeded by up to 6 times and by up to 5 times for PM_{10}. The cities on the eastern coast of the Arabian Peninsula have the highest 90th percentiles of daily mean PM concentrations. For example, in Dammam, Abu Dhabi, Doha, and Kuwait City, the 90th percentiles of daily mean surface concentration of PM_{10} and $PM_{2.5}$ are in the range of 400-740 μg/m³ and 130-180 μg/m³, respectively. This is above the KSA-PME air-quality limits for daily mean PM_{10} and $PM_{2.5}$.

DISCUSSION

This study evaluates the impact of aerosols on PM air pollution over the Middle East for the 2015-2016 period. WRF-Chem, MERRA-2, and CAMS-OA capability in reproducing the total amount of dust and other aerosols in the entire atmospheric column are tested by comparing the simulated AOD with that measured by AERONET and by satellite sensors. At all considered AERONET sites, WRF-Chem, CAMS-OA, MERRA-2 are capable of reproducing the magnitude and temporal evolution of the AERONET AOD time series during the whole period. MERRA-2 has the highest correlation to AERONET AOD. CAMS-OA tends to overestimate AERONET AOD, especially during severe dust events. The AOD fields from WRF- Chem and assimilation products exhibit similar spatial patterns, but WRF-Chem, and MERRA-2 underestimate, and CAMS-OA overestimates observed MODIS-DB&DT AOD. All tree products have high spatial correlation with the observed MODIS-DB&DT AOD.

The capability of WRF-Chem, MERRA-2, and CAMS-OA in reproducing PM air pollution over the Middle East was tested against in situ measurements. These PM measurements are conducted in the industrial regions of Jeddah, Riyadh, and Dammam, which complicates one-to-one comparison with the output from global and regional models. Annual mean PM concentrations from WRF-Chem and MERRA-2 exceed the WHO limit almost 20 times. The KSA-PME limit for annual average concentrations is also exceeded more than 6 times.

The PM composition analysis over rural areas shows that in WRF-Chem, the annual average $PM_{2.5}/PM_{10}$ ratio over the ME is about 0.3. It decreases to 0.25 over the major dust source regions, i.e., in the eastern Arabian Peninsula, Iraq, and northern Africa. In most parts of the Middle East, dust is the major contributor to PM. The sulfate aerosol contribution to $PM_{2.5}$ is essential in the areas where strong SO_2 sources are present, i.e., on the west and east coasts of Saudi Arabia and over the Arabian Gulf. In these areas, sulfate surface concentration reaches 8-11 μg/m³, while the "clean" background level is 2-4 μg/m³. High sulfate content along the west coast of Saudi Arabia is consistent with the increased volume of the fine mode in the KAUST Campus AERONET site in comparison with Mezaira and Sede Boker sites.

In WRF-Chem, sulfate is the major non-dust pollutant in the Middle East. Sulfate aerosols contribute 60-90 % to the total $PM_{2.5}$ non-dust aerosols over the central and southern parts of Saudi Arabia. Over the other parts of the Arabian Peninsula, northern Sudan, Libya, and Egypt, sulfate contributes approximately 40-60 % to the total $PM_{2.5}$ non-dust aerosol concentration.

The analysis of the annually averaged $PM_{2.5}$ and PM_{10} surface concentrations in the Middle East's major cities shows a very high PM pollution level. In Dammam, Abu Dhabi, Doha, and Kuwait City, the 90th percentile of PM_{10} and $PM_{2.5}$ annual mean surface concentrations exceed 400-740 μg m^{-3} and 130-180 μg m^{-3}, respectively, which is above the KSA-PME air-quality limit. In the cities located in the Arabian Peninsula contribution of the non-dust component to $PM_{2.5}$ is 8-25%, which limits the effect of the emission control on air quality. In the major cities over the Arabian Peninsula the US-EPA air- quality daily mean limit exceeded 94-627 days for PM10 and 213-640 days for $PM_{2.5}$. In Jeddah and Dammam, WRF-Chem and MERRA-2 show similar relative contributions of the non-dust component to $PM_{2.5}$ (30-34% in Jeddah and 12-14% in Dammam). In Riyadh, the contribution of the non-dust component to $PM_{2.5}$ is ≈9-12% for both MERRA-2 and WRF-Chem. MERRA-2 shows the highest contribution of sea salt and the lowest contribution of black carbon and sulfate to PM_{10} in all locations. The minimum contribution of non-dust components to PM_{10} is observed in Riyadh among all models.

Thus, we conclude that MERRA-2 and CAMS-OA assimilation products, as well as WRF-Chem output, despite some intrinsic uncertainties, could be used for evaluating the PM air pollution over the ME. All products show the dominant contribution of mineral dust to PM. However, in the Arabian coastal areas where SO_2 emissions are high, both contributions of sulfate and sea salt could be significant. The broad effect of natural aerosols on air quality in the ME puts stricter requirements on anthropogenic pollution control. The impact of dust could be alleviated by employing specific to desert areas architectural solutions, increasing in-city vegetation cover, and providing air-quality forecasts to alarm the population on hazardous air quality.

2.5.3

AIR QUALITY AND HEALTH IMPACTS – FROM CITY TO STREET SCALE

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CESAM & Dept of Environment and Planning, University of Aveiro, Portugal

INTRODUCTION

Air quality assessment at different spatial scales is crucial for a full understanding of sources and effects of air pollution. The city scale is particularly relevant because air pollution hotspots are more frequent and the population density is higher, and thus more exposure to the harmful effects of poor air quality is expected. Air quality assessment has been carried out in Saudi Arabia, mostly based on fixed air quality monitoring stations measuring both gaseous and particulate pollutants, and on field campaigns devoted to investigate the mass, composition, origins and seasonality of airborne particulate matter in Saudi Arabia, with a focus on specific regions along the Red Sea coast [1], mainly the most populated urban areas.

For Jeddah, an analysis of the seasonal variations and weekday/weekend differences in fine ($PM_{2.5}$) and coarse ($PM_{2.5\text{–}10}$) particulate matter mass concentrations, elemental constituents, and potential source origins was performed [2]. The average mass concentrations of $PM_{2.5}$ and PM_{10} during a one-year sampling period exceeded the WHO recommended annual average levels for $PM_{2.5}$ (10 μg/m^3) and PM_{10} (20 μg/m^3). Similar to other Middle Eastern locales, PM2.5-10 is the prevailing mass component of atmospheric particulate matter at Jeddah, accounting for approximately 80% of the PM_{10} mass. The following source categories for both $PM_{2.5}$ and $PM_{2.5\text{–}10}$ were identified: (1) soil/road dust, (2) incineration, and (3) traffic; and for $PM_{2.5}$ only, (4) residual oil burning, suggesting that targeted emission controls could significantly improve the air quality in the city. The highest concentrations are observed in spring, due to increased dust storm frequency, and on weekdays (due to increased traffic). These results support the need for region-specific epidemiological investigations.

The Saudi Arabian capital, Riyadh, is experiencing a rapid development in its metropolitan area, as a consequence of the impressive increase of urbanization and industrialization, leading to social and environmental sustainability challenges that include worsening air quality and its associated health impacts. An air quality assessment is going on, which is based on a monitoring and modelling approach, aimed at identifying key pollutants and apportion their emissions by source in a robust way. The Royal Commission for Riyadh City and the General Authority of Meteorology and Environment Protection are operating 32 fixed and mobile air quality control stations in Riyadh, over the past few years, to monitor the air quality. This will contribute to a comprehensive picture of air quality across the city now and in the future, beyond the currently available measured concentrations. In addition, the General Authority of Meteorology and Environment Protection disseminates an hourly Air Quality Index bulletin to communicate health information to the public and to provide associated air quality alerts. The anthropogenic influence on air quality is evident in Riyadh, having shown in 2020 a marked decrease in nitrogen dioxide (NO_2) due to the impacts of lockdown on various activities during the coronavirus pandemic [3].

Though sand storms contribute a substantial proportion of air pollution in Saudi Arabia, several studies [4] have shown a significant input from anthropogenic emissions mostly related to fossil-fuel combustion and vehicular emissions. Thus, there is a need for more air quality assessments in Saudi Arabia's major urban areas.

New monitoring techniques relying on air quality sensors have arisen as a valuable support to urban air quality management, allowing for more measurements over space and time. Sensors can be portable, less expensive, designed to be low maintenance, and require minimal training to operate. They may be helpful in air pollution hot spot identification, and they can also inspire behavioral changes and educate people about pollution where they live, work and play. However, sensors performance is highly variable and in general they provide less accurate measurements than regulatory monitors and may not operate well in extreme environments like high temperatures and humidity [5]. Also, many people operate sensors with limited if any quality assurance. Further, some sensors lose their ability to take accurate measurements over time. In Europe sensors can be used for regulatory purposes, but should comply with the Data Quality Objectives defined in the Air Quality Directive [6]: 50% uncertainty for PM_{10} and $PM_{2.5}$, 30% uncertainty for O_3, and 25% uncertainty for CO, NOx, NO_2, and SO_2.

Accurate characterization of population exposures to PM from specific sources is a prerequisite for more informative studies of the health effects. Temporal and spatial differentiation of PM composition requires dispersion models with high spatial and temporal resolution, based on reliable emission inventories. Health impact assessments should be performed in an integrated way from the identification of sources, to the effects on air quality, exposure and health, to support

effective and efficient strategies to improve air quality for population's health protection. Calculations of county-level mortality show that coarse-model resolution tends to underestimate mortality in counties where large urban centres are located, particularly mortality attributed to primary particulates including black carbon (BC) and organic carbon (OC) [7]. On the other hand, deaths due to dust are overestimated because of the coarse-model resolution, mainly owing to the fact that dust concentrations are largely uncorrelated with population, whereas concentrations of the other PM species tend to be positively corrected with population [7]. Moreover, integrated modelling tools applied at different spatial and temporal scales, for past and future situations, are essential to better understand the site-specific sources and impacts of air pollution occurring at regional and city scale, to support policy decisions, especially in large and densely populated urban areas of Saudi Arabia, where climate conditions and geographical location may trigger air quality degradation with health and socio-economic effects.

FROM CITY TO STREET SCALE MODELING

Air quality modelling applies mathematical tools to simulate the physical and chemical processes that involve air pollution transport and reactions in the atmosphere. It has been used to provide scientific advice on the definition of air quality improvement measures towards the reduction of human exposure to air pollutants [8], air quality forecast [9], atmospheric pollution assessment [10] and air quality policy regulations [11] from global to local scales.

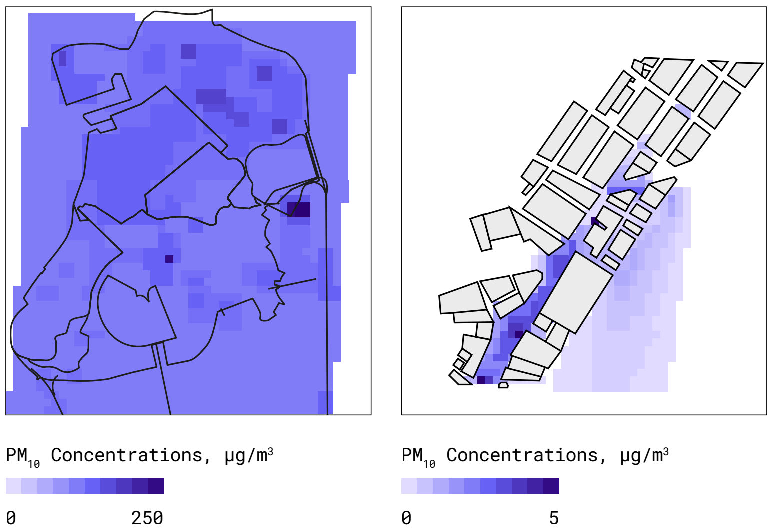
CITY AIR QUALITY — Urban air pollution is the largest single environmental risk to human health since most of the worldwide population lives in these areas and many of them are exposed to high air pollution levels. City air quality is affected by transboundary pollution from neighbouring regions and natural sources (e.g., dust emissions from deserts), atmospheric emissions from anthropogenic sources (mainly from transport, road resuspension, industries, residential, commercial and services activities) and the complexity of the urban morphologies (e.g. buildings volumetry, road network). Chemical transport models are commonly used to assess air quality impacts at national to regional scale. However, this type of models cannot be used to represent air pollution concentrations at the scale needed to fully assess human health impacts. Hence, air quality models based on the Gaussian dispersion equation are typically considered to evaluate the air pollution levels in the city scale with a horizontal spatial resolution (i.e., grid cells) that can vary between 1000 m and 10 m. The last generation of gaussian models assumes a continuous variation of pollutants dispersion parameters with atmospheric stability and considers the effect of topography (both simple and complex terrain) and built-up structures

on the air pollution dispersion.
The URBan AIR (URBAIR), developed by the University of Aveiro (Aveiro, Portugal), is an air quality model considering this type of approach [12] and has been applied for a set of urban applications worldwide [13] as well as evaluated against measured air quality data (an example of URBAIR outputs is presented in FIGURE 13A).

FIGURE 13 Monthly average PM_{10} concentrations in Macau peninsula (China) applying the URBAIR model and daily average PM_{10} over the "Rua do Campo" (Macau, China) using the VADIS model.

A. MACAU, CHINA

B. RUA DO CAMPO, MACAU, CHINA



URBAIR is modular and includes the pre-processing of topography, urban elements geometry, meteorological conditions and atmospheric emissions, coupled with a dispersion module providing air quality patterns for a given spatial domain (up to about 50 km from the domain centre) and temporal period (hourly, daily, one year or multiple years simulations) for different atmospheric pollutants, namely particulate matter (PM_{10} and $PM_{2.5}$), nitrogen dioxide (NO_2) and carbon monoxide (CO). The system framework is designed in a way that inputs/outputs of the meteorological, emissions, geo- information and dispersion modules are shared and linked along the modelling process.

The main goal of the meteorological module is to characterize the dynamics of the atmospheric boundary layer (ABL) during the simulation period and pre-process relevant meteorological parameters for the dispersion module, following the Monin-Obukhov similarity theory approach. This module requires surface and upper-air (soundings) meteorological data provided by meteorological models (e.g., Weather Research and Forecasting – WRF) or by meteorological measurements. This information (e.g., pressure, temperature, wind speed, wind direction and precipitation) could be obtained from the average of the grid cells of the meteorological model simulations over the study area or from the nearest meteorological station. The main outputs of this module consist of ABL turbulence scaling parameters (such as Monin-Obukhov length scale, surface friction velocity or convective velocity scale) and the mixing height of the ABL.

The emission module considers different types of emissions, namely area, volume and point (such as industrial stacks) sources. This module can use atmospheric emission data from top-down and bottom- up approaches. In the top-down approach, the coarse horizontal spatial resolution (> 0.0625°) of regional inventories (e.g., EDGAR - Emission Database for Global Atmospheric Research [14]) is improved using different proxies (e.g., land use, population data, road network). Regarding the bottom-up approach, the atmospheric emissions with high spatial (exact location of emission sources) and temporal (hourly values) resolutions are quantified applying, whenever possible, the more accurate methodology provided by the European air pollution inventory guidebook [15].

The geo-Information module requires the characterization of the terrain surface elevation, land use, three-dimensional (3D) buildings, to realistically represent the topography and build-up structures. This module relies on a cartesian coordinate system, in which regular and discrete gridded data can be used to input and spatially distribute terrain and obstructions within the simulation domain. Topography is specified in the form of terrain heights at receptor locations. The influence of buildings on air pollutants dispersion depends on the orientation of the obstacles relating to the source, the wind direction and the shape of the building. Direction-specific downwash parameters, in the form of projected building height and width dimensions, are estimated using the EPA's Building Profile Input Program PRIME (BPIP- PRIME) modelling approach [16]. This module's input information can be provided by Geographic Information System (GIS) based maps in a compatible format to be readily processed.

The dispersion module has implemented an improved version of the second-generation Gaussian model POLARIS to estimate the air pollutants concentration. The module uses a steady-state multi- source plume air Gaussian dispersion modelling approach, where the effects of meteorological conditions, topography and the presence of buildings are considered for the numerical simulation of air pollutants within urban areas. Under stable ABL conditions, it assumes the concentration spatial distribution to be Gaussian in both vertical and horizontal lengths; whereas in unstable conditions, the horizontal distribution is also assumed to be Gaussian, but the vertical distribution is described with a bi-Gaussian probability density function. The meteorological conditions are assumed to be steady during the modelling period steps (typically hourly) and horizontally homogeneous. Vertical variations can be also considered if concentration fields are estimated at various levels. Complex terrain influence is provided following the concept of a dividing streamline by combining a horizontal plume and a terrain-following state. An additional feature is the capacity to account for the dispersive nature of the 'convective like' boundary layer that forms during night-time conditions over urban areas, by enhancing the turbulence resulting from urban heat flux. As outputs, the URBAIR provides the air pollutants concentration spatially distributed over a regular grid, and, if the user required it, the air pollutant levels for specified receptor points.

Since the city air quality is affected by local emission sources, but also by air pollution from other regions/cities, at this spatial scale it is required to consider background concentrations (background concentrations are defined as that portion of the modelled ambient levels that is not attributable to emission within the study area). For this purpose, hourly air quality measurements from the nearest background station can be considered or the air pollution levels estimated by chemical transport models in the study area can be used.

STREET AIR QUALITY — Human exposure (e.g., pedestrians, cyclists, drivers, street vendors and residents) to air pollution in urban streets is expected to be higher, mainly near busy roads in city centers where population density, road traffic volume, building street geometry, aerodynamic effects and microclimate may contribute to the poor air pollution dispersion giving rise to contamination hotspots. The highest air pollution levels are typically recorded in street canyons, where a narrow street is bounded by buildings that line up continuously along both sides. There, the air pollution dispersion depends on the rate at which the street exchanges air vertically with the above roof-level atmosphere and laterally with connecting streets [17]. In this sense, street air pollution simulations are a complex task and for that Computational Fluid Dynamics (CFD) models based on Lagrangian approaches are required to evaluate the air quality due to local emissions (e.g. road transport emissions) within the street of building clusters with high spatial horizontal (< 10 m) and temporal resolutions (by seconds).

The VADIS (pollutant DISpersion in the atmosphere under VAriable wind conditions) developed by the University of Aveiro (Aveiro, Portugal) is an air quality model suitable to estimate the dispersion of atmospheric pollutants (PM_{10}, $PM_{2.5}$, NO_2, and CO) in complex urban morphologies, by considering multi-obstacle (buildings and vegetation), time-varying wind flow fields and atmospheric emissions [18] (an example of VADIS outputs is presented in FIGURE 13). VADIS performance has been evaluated and improved through the years. Simulation results have been evaluated with measured data from meteorological and air quality monitoring stations [18, 19] as well as with physical measurements conducted in a wind tunnel [20]. The model performance was also evaluated through comparison with other numerical models (e.g., FLUENT model [19]). All of these works show the VADIS's capability to simulate different air pollutant concentrations, at different study areas, with a good agreement between modelled results and measured values. Such as URBAIR, the VADIS model was designed to be modular and it is composed of three coupled distinct modules: FLOW, DISPER and Urban Vegetation (URVE).

The FLOW module is able to simulate the turbulent flow dynamics under stationary conditions within the ABL. In this module two different grids are used: i) a cartographic grid, to include the information related to obstacles (buildings and vegetation); and ii) the Eulerian grid, to calculate the wind fields. The wind grid is overlaid to the cartographic one and rotates according to the wind direction. The mean velocity profile is calculated from the logarithmic profile corresponding to the upwind terrain via the roughness length, through the [21] equations. The grids dimension and number of cells in each axis must be defined as a compromise between the required resolution and accuracy, and the computational demand. This FLOW module needs the following input data: i) local wind information (wind speed and wind direction) at the entrance of the study area (simulation domain) at a reference height (usually 10 m) that can be provided by numerical meteorological models or by meteorological measurements (the nearest meteorological station); and ii) buildings volumetry (buildings coordinates and height).

The DISPER module computes the 3D pollutant concentration field using the 3D wind field previously estimated by FLOW and the multiple atmospheric emission sources (with different positions, dimensions and emission rates) in the study area. At street scale, the emissions from road traffic are the main source of air pollution and they should be estimated by applying road transport emission models (e.g., the Transport Emission Model for line sources – TREM [22]) where the main input data are road network, road length (in km), road traffic volume (from road traffic models or car counting), vehicle speed (in km.h-1), road gradient (in degrees), road type (rural, urban and highway), vehicle categories (e.g., gasoline passenger cars and diesel heavy-duty vehicles) and vehicle class based on age (e.g., Euro 5) and engine capacity (e.g., cubic centimetres < 1400 cm^3). The DISPER module assumes that the spatial and temporal dispersion of the mass of pollutant emitted is represented by a large number of numerical particles arbitrarily released in the flow.

The VADIS model also includes the URVE module. This module was developed to better understand the aerodynamic effects of trees by calculating the perturbations induced by vegetation elements in the flow dynamics and dispersion patterns. It requires inputting the volumetry and leaf area density of the trees in the simulation domain. The dispersion of the emitted air pollutants is conditioned by vegetation through the disturbed wind flow. The magnitude of this perturbation depends on the conjoint influence of the characteristics of the vegetation itself (e.g., location, size) and of the flow conditions (e.g., velocity, direction, turbulence).

As output, VADIS provides the three wind velocity components, the turbulent viscosity, the turbulent kinetic energy, the turbulent dissipation, the temperature and the pollutant concentration in each grid cell for the entire study area.

HEALTH IMPACTS OF AIR POLLUTION

Air pollution causes a wide range of diseases in particular respiratory and cardiovascular diseases. Short- and long-term exposure of children and adults to air pollution is linked to reduced lung function, respiratory infections and aggravated asthma. Air pollution is classified as carcinogenic, while emerging evidence links exposure to air pollution to new-onset type 2 diabetes, obesity, systemic inflammation, ageing, Alzheimer's disease and dementia [23]. Air pollution also has considerable economic impacts, cutting lives short, increasing medical costs and reducing productivity through working days lost across the economy [24].

METHODS FOR HEALTH IMPACT ESTIMATION — Health impacts of air pollution have been estimated using information from epidemiological studies and methods that describe how health can be integrated in air quality assessments. Human exposure to air pollution may result in a variety of physical health impacts, depending on the types of air pollutants, atmospheric concentration levels, duration and frequency of exposure, and stratification of the exposed population (e.g., age, current health status) [23]. These physical impacts can occur in a short time period after exposure (short-term exposure) and result in acute effects, or are a consequence of the cumulative exposure over time (long-term exposure) resulting in chronic effects. They are often expressed through morbidity and mortality indicators, mostly related with respiratory and cardiovascular diseases.

In order to quantify the magnitude of these effects, many epidemiological studies combining meta-analyses recorded during air pollution episodes have been conducted to provide statistical associations by relating unit changes in ambient concentrations and different types of health outcomes (i.e. specific effect of exposure to air pollutants). To assess the exposure, defined as the pollutant concentration existing in a person's breathing zone over a specified period of time, the following methods can be used [25]: (i) exposure monitoring, with the advantage of producing accurate exposure data on individuals in known and real life conditions; (ii) exposure modelling, allowing exposure assessments for past and future periods, recommended for estimating potential long-term effects and for densely populated areas. In epidemiological studies, exposure modelling techniques are often applied, since large cohorts and populations of entire cities over long periods of time are needed to design the overall effect of air pollution.

To calculate the exposure of a population to different levels of air pollution, information is needed on the spatial distribution of both air pollutant concentrations and population at the same grid spacing. The methodology applied by the European Environment Agency based on WHO recommendations is schematically represented in FIGURE 14, from step A to step H. Concentrations are estimated from measurements at air quality monitoring stations or from air quality modelling (step A), and allow to produce concentration maps covering the area of interest (step B) where concentrations are gridded at a scale resolution of 1x1 km^2, as an example. Placing population density maps over the concentration maps at the same resolution produces a picture of population exposure (step C). Using these maps, the percentage of the population exposed to the whole range of concentrations, in increments of 1 $\mu g/m^3$, can be estimated. In addition to total population figures, information on the age and sex distribution of the population is also used in the calculation.

To calculate the health risks, concentration-response functions (CRF) and baseline health statistics are needed. CRF have been established by epidemiological studies and represent the relationship between the concentration of an air pollutant to which a population is exposed and the risk of a health outcome. These CRF are based on relative risk (RR) models that are applied to translate concentration changes into health impacts, and take into account a greater health risk for certain vulnerable groups within a population (e.g. elderly people, children and those with underlying diseases) [26, 27]. Given the lack of country/region specific data, the CRF defined by the World Health Organization are commonly used [27], which are based on the relative risks. Relative risks capture the increase in mortality that can be attributed to a given increase in the air pollutant concentration. Relative risks are defined at the population level (as statistical averages) and cannot be assigned to specific individuals. In the case of mortality it is therefore not possible to identify which individual cases are caused by air pollution (step D) [23].

CRF are in general linear, but this may not be true for very low or very high concentrations. Also, the evidence on the impacts of human health for very low or very high concentrations may not be as robust, as for the intermediate concentrations. This is why sometimes the impact cannot be analysed with the same confidence for the whole range of concentrations and an initial concentration or counterfactual concentration is used (step E). The counterfactual concentration is therefore the concentration above which the impacts are estimated. Baseline health statistics include country-specific life expectancies, stratified by age and sex, and total mortality data for each country, also by age and sex. These statistics are characteristics of the population as a whole, and thus, the estimated number of premature deaths derived using these statistics is a measure of the general impact of air pollution across a given population [23].

The relative risks allow the percentage of the baseline incidence that can be attributed to exposure to a pollutant to be determined. For mortality, the total number of deaths per year (step F) in a country is used as baseline incidence. The burden of disease, in terms of premature deaths, is estimated based on the relative risks. These results are obtained at the grid level and then summed for all the grids in an area (as for instance a country or all of Europe) (step G).

The main uncertainty is associated with the concentration-response functions used in the health risk assessment. This uncertainty is calculated as a confidence interval (95%) around a mean or central estimate. This implies that there is 95 % probability that the true value lies in the range defined by the interval (step H).

In addition to the estimation of deaths attributable to air pollution, other health metrics are also quantified in many health impact assessment studies, such as:

→ Years of life lost (YLL) in the target population due to changes in mortality risk. YLL can be calculated by multiplying the number of premature deaths by the remaining life expectancy at the age of death, reliably represented through life table methods. For each death, the current age of death is subtracted from the life expectancy at that age to obtain the years of life lost due to that specific death. Summing up the years of life lost for all premature deaths results in the total years of life lost for the population.
→ Years lost due to disability (YLD) reflecting the extent of the disability associated to a specific disease. YLD can be estimated by multiplying a disability weight factor, which varies between 0 (perfect health) and 1 (death), by the average duration of the disease.
→ Disability-adjusted life years (DALY) provide a relevant measure of the overall disease burden, because it combines both mortality and morbidity. Thereby, DALY are the sum of the YLL with YLD, which account for the number of years lived in less than optimum health.

The health impact assessment is a valuable tool to support the definition of strategic action plans to control air pollution. However, from the decision-maker perspective, it is important to complement the health impact assessment with an economical evaluation, which consists in a monetary valuation of benefits, including a cost-benefit analysis. In this way, the development of a management plan could be informed by cost-effective strategies to persuade its full implementation.

The cost-benefit analysis is a balance between the costs associated to the implementation of a certain air quality improvement measure or strategy (set of measures), known as internal costs (Costint) (e.g. the cost of establishing a Low emission Zone in an urban area), and the economic benefits, known as external costs (Costext), resulting from the reduction of premature deaths or the air pollution related diseases (e.g. costs of medical treatment, gains in productivity).

The monetary health impacts, health damage costs arising from air pollution to repair a given reference situation or avoid welfare losses, are generally quantified through the cost-of-illness (COI) methodology [26]. According to this approach, total health costs per case are determined by the sum of direct, indirect and intangible costs.

FIGURE 14 Schematic representation of a methodology to estimate the health impacts of air pollution based on spatially distributed air quality levels and population data. Numbers considered in steps A, B and C are arbitrary, just as examples.

A. STATION
The area for which the health risk assessment will be calculated consists of four grids (1x1 km^2 each) and one monitoring station (S), which registered in year Y an annual mean $PM_{2.5}$ concentration of 17µg/m^3

B. CONCENTRATION MAP
The concentration map from that monitoring station (S) and the supplementary data provides the result shown in B

C. POPULATION/EXPOSURE
The populations in the grids are shown in C. In grid 1, the 10.000 inhabitants are exposed to 15µg/m^3; in grid 2, the 5.000 inhabitants are exposed to 10µg/m^3; in grid 3, the 2.000 inhabitants are exposed to 10µg/m^3; in grid 4, the 1.000 inhabitants are exposed to 5µg/m^3

D. RELATIVE RISK
In the case of $PM_{2.5}$, the concentration-response function used for total (all cause) mortality in people above 30 years of age implies a relative risk of 1.062 per 10µg/m^3. This means that, assuming linearity, an increase of 10µg/m^3 of $PM_{2.5}$ is associated with a 6.2% increase in total mortality in the total population considered.

E. COUNTERFACTUAL CONCENTRATION
The counterfactual concentration for $PM_{2.5}$ is 0µg/m^3, meaning that, for instance, for grid 1 the effect of the whole range of 15µg/m^3 will be estimated.

F. MORTALITY
The total mortality (incidence baseline) in the country for year Y and for population over 30 years of age is 10 deaths per 1.000 inhabitants, so the number of deaths per grid are shown in F.

G. PREMATURE DEATHS
The number of deaths attributed to exposure to $PM_{2.5}$ in each grid (assuming, according to the concentration-response function, an increment of 6.2% in total mortality per 10µg/m^3) are as shown in G.

This is obtained from:
Relative Risk (RR)=
exp(β*concentration)=
exp(0.0062*concentration).
For grid 1: 1.097462
The attributable fraction (AF)=
(RR-1)/RR.
For grid 1: 0.0888065
Premature deaths (PD)=
AF*mortality*pop.
For grid 1: 8.88 ≈ 9.

And the total number of deaths attributed to $PM_{2.5}$ in the whole area in year Y: 9+3+1+0=13.

H. UNCERTAINTY RANGE
The uncertainty range is calculated using the lower and upper limits of 1.040 and 1.083, instead of the relative risk of 1.062.

The total mortality is then expressed as 13 premature deaths with a 95% confidence interval between the values of 9 and 18.

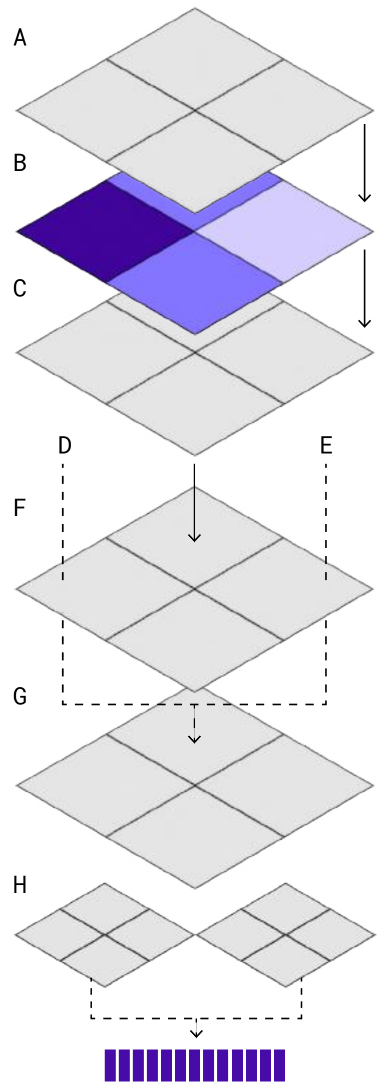
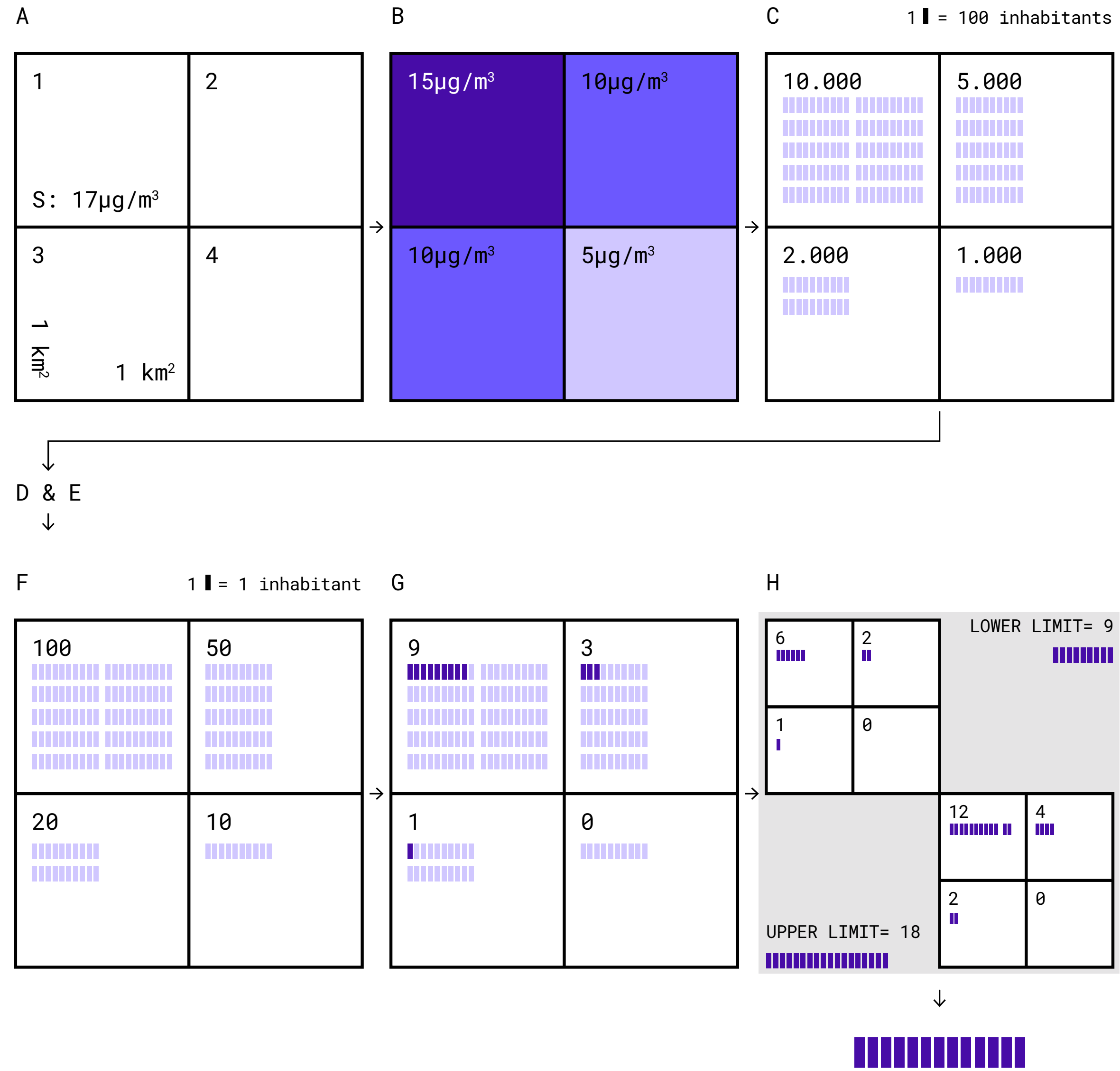


FIGURE 14 Schematic representation of a methodology to estimate the health impacts of air pollution based on spatially distributed air quality levels and population data. Numbers considered in steps A, B and C are arbitrary, just as examples.



Direct costs include both health care and non-healthcare costs associated with treatment and caring. These costs are based on market values, e.g., medical staff, examinations, laboratory tests, medication, consumables and hospital facilities. Indirect costs include costs associated with loss of productivity due to morbidity as well as loss of production due to morbidity or mortality. These costs are based on market values, e.g., wages, incomes and earnings. Intangible costs include non-market costs associated with pain and suffering from morbidity and mortality. For each health indicator, after identifying the different cost components related with the impacts and determining how to assess them in monetary terms, the overall health damage costs over a given region due to air pollutants exposure are estimated as follows:

$$Costs_{(i,p)} = HI_{(i,p)} \times C_{health}$$

Where $Costs_{(i,p)}$ express the overall damage, occurred or avoided, on the health indicator i due to pollutant p's short and/or long-term population exposure over a given region; $HI_{(i,p)}$ represents the number of unfavorable implications associated to the health indicator i, that could be avoided or not, due to pollutant p's short and/or long-term population exposure over a given region; C_{health} is the monetary value to repair a person's initial heath status or, at least, to remediate the damages of air pollution on the health indicator i.

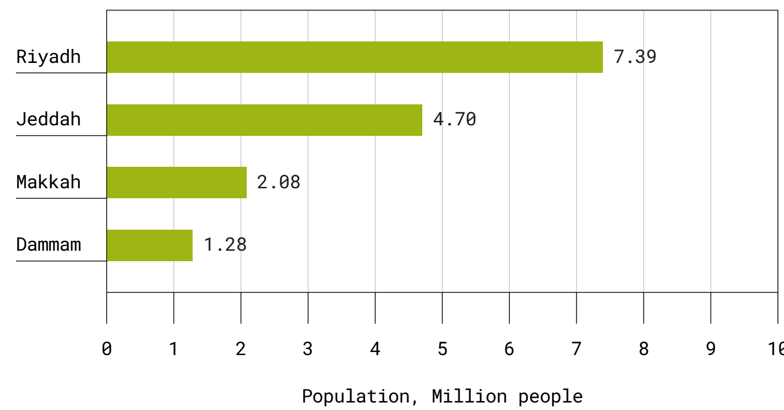
The cost-benefit analysis is calculated as a net benefit that should be negative to consider the set of improvement measures as a cost-effective strategy:

$$Net\ Befefit = Cost_{int} \times Cost_{ext}$$

HEALTH IMPACTS IN SAUDI ARABIA CITIES

Saudi Arabia is the world's 13th largest country by area, but more than 84% of its population lives in the urban centers. The city of Riyadh is the country's largest, boasting a population of over 7 million, which contributes heavily to the total population. In addition to Riyadh, the other three cities (Jeddah, Makkah and Dammam) have populations exceeding one million. FIGURE 15 shows the total population in Jeddah, Riyadh, Dammam and Makkah cities.

FIGURE 15 Population of the main Saudi Arabia cities in 2019.



For the estimation of health impacts in these major Saudi Arabia cities is crucial to have air quality data. The air quality data ($PM_{2.5}$ and PM_{10}) used for the health calculations comes from the modelling study of [28] who performed an assessment of natural and anthropogenic aerosol air pollution in the Middle East based on a modelling approach, presented in part 2 of this chapter. The annual mean concentration values for each pollutant and city are present in FIGURE 16.

FIGURE 16 Shows that the annually-averaged $PM_{2.5}$ and PM_{10} strongly exceed the WHO air quality guidelines (10 and 20 μg/m^3 for $PM_{2.5}$ and PM_{10}, respectively) in all cities. According to [28] the contribution of the non-dust component to $PM_{2.5}$ is < 25 %, which limits the emission control effect on air quality. A base scenario (current situation) was compared with a health-protective scenario, where the level of $PM_{2.5}$ pollution would not exceed the WHO recommendation, set at 10 μg/m^3 for $PM_{2.5}$, and a scenario where the levels of $PM_{2.5}$ would meet the Kingdom of Saudi Arabia legal limits (15 μg/m^3).

The previously described health impact estimation methodology was implemented using the AirQ+ software [29] developed by the WHO to calculate the magnitude of the burden and impacts of air pollution on population's health. The AirQ+ software version 2.1 was applied to Saudi Arabia based on publicly available data to estimate the mortality and years of life lost (YLL) as a result of exposure to $PM_{2.5}$ in Jeddah, Riyadh, Dammam and Makkah cities.

All calculations performed by AirQ+ are supported by methodologies and concentration-response functions from epidemiological findings based on a systematic review of studies available until 2013 and their meta-analysis. The mortality was estimated using pollutant-health outcome pairs concentration-response functions by WHO for $PM_{2.5}$ mortality for all (natural) causes (adults age 30+ years). The applied Relative Risk (RR), considering a 95% Confidence Interval (CI), was 1.062 (95% CI 1.04–1.083). The population distribution by age group of the Kingdom of Saudi Arabia [30] was used to estimate the number of people with 30+ years in each city. It was assumed a crude death rate of 3.5 per 1,000 population, based on statistic data [31].

FIGURE 17 Presents the number of avoided premature deaths due to $PM_{2.5}$ pollution exposure in Jeddah, Riyadh, Dammam and Makkah cities (central estimate), for the scenario considering the fulfilment of the WHO guidance value. The values in the lower and upper columns correspond to calculations with, respectively, the lower and upper confidence interval limits of the RR. This range is the 95% Confidence Interval (CI) based on the uncertainty in the RR values for all-cause mortality considered when creating the impact evaluation and shows some of the uncertainty associated with the estimates.

The results indicate that 1551, 3658, 838 and 829 annual premature deaths (central estimate; FIGURE 17) caused by long-term exposure to $PM_{2.5}$ could be "avoided" if the concentration of $PM_{2.5}$ would not exceed 10 μg/m³, the threshold recommended by the WHO AQG 2005. These results are consistent with the estimation shown in Section 1 using the GBD (2020) functions for $PM_{2.5}$, which gives 16 000 (12 000-22 000) excess deaths per year for Saudi Arabia (total population around 34 million people). In fact, the total number of premature deaths for the Jeddah, Riyadh, Dammam and Makkah cities is 6 876 for a total population around 15.5 million people. To estimate the Years of Life Lost (YLL), population and all-natural causes of mortality data by age groups are required. It was assumed that the population and mortality profile of each city is equal to the one of the regions to which it belongs. This assumption was considered due to the lack of data for each city, only regional data stratified by age groups was available. FIGURE 18 Presents the age-grouped population of each city.

The YLL indicator takes into account the age at which deaths occur, giving greater weight to deaths at a younger age and lower weight to deaths at an older age. FIGURE 19 Displays the YLL values calculated for each one of the cities, considering a central value and

FIGURE 16 Modeled annual mean $PM_{2.5}$ and PM_{10} concentrations for Jeddah, Riyadh, Dammam and Makkah cities.

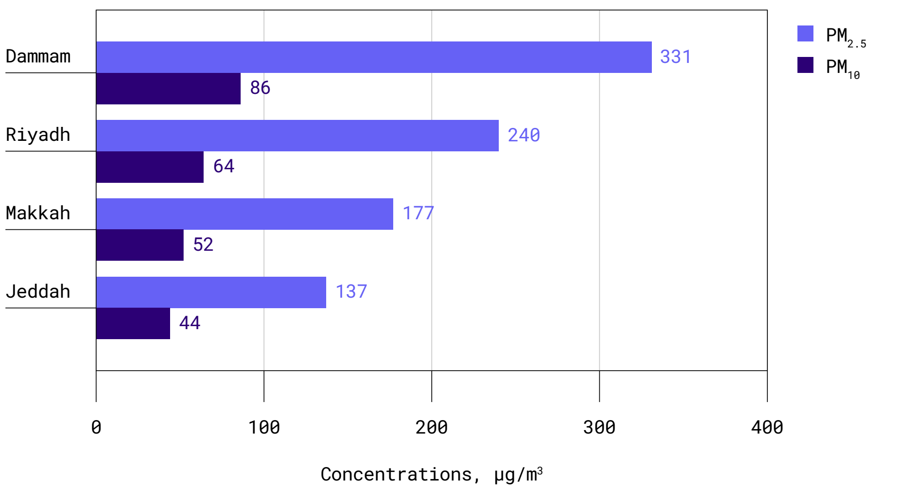


FIGURE 17 Estimates of avoided premature deaths, on an annual basis, caused by $PM_{2.5}$ air pollution levels when the WHO guidance value is accomplished.

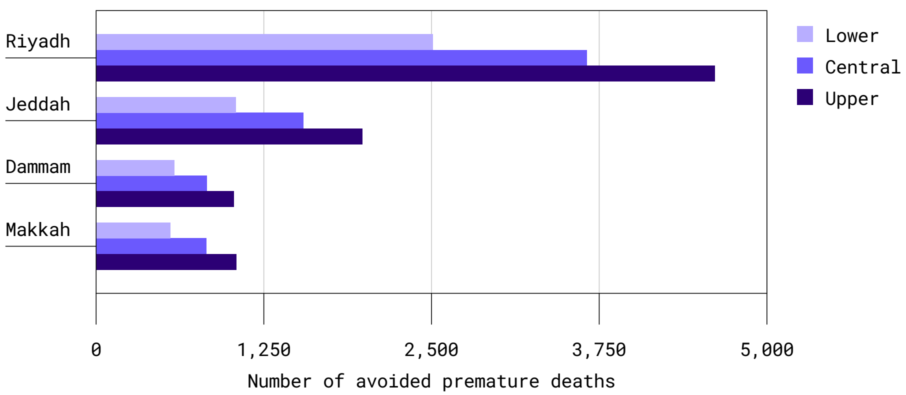
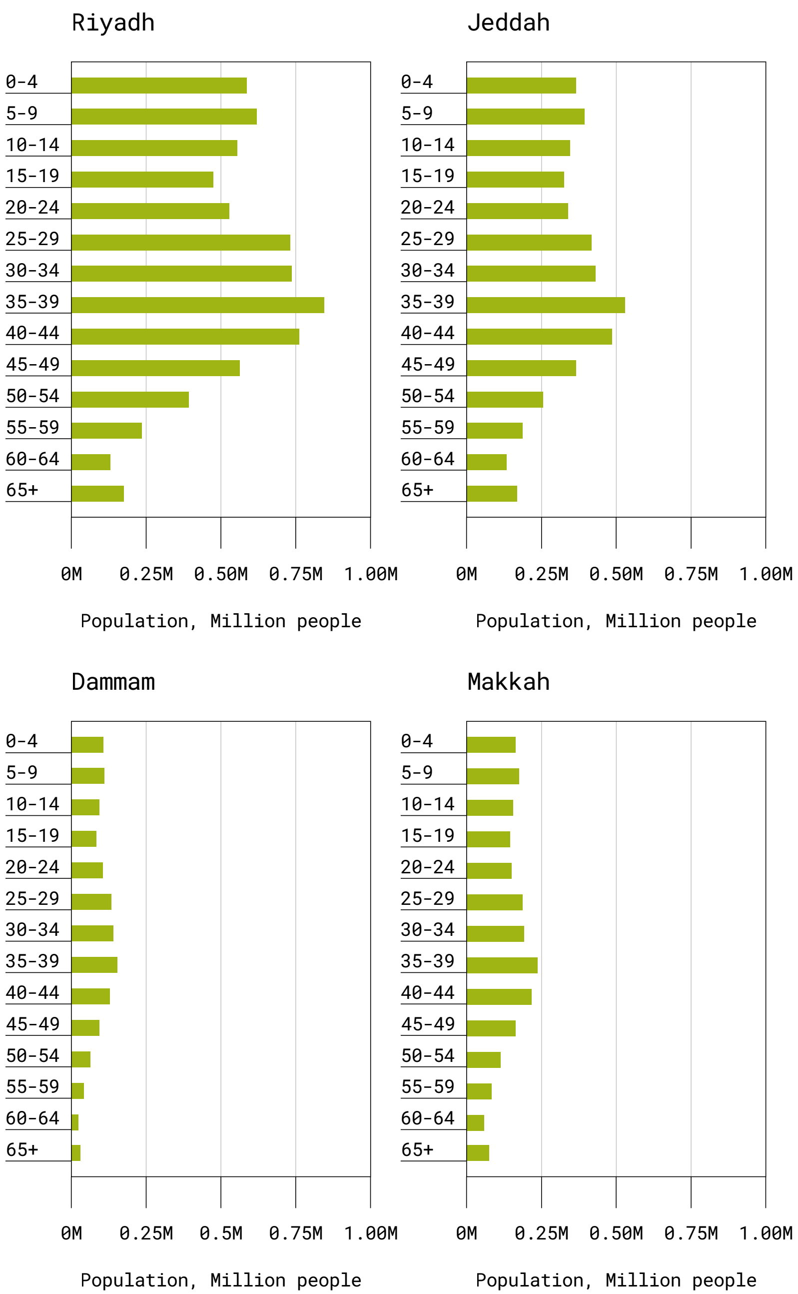
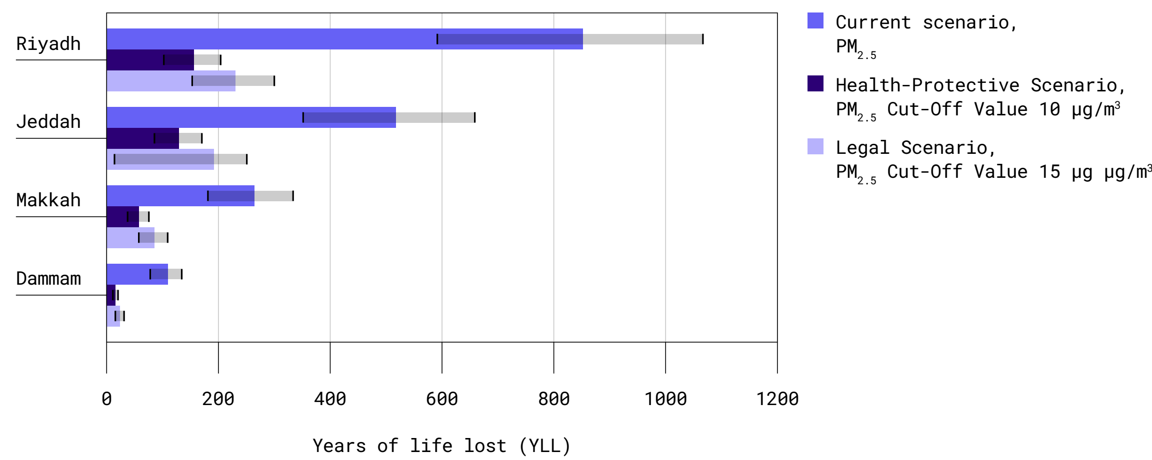


FIGURE 18 Population by age groups for Jeddah, Riyadh, Dammam and Makkah cities.



an uncertainty range. The three scenarios were considered: the base case (current), a health-protective scenario where the concentration of $PM_{2.5}$ was reduced to 10 μg/m³, and a scenario were the levels of $PM_{2.5}$ would meet the Kingdom of Saudi Arabia legal limits (15 μg/m³). The highest YLL values are found in Riyadh (852) followed by Jeddah (517). Although these are not the cities with the highest $PM_{2.5}$ levels, their population is higher, and for that reason, more years of life are lost due to $PM_{2.5}$ exposure.

FIGURE 19 Years of life lost (YLL), on an annual basis, due to premature mortality for Jeddah, Riyadh, Dammam and Makkah.



The impact of accomplishing the $PM_{2.5}$ recommended thresholds is clear, but it should be highlighted that those factors likely to affect individual exposures, such as personal time-activity patterns, were not considered. The air quality simulations and the annual mean concentrations may not fully represent the general $PM_{2.5}$ situation in each city.

More detailed data and information about demographics at the city level or even neighbourhood, health (e.g., mortality rate due to Chronic Obstructive Pulmonary Disease (COPD) for adults, the mortality rate due to lung cancer (LC) for adults, hospital admissions due to respiratory disease), as well as more detailed air quality data (combining measurements with modelling tools), will improve considerably the estimation of the impact of the air pollution on human health. Moreover, data regarding the costs of the health care system in Saudi

Arabia would allow to calculate the external costs associated to the estimated health impacts.

NEEDS AND LIMITATIONS

Decision-makers and researchers need accurate and reliable estimates of air pollution exposure and the related health impacts. Different needs (cause-specific vs all-cause mortality, national or regional assessment), require different approaches and data, that affects the results. Moreover, in the quantification of potential health impacts, uncertainties about the number of deaths or cases of disease may be present for a variety of reasons:

→ The use of different methodologies to calculate the value of health impacts could result in relevant variations, even if the equations are based on the same input data sets (e.g., AirQ+ methods);
→ Possible double counting of health effects from several air pollutants, since one health outcome may be captured from different pollutants, or the same effect may be added from two health indicators (e.g. mortality due to a specific cause is a part of all-cause mortality [32];
→ The choice of CRF derived from epidemiological studies inevitably introduces uncertainty into the results, given the random effects and high variability in the CRF estimates. It should be noted that most epidemiological studies have been conducted in developed countries, and the range of studied exposures does not necessarily represent what is observed worldwide [32];
→ Baseline incidence and prevalence rates for health indicators of interest may also be highly uncertain with regard to the impact of ambient air pollution. These baseline rates are usually expressed as national statistics, available for most countries through the following online platforms: Global Health Observatory data repository [33] and European Health for All database [34].
→ The introduction of a counterfactual level of air pollution, assuming no health impacts below that reference exposure value, raises some doubts about the theoretical minimum concentration that results in minimum population risk. This uncertainty degree becomes more noticeable when different air pollution management policies are tested in order to quantify air quality and health benefits [23].

The health impacts associated with exposure to dust are not yet fully understood, and are currently treated the same way as those from air pollution in industrialized countries where most of the epidemiological studies have been performed. There is a need for a better assessment of the health impacts from natural dust, as it could result in a lower burden than those from anthropogenic particulate matter [23].

DISCUSSION

Effective air quality abatement strategies in urban areas depend on local and regional mechanisms by which air pollution causes adverse health effects. In addition to high concentrations of anthropogenic particulate matter, highly populated cities in the GCC region experience severe dust outbreaks from 7 to 15 times a year. To comply with the WHO guideline values set to protect public health, anthropogenic sources of particulate pollution need to be very strictly limited in the areas affected by dust outbreaks.

In the future, a better understanding of the relative toxicity and health effects of particles from various sources could facilitate targeted abatement policies and more effective control measures to reduce the burden of disease due to air pollution.

There is a significant gap in monitoring and reporting air pollutants especially in low and middle-income regions. Strengthening capacities of cities to monitor their air quality with standardized methods, reliable and good quality instrumentation, and sustainable structures is key.

From the point of view of the main pollution hotspots, particular attention should be attributed to urban areas since most of the population in the GCC region lives there. Usually, a dense network of emission sources is present in the big cities, namely transports, industry, and households. The causes of air pollution must be analyzed beyond the city/street scales since air pollutants are often transported across continents and ocean basins. Thereby, the use of emerging modelling tools is encouraged by environmental regulations to cover multiple pollution transport and dispersion scales and to achieve the following purposes:

→ To analyze the relative importance of the primary emitting sources.
→ To understand atmospheric and demographic dynamics that allow relating air concentrations with human exposure.
→ To assess health impacts resulting from short and long-term exposure to air pollutants.
→ To accomplish legal impositions for air quality improvement, particularly those related to air pollution management strategies for the zones/agglomerations where air quality standards are exceeded.

In a typical city atmosphere, the complexity of the urban morphologies (e.g., buildings volumetry, road network) affect the physical and chemical processes governing the transport, dispersion, reactions, and deposition of air pollutants. In this sense, applying air quality models at city/street scales requires that these small processes be explicitly well resolved. But considering the influence of larger spatial scales is essential since the dispersion and atmospheric chemistry happening on large scales contribute to variations in polluted air arriving in a region from other regions and/or countries. However, no single air quality model can reproduce all chemical and physical air pollution processes, ranging from regional to local scales. A modelling system based on an appropriate set of air quality models to simulate the air pollution phenomena at different spatial scales could have a significant added value. In the dynamical downscaling approach, a set of air quality models are integrated into a common system. Each model is used to simulate the dominant air pollution processes at a particular scale. Therefore, the different air quality models are combined to provide the air pollution levels with high temporal and spatial resolution. The regional model provides the contribution from transboundary pollution to the urban and local air quality (i.e., background concentrations); the urban and local models simulate the air pollution levels from nearby sources (less than 100 m). The main advantage of this approach is that it can be applied for a wide range of horizontal resolutions (from several km to 1 m).

In summary, air quality management strategies at a city scale should be addressed following a multiscale integrated approach to account for regional and local air pollution sources. They should include a health impact assessment to define adequate air quality improvement and health protection measures.

CLIMATE CHANGE AND PROJECTIONS OF FUTURE AIR QUALITY IMPACT

Air quality scenarios for model projections of the future have been studied to assess the role of short- lived climate pollutants (SLCPs), of which emission mitigation is expected to have co-benefits for climate and public health [35-37]. SLCPs include methane (of which photochemical reactions contribute to tropospheric ozone), particulate black carbon, and ozone formed from CH_4, other Volatile organic Compounds (VOCs), and NOx that act as precursor gases. For example, ozone pollution episodes and heat extremes often coincide, with both aspects of such events being about equally responsible for adverse health impacts and excess mortality [38]. [39] estimated that by reducing methane and black carbon emissions alone, global greenhouse warming could be reduced by 0.5°C by the year 2050, while simultaneously avoiding 2.7 (±2.0) million excess deaths from air pollution. Further, the International Panel for Climate Change (IPCC) concluded that climate change affects future air quality through ozone and $PM_{2.5}$ [37]. Carbon dioxide emission reduction measures would therefore help avoid illness and excess mortality from air pollution. It was shown that CO_2 and SLCPs must be considered coherently to limit climate change both in the near- and long-term [40]

Major health benefits can be expected from a decrease in fossil fuel use, particularly coal and oil combustion in energy generation and traffic, through reduced concentrations of $PM_{2.5}$, nitrogen oxides, and ozone. From all continents, Asia has the largest potential to avoid health impacts through climate change mitigation measures [41]. [42] found that the combination of stringent policies on ambient air pollution, climate change, and the availability of clean fuels for domestic energy use (cooking, heating) can drastically reduce $PM_{2.5}$ levels, needed to reach the WHO annual guideline concentration of 10 µg/m^3. Such measures could achieve that about half of the global population will experience levels below the WHO guideline in the coming decades, whereas currently, more than 90% are exposed to higher levels. Strict global policies have the potential to decrease excess mortality from anthropogenic $PM_{2.5}$ by two-thirds and from ozone by 85% [43, 44]. Assuming the strong effect of $PM_{2.5}$ on human health, WHO recently reduced its recommended limit to 5 µg m^{-3}.

Without additional air pollution regulations $PM_{2.5}$ concentrations are expected to increase by about 50% in 25 years. A business-as-usual pathway up to 2050 may double the global disease and mortality burden caused by a combination of increasing air pollution and population growth [45]. For the Middle East, this pathway would imply an increase in annual excess mortality by a factor of 2.5, related to deteriorating air quality and a strongly increasing population in the region.

SUMMARY FOR POLICYMAKERS

Air pollution is the fourth leading risk factor for early death worldwide after high blood pressure, tobacco use, and poor diet. The evidence is mounting that much lower air pollution levels than previously thought can cause harm to health. Systematic and consistent efforts to track progress toward reducing air pollution and its impacts on human health remain of high priority. This is especially important in the Middle East, where natural dust causes high background particulate matter (PM) pollution in rural and urban areas. The health effects of particulate matter air pollution are the main environmental health concern of the World Health Organization (WHO) worldwide. Ambient fine particle air pollution refers to $PM_{2.5}$. These particles and precursor chemicals that contribute to their secondary formation in the atmosphere are emitted from vehicles, fossil fuel-burning power plants, industrial activities, waste burning, and many other human and natural sources. Natural dust is especially important in desert and semi-desert regions, like the Middle East (ME) [2].

According to the current understanding, natural dust affects health similarly as PM from other sources, and potentially more after mixing with air pollution. Although exposures to both smaller and larger airborne particles can be harmful, studies have shown that exposure to high average concentrations of $PM_{2.5}$ for several years has been the most consistent and robust predictor of morbidity and mor-

[2] $PM_{2.5}$ is fine particulate matter with a diameter less than 2.5 µm, PM_{10} has a diameter less that 10 µm.

tality from cardiovascular, respiratory, and other diseases. $PM_{2.5}$ can penetrate particularly deeply into the lungs while PM_{10} mostly affects the upper airways.

Anthropogenic emissions significantly contribute to overall air pollution in the Middle East urban centers despite substantial dust pollution. Therefore, collecting, updating, and maintaining up-to-date emission inventories is paramount. Most air pollutants are optically active in the atmosphere and could affect climate on regional and global scales. At the same time, atmospheric chemistry and emission of natural contaminants, like dust, sea salt, and dimethyl sulfide (DMS), depend on changing environmental conditions. This links the air quality studies to ongoing climate change.

CURRENT AIR QUALITY IMPACT IN THE MIDDLE EAST

Air pollution develops on multiple spatial and temporal scales. There is no unique model or data set that would cover all aspects of the problem. Instead, satellite and ground-based observation combined with the model simulations and reanalysis products need to be employed to develop an integrated approach for analysing and predicting air quality and its effect on the population's well-being.

A global estimate of excess mortality attributed to the exposure to $PM_{2.5}$ is about 4.23 (3.0–6.14) million per year, accounting for specific disease categories. Including other non-communicable diseases caused by gaseous air pollution, including ozone (in addition to $PM_{2.5}$), estimates of global excess mortality are about twice as high, most recently exceeding 10 million per year for the fossil fuel component of $PM_{2.5}$ only. By adopting health outcomes from recent studies of $PM_{2.5}$ and ozone in the Middle East, it was possible to estimate excess mortality for the region (17 countries including 7 Gulf Cooperation Countries - GCC) of 274 (193–391) thousand per year and 18,6 (13,7–25,6) thousand per year for Saudi Arabia. The mean loss of life expectancy from air pollution estimated for the Middle East is about 2.3 years and about 2.0 years in Saudi Arabia. Along with $PM_{2.5}$, the NO_2-related asthma incidence (NINC) in children and adolescents is much higher than in most other countries. Nitrogen dioxide (NO_2) in the region originates from fossil energy use, including traffic. The estimated NINC in the Middle East is 440 (280–760) thousand per year and 27 (16–44) thousand per year in Saudi Arabia. Due to the high levels of photochemical air pollution, the health outcomes of ozone are also well above- average.

The estimates of regional aerosol pollution in the Middle East using model predictions and reanalysis products show that annual mean $PM_{2.5}$ concentrations exceed the WHO guidelines limit by an order of magnitude or more. The Kingdom of Saudi Arabia Presidency of meteorology and Environment (KSA- PME) limit for average yearly concentrations is also exceeded more than six times. The PM

composition analysis over rural areas shows that the annual average $PM_{2.5}$/ PM_{10} ratio over the ME is about 0.3. It decreases to 0.25 over the major dust source regions, i.e., in the eastern Arabian Peninsula, Iraq, and northern Africa. In most parts of the Middle East, dust is the major contributor to PM. The sulfate aerosols form in the atmosphere as a result of the oxidation of sulfur dioxide (SO_2) from fossil energy use. Its contribution to $PM_{2.5}$ is essential in the areas where strong SO_2 sources are present, i.e., in the west and east coasts of Saudi Arabia and over the Arabian Gulf. In these areas, sulfate surface concentration reaches 8-11 $\mu g/m^3$, while the "clean" background level is 2-4 $\mu g/m^3$. Sulfate is the major non-dust pollutant in the Middle East. Sulfate aerosols contribute 60-90 % to the total $PM_{2.5}$ non-dust aerosols over the central and southern parts of Saudi Arabia.

Large cities in the Middle East are the main pollution hotspots because high anthropogenic emissions are coming on top of dangerously high natural dust concentrations. The main urban centers deserve particular attention since more than half of the population lives there. Typically, a dense network of emission sources is present in cities, namely transports, industry, and households. The analysis of the annually averaged $PM_{2.5}$ and PM_{10} surface concentrations in the Middle East major cities shows a very high PM pollution level. In Dammam, Abu Dhabi, Doha, and Kuwait City, the 90th percentile of PM_{10} and $PM_{2.5}$ annual mean surface concentrations exceed 400-740 $\mu g/m^3$ and 130-180 $\mu g/m^3$, respectively, which is well above the KSA-PME air-quality limit. In the cities located in the Arabian Peninsula, the contribution of the non-dust component to $PM_{2.5}$ is typically less than 25%, limiting the effect of the anthropogenic emission control on air quality. In the major cities over the Arabian Peninsula, Iraq, and Iran, the US-EPA air-quality daily mean limit on average is exceeded 180 days per year for PM_{10} and 210 days per year for $PM_{2.5}$.

The air pollution in cities is patchy and must be analyzed on the city/street scales. Thereby, developing and using fine-scale modeling tools is essential. In a typical city atmosphere, the complexity of the urban morphologies (e.g., buildings volumetry, road network) affect the physical and chemical processes governing the transport, dispersion, reactions, and deposition of air pollutants. Air quality models applied at city/street scales should explicitly resolve these small-scale processes and consider pollutants from larger spatial scales. The global and regional models calculate the transboundary pollution transport. The urban and local models simulate the air pollution levels from nearby sources.

To demonstrate the health effects of air pollution in the Middle East on a city scale, the impact of PM pollution above WHO air quality guidelines on mortality and Years of Life Lost (YLL) in four major Saudi Arabian cities, Jeddah, Riyadh, Dammam, and Makkah was estimated. The excess mortality yearly reaches around 1550 in Jeddah, 3660 in Riyadh, 840 in Dammam, and 8230 Makkah. This is about a 10%

increase compared to the average country's mortality of 3.5-4 people per one thousand. YLL in the considered cities would decrease by 10% if the legal limit of $PM_{2.5}$ concentration in Saudi Arabia, which is currently 15 μg m^{-3}, reduces to the WHO health-protective level of 10 μg m^{-3}. Assuming the strong effect of $PM_{2.5}$ on human health, WHO recently reduced its recommended limit to 5 μg/m^3.

FUTURE AIR QUALITY IMPACT IN THE MIDDLE EAST

Future air quality levels are strongly dependent on pollution emission scenarios and the degree to which climate change mitigation will be implemented, e.g., to achieve the 1.5-2°C target of the Paris Agreement. Emission reductions from fossil fuel use in energy production and traffic can have important co-benefits for climate, air quality, and public health. Strict global emission regulations could decrease the excess mortality from anthropogenic $PM_{2.5}$ by two-thirds and from ozone by 85%. On the other hand, a business-as-usual pathway up to the middle of the century may double the global burden of disease from air pollution caused due to a combination of intensifying emissions and population growth. In the Middle East, business-as-usual would imply an increase in excess mortality from air pollution by a factor of 2.5 towards the year 2050.

FUTURE RESEARCH

In this study, air pollution data for the Middle East have been derived mostly from satellite observations and modeling. Exposure-response functions and uncertainty analyses relied on epidemiological studies in North America, Europe, and East Asia. Such data and studies are not yet available for the region.

Concern should focus not only on ambient air quality in cities but also on the air quality of different indoor environments (residential, workplace, and public spaces) where people spend most of their time. This is particularly significant in GCC countries, where time spent indoors can surpass 90% due to frequent unfavorable outdoor weather conditions (higher ambient temperature and humidity) and natural events, such as dust storms, which will be potentially exacerbated under a changing climate. Exposure to high indoor air pollutants concentrations due to infiltration of outdoor sources and poor ventilation and various indoor sources (e.g., cooking, incense) contributes significantly to the overall burden of disease in the population. The knowledge of this contribution is essential for a comprehensive health risk assessment and management.

Therefore, ambient and indoor air quality monitoring and modeling, and epidemiological studies based on country/region-specific data are essential to better quantify the health effects of air pollution and develop solutions that are optimal for the Middle East.

AREAS FOR FURTHER RESEARCH:

- → Systematic and consistent efforts to track progress toward reducing air pollution and its impacts on human health remain of high priority.
- → Air pollution develops on multiple spatial and temporal scales. No unique model or data set would cover all aspects of the problem. Instead, satellite and ground-based observation combined with the model simulations and reanalysis products must be employed to develop an integrated approach for analyzing and predicting air quality and its effect on the population's well-being. Thus establishing dense air quality monitoring and air quality modeling is paramount.
- → The air pollution in cities is patchy and must be analyzed on the city/street scales. Thereby, developing and using fine-scale modeling tools is essential. In a typical city atmosphere, the complex urban morphologies affect the physical and chemical processes governing air pollutants' transport, dispersion, reactions, and deposition. Air quality models applied at city/street scales should explicitly resolve these small-scale processes and consider pollutants from larger spatial scales. Adequate city-scale models and emission databases for the major Middle East cities do not exist yet. The current projections of the potential distribution of Aedes aegypti under different scenarios of climate change suggest that the potential distribution of this vector in the Gulf region seems insensitive to climate change. Further local and regional research, including field studies, is urged to confirm this welcome conclusion.
- → In this study, the exposure-response functions and uncertainty analyses relied on epidemiological studies in North America, Europe, and East Asia. Such data and studies are not yet available for the Middle East region. Therefore, epidemiological studies based on country/region-specific data are essential to quantify air pollution's health effects better and develop optimal solutions for the Middle East.
- → Future air quality levels are strongly dependent on pollution emission scenarios and the degree to which climate change mitigation will be implemented, e.g., to achieve the 1.5-2°C target of the Paris Agreement. Emission reductions from fossil fuel use in energy production and traffic can have important co-benefits for climate, air quality, and public health. Strict global emission regulations could decrease the excess mortality from anthropogenic $PM_{2.5}$ by two-thirds and ozone by 85%. On the other hand, a business-as-usual pathway up to the middle of the century may double the global disease burden from air pollution caused by a combination of intensifying emissions and population growth. In the Middle East, business-as-usual would imply an increase in excess mortality from air pollution by a factor of 2.5 by the year 2050.

POPULATION GROWTH'S MULTIPLIER EFFECT ON CLIMATE IMPACTS

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KEY MESSAGES

→ Climate change is a result of human overshoot of the carrying capacity.

→ The current population of Arabia is roughly 18 times the natural carrying capacity, and is supported in large part by fossil fuels.

→ Cities in the GCC are built around population sizes and lifestyles that are dependent on fossil fuels. As the climate warms this dependence will grow.

→ Traditional environmental knowledge and resource management systems will be essential for navigating a low-energy future. This knowledge must be preserved before it is lost.

ABSTRACT

Climate change is one symptom of humans overshooting the global carrying capacity. To fully grasp the implications of the climate crisis and to develop an adequate response, we must consider the interplay between human populations, material and energy consumption, and the biosphere. Here we give an overview of the demography of the Arabian Peninsula and the divergence of per-capita consumption from sustainable amounts in the GCC countries. Additionally, we discuss the need for preserving traditional ecological and agricultural knowledge and provide a rough estimate of the people alive today that might possess such knowledge.

INTRODUCTION

Climate poses severe limits on the development of human civilization and population; these constraints are especially severe on the Arabian Peninsula. This part serves as a review of the interplay between human populations and our impact on the local environment, and areas of much needed research in regard to feedbacks between populations and climate.

Before tackling the issue of climate change, it must be noted that it is but one symptom of human overshoot beyond global carrying capacities. Climate change can not be addressed without facing the root problem of overconsumption and overpopulation, that form the core of the basic "IPAT" equation which quantifies human impact [1, 2].

If we put aside climate change for a moment, and look merely at human overshoot in the Arabian Peninsula, we see that we are 18x the historical population [3] and according to the ecological footprint network it requires 3.1 earths if the entire world wanted to live like the average Saudi [1]. This growth was enabled by the discovery of oil in the GCC countries, which temporarily raised the carrying capacity. With fossil fuels being a finite resource and a necessary precursor for any high-tech transition, the peninsula must grapple with a return to baseline carrying capacity in the future.

[1] For the other Arabian Peninsula countries: 9 earths for Qatar, 5.2 for Bahrain, 5.1 for U.A.E., 4 for Oman, 1.1 for Jordan, 0.3 for Yemen. Source: Earth Over-shoot Day and the Ecological Footprint Network.

Tackling a transition to a low consumption, ecologically sound society, is made orders more complicated when we consider the changing climate. A changing climate acts as a feedback increasing drought, expatriating flora and fauna from their native ranges, and causing inhospitable heat indices. Technological solutions to these issues, including desalination and air-conditioning, increase demand for energy, exacerbating resource shortages and driving further climate change. The more the peninsula has to depend on resource intensive technologies to merely survive, the further the baseline carrying capacity decreases [4, 5].

Given the feedback between population growth and climate change, it is essential to reflect on what the history of population and per-capita consumption on the peninsula and to perform a landscape

assessment of the future research that is needed.

CARRYING CAPACITY

The term carrying capacity, in a wildlife biology context, generally means the number of individuals a given area of land can support. This definition may be strengthened by considering a subsistence density, which is an upper limit of the environment to provide food and water resources and the optimum density, which is lower and considers the health, growth and fecundity of a population [6]. In human societies, extracorporeal consumption is both significant and highly variable, depending on the economic development of a society and an individual's place in the socioeconomic hierarchy.

When we use the term carrying capacity, we generally mean the number of individuals that a society can support with adequate food, water and housing. Once these basic needs are met, we might also consider education and healthcare.

The human carrying capacity of the planet has increased with the utilization of fossil fuels and the appropriation of habitat and niches that other species occupied. In fact, the mass of humans is an order of magnitude larger than the sum of all wild mammal biomass [7]. Intensive agriculture is now supporting 550 kg of human biomass per hectare, while early human foraging societies could support 0.5 kg per hectare [8].

We may get an idea of the carrying capacity of the Arabian Peninsula by examining its history. If we take a long-term population sizes and the general habitability of the peninsula has been greatly dependent on climate. During periods such as the African Humid Period in the Arabian Peninsula (11-5 ka), the climate was much wetter with increases in vegetation and the formation of paleolakes that could support additional human settlement [9, 10]. A shift to more arid conditions began roughly 6 thousand years ago and altered settlement patterns on the peninsula [10].

Over the past century the population of the Arabian Peninsula (The GCC countries plus Yemen) has grown from roughly 5 million people at the beginning of the 20th century to around 88 million people in 2020 (including migrants). A century ago, most of the population was rural and large cities, with the exception of Medina and Makkah, were around 10-20k people [3] Makkah and Medina were able to support slightly larger populations because of resource inflows related to the pilgrimage [3, 11]. The massive expansions the last century wouldn't be possible without pumping fossil groundwater, desalination and the profits from the fossil fuel industry that enable food imports.

DEMOGRAPHIC TRANSITION AND EXPONENTIAL GROWTH

The demographic transition model developed in the early 20th century, has been used to model the population of many countries, although there are exceptions and the exact mechanism behind the transition may be country dependent. Because the general transition model ignores the material and technological foundations, it is silent to how demographics will respond to resource limitations.

Whether increased lifespans, decreased child mortality, and urbanization will continue is not a given. That these trends continue shouldn't be taken for granted as there are instances where they have reversed [2]. With humanity drawing down the earth's material and energy reserves, the hysteresis characterization of the system, and thus the amount of societal advancements that will be maintained is unknown. Additionally, differences in customs, and wealth inequality can led to trajectories that vary from the common demographic transition[3]. FIGURE 1 Shows the demographic transition of the GCC countries plus Jordan and Yemen. Note that the birth rate still has a considerable distance from the death rate, and doesn't decline at a constant rate.

[2] The total fertility rate in Iran rapidly fell below replacement rate by the year 2000, but it is now increasing. Additionally, there is some evidence of an increase in child marriages in the region due to pandemic related economic conditions [12]. In Latin America, lack of contraceptive availability has been linked to an increase in the teenage birth rate [13].

[3] For example, in the United States, until recently the state of Utah deviated from other states in maintaining a high birth rate above the replacement rate. This may in part be due to the influence of the Church of Jesus Christ of Latter-Day Saints in the state.

FIGURE 1 Demographic statistics for GCC countries, plus Jordan and Yemen.

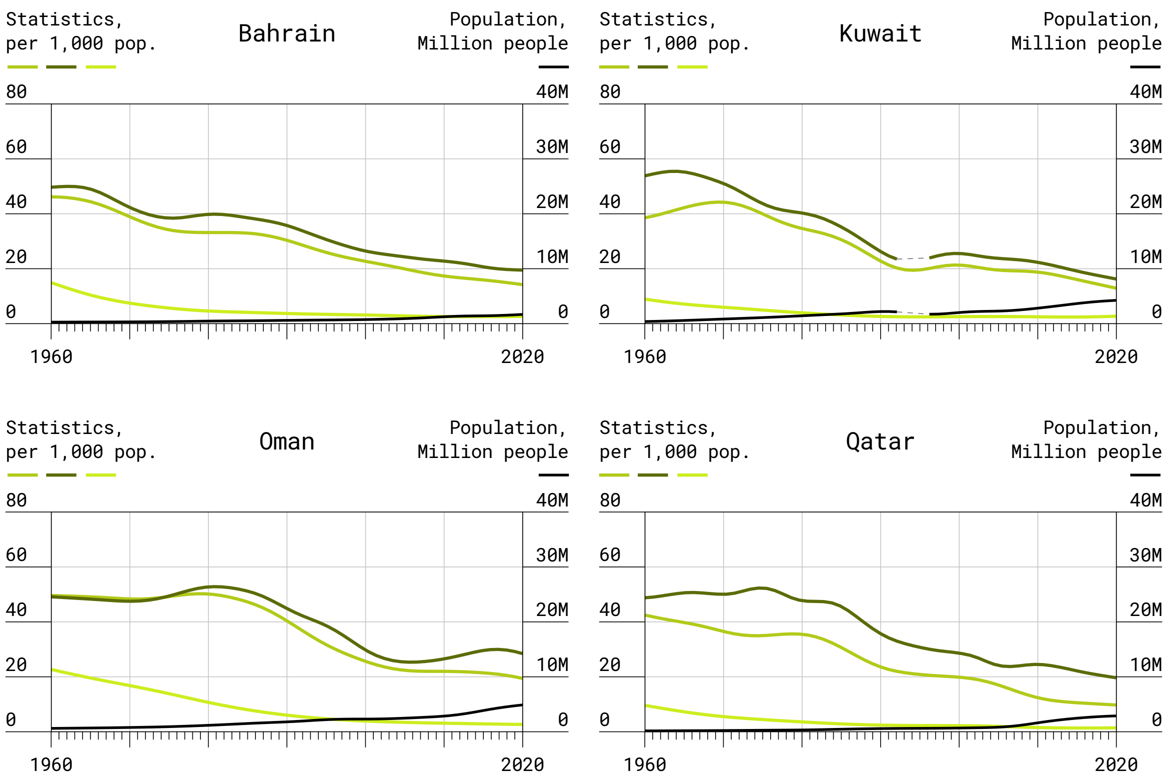
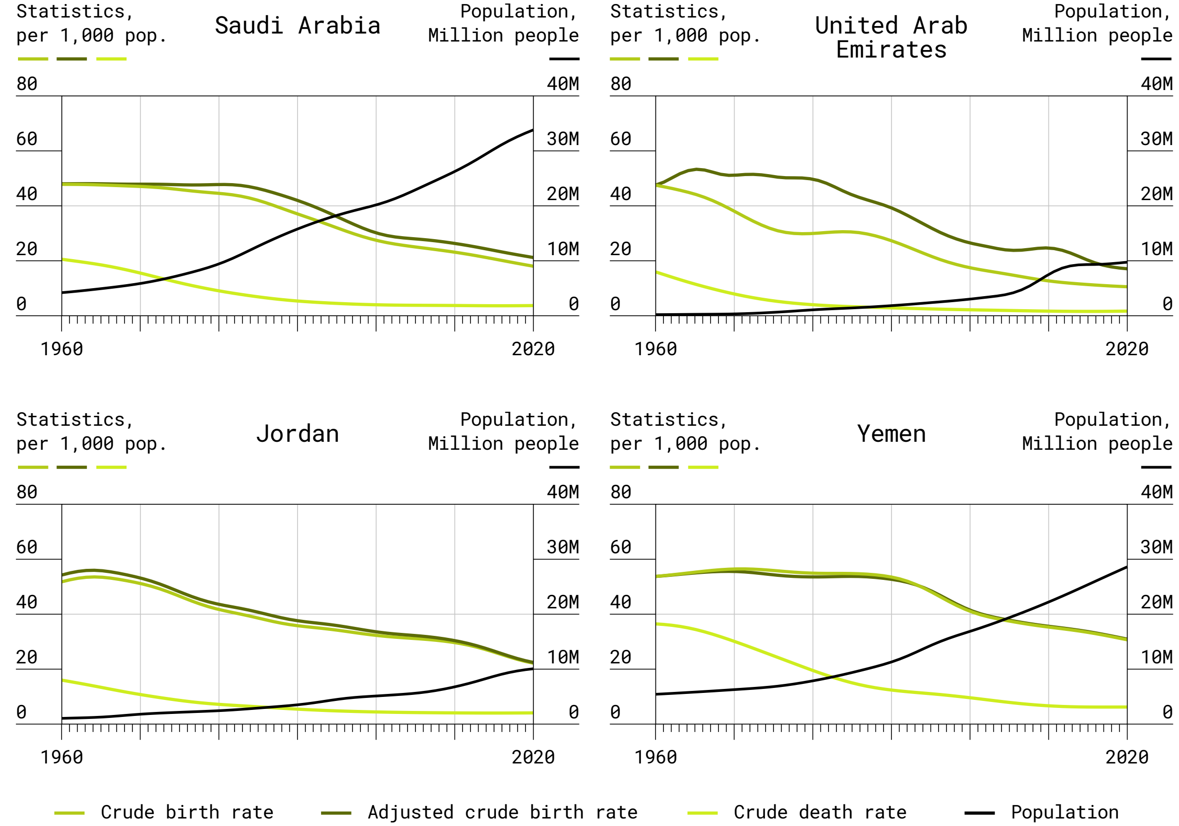


FIGURE 1 Demographic statistics for GCC countries, plus Jordan and Yemen.



Source: [14]. Data from UN Population Division via the World Bank.

Note: The adjusted crude birth rate is calculated by adjusting the denominator of the population to equal twice the female population. This helps compensate for the disproportionately male foreign labor force in some GCC countries.

The late Prof. Al Bartlett, introduced his famed lecture Arithmetic, Population and Energy: Sustainability 101 with the following statement: “The greatest shortcoming of the human race is our inability to understand the exponential function. Exponential growth in population or material consumption is impossible to maintain on a finite planet” [15]. Furthermore, environmental limits have a tendency to sneak up on populations pursuing exponential growth. If we consider a population of water lilies in a pond that doubles every day, on the day before the pond is full, the pond is still half empty and from the perspective of the lilies it might seem that there is plenty of space left [16]. In the case of humans we have surpassed the biophysical capacity of the earth to support us, that is the renewable excess or interest, that we can consume without damaging the underlying ecosystems. This overshoot has been enabled by the exponential increase in fossil fuel consumption over the last century. Like human populations, exponential growth in consumption can’t be continued indefinitely, with resource extraction following a Gaussian distribution, or Hubbert curve [15-18]. The exponential phase of resource extraction is in the process of peaking globally, with dire consequences for humans, whom now contain on average 80% of nitrogen that was fixed using the industrial, energy-intensive, Haber-Bosch process [19].

The populations of the Arabian Peninsula are incredibly young, which means that there is a wave of people that are about to enter reproductive age. This can be seen clearly in the Population Pyramids in [FIGURE 2]. To get an idea of the extent of the exponential growth that can be expected in the peninsula, we plot [FIGURE 3] the doubling times of the GCC countries plus Yemen and Jordan [4]. Only looking at the bottom graph, we see a significant separation in some of the wealthier gulf countries from Yemen and Jordan. However, if we return to the population pyramids, we can see that these Gulf countries have a large number of male migrant workers included in their total populations. If we consider that women are required for reproduction, we can modify the total population to be twice the female population, which gives a better idea of the actual doubling time of the permanent population [FIGURE 3A].

The concept that a population may contain subpopulations experiencing different reproductive rates, leads us to another quirk of exponential growth: renegade populations [21]. We can illustrate with this an example modified from Warren and included in [3]. Let’s consider a hypothetical family planning program in the GCC that dropped the fertility rate below the re- placement consistently. If this program excluded Yemen, and they continued to have a total fertility rate (TFR) of 3.8 and a time at first birth equal to 21, it would only take 28.6 years for them to reach the current population of the peninsula [5].

[4] See Methods section for calculations.

[5] Starting with a population of 28.5 million and a calculated doubling time of 22 years [3].

FIGURE 2 Population of the GCC countries plus Jordan and Yemen.

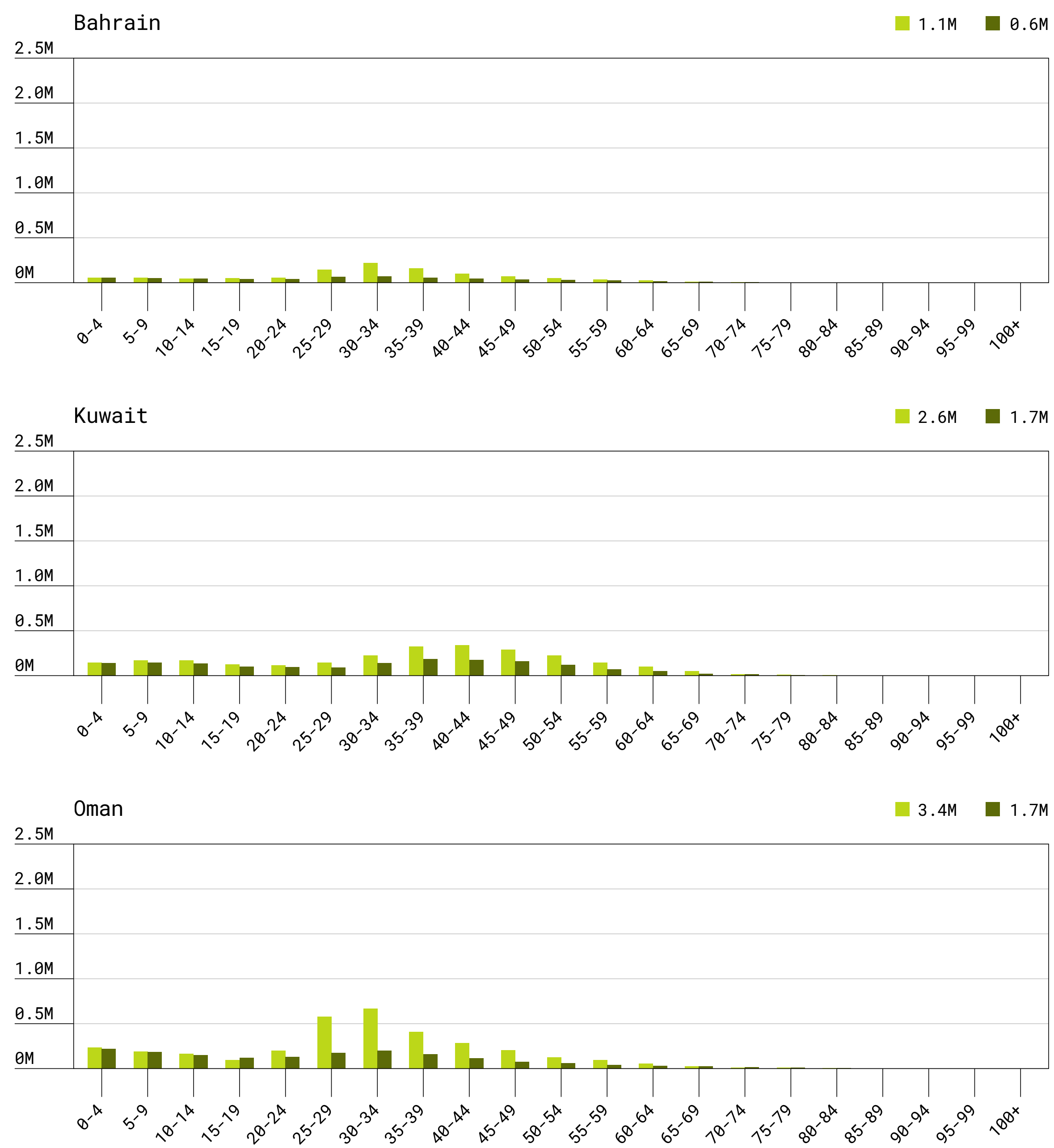
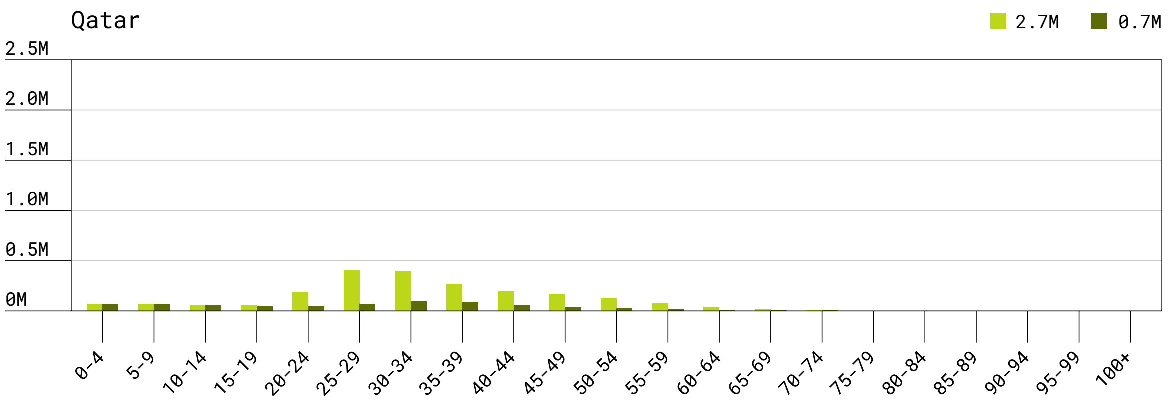
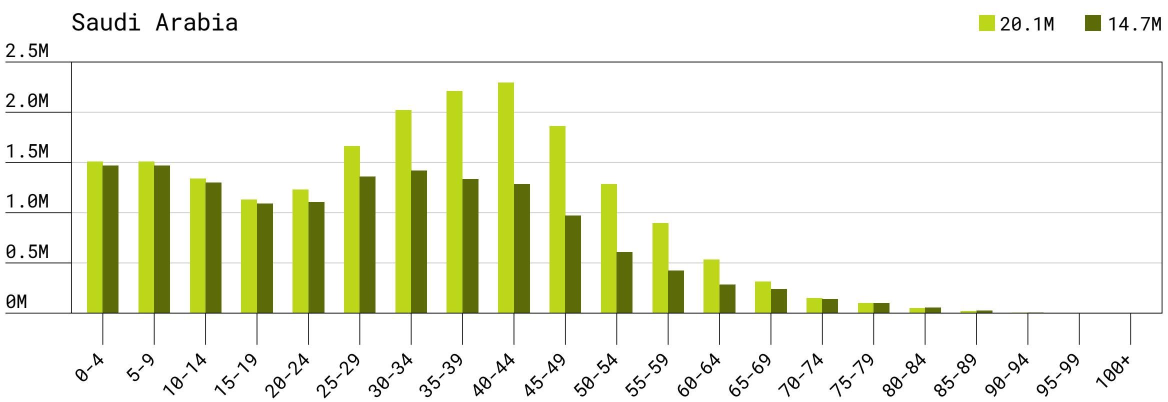


FIGURE 2 Population of the GCC countries plus Jordan and Yemen.

Male Female





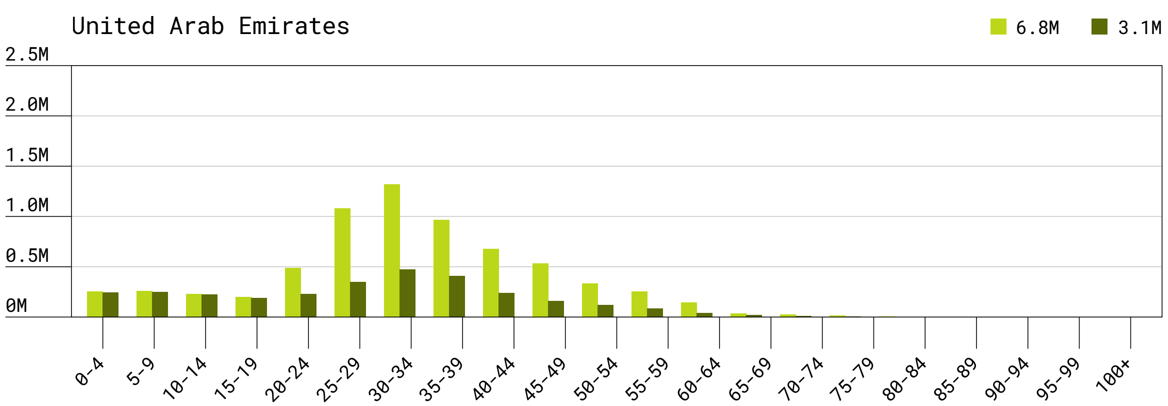
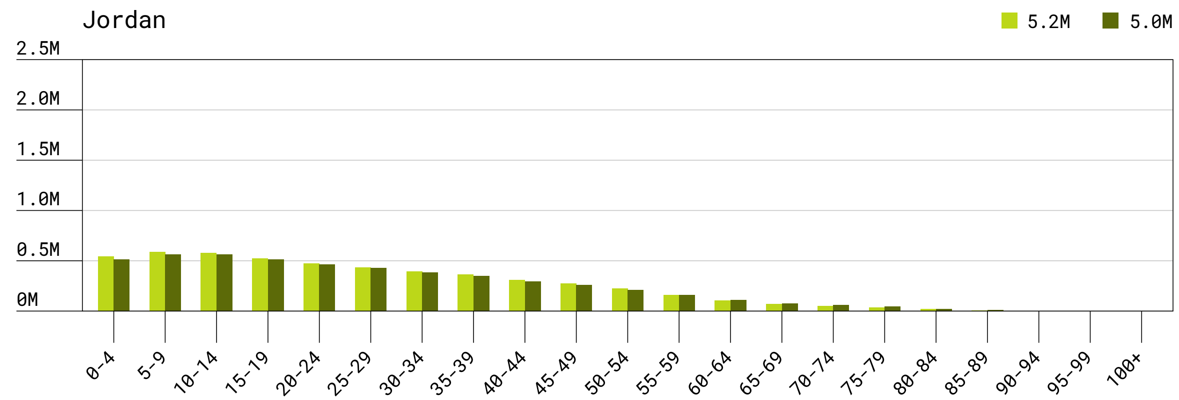
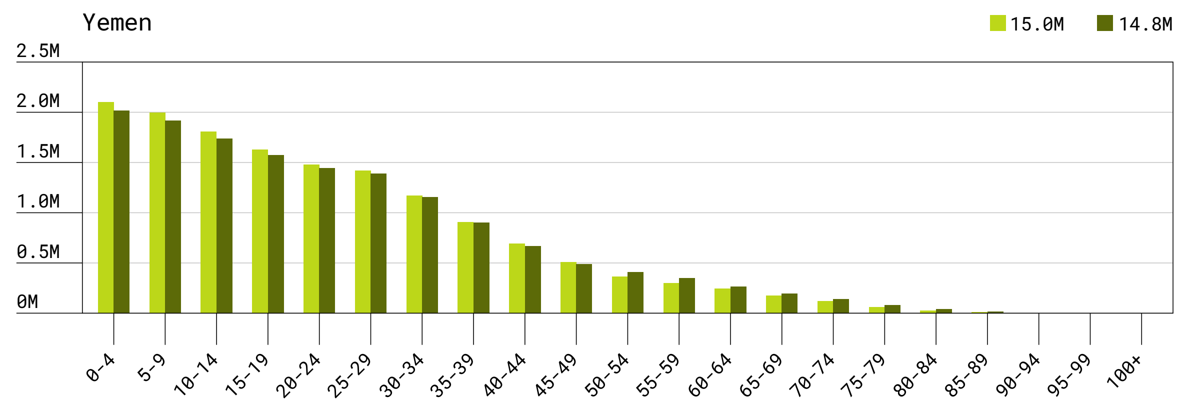


FIGURE 2 Population of the GCC countries plus Jordan and Yemen.

Male Female

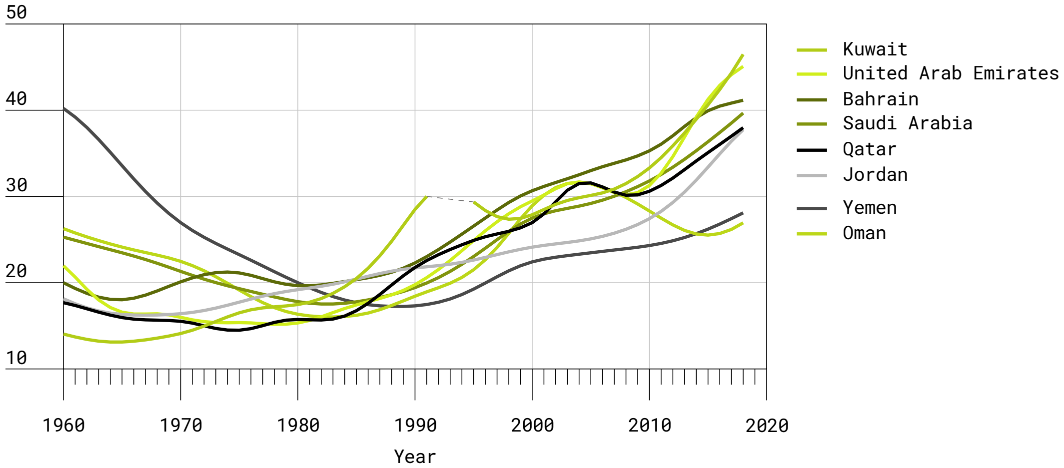




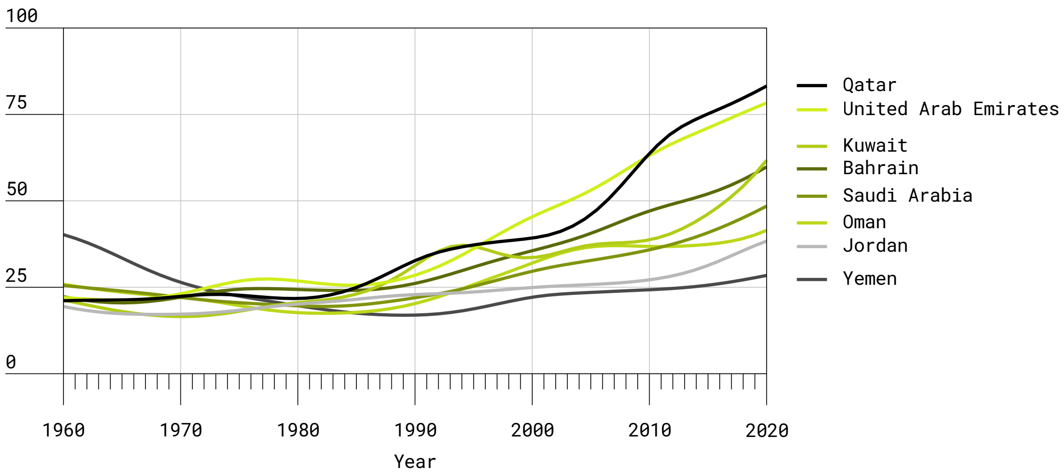
Source: Data from the UN [20] via populationpyramid.net

FIGURE 3 Population doubling times of GCC countries, plus Jordan and Yemen.

A. DOUBLING TIMES ADJUSTED TO COMPENSATE FOR MALE FOREIGN WORKERS



B. DOUBLING TIMES



Source: [3].

Note: The first graph uses an adjusted population size to account for the large number of male foreign workers.

TRADITIONAL KNOWLEDGE

Past ways of life on the peninsula were intricately tied to the ebb and flows of the natural life and thus required knowledge of flora, fauna, soil, topography and climate. Beginning with Bedouin settlement programs appearing at the beginning of the 20th century, this way of life and much of the practical knowledge required faded into historical memory [6] [3]. The discovery of fossil fuels on the peninsula drove internal migration to cities and the tools of industrial agriculture to rural communities. Rules around conservation disappeared in many communities, as did traditional knowledge.

Navigating a low-energy future, will require knowledge of the local environment and conditions. There are elder citizens of the GCC countries who still remember this time, but historians and scientists must act fast to preserve their valuable knowledge. We performed some general calculations to ascertain that the size of this interview pool and is small and growing smaller every year. The growing number of pandemics related to human encroachment on nature unfortunately adds to the time sensitivity of this task.

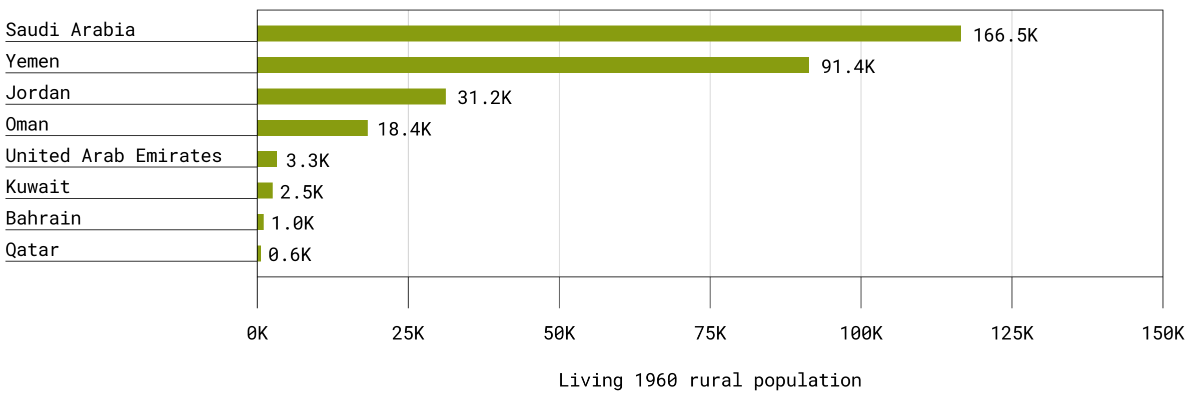
Here we consider the rural population alive today that may remember the rural environment in 1960 (at least 10 years old). Our goal is to get a very rough idea of how many people may still have knowledge about the local flora, fauna and traditional agricultural or herding systems).[7] It should be noted that even during this period the industrialization of agricultural practices was well under away and many traditional practices going unobserved. An exemplar study of Al-Alkhalaf in the Asir region showed increasing abandonment in the 1970's following the growth of cities in region [22,23] with a prior transitional stage away from traditional practices starting with the unification of the Kingdom in 1932 [23]. In poorer or remote regions, traditional agricultural practices may still be practiced today. An additional caveat is that the definition of rural itself has changed over the past century. In 1920, virtually the entire peninsula could be considered rural from the modern definition as a large city was around 20k people.

With the qualifications out of the way, we find that the number of interview targets meeting our criteria ranging from a high of 116k people in Saudi Arabia to 600 people in Qatar FIGURE 4. A large scale effort to interview a portion of this population, and document traditional agricultural, water and forest management, medicinal plant uses, low-energy engineering solutions, and human connections with local flora and fauna would greatly aid the transition to a low impact society. Incorporating this information in local education programs will help instill in students a land ethic informed by traditional culture. This appreciation for nature maybe necessary to make the needed behavioural changes that place social and ecological well-being above material consumption [25,26].

[6] In the Nejd region these settlements were called hijar and appeared in 1912 under King Abdul Aziz Al Saud [24].

[7] 1960 is chosen for simplicity as it is the furthest back UN rural population estimates go. It should be noted that these estimates themselves are rough, with even contemporaneous censuses giving wildly different notions of rural and nomadic populations [3, 24]. Additionally, going any further back significantly decreases the number of people still alive who witnessed and may recall these ways of life.

FIGURE 4 Estimated population alive today that remembers rural life in 1960 (was at least 10 years old).



Note: Based on rural population in 1960 from the world bank, and the 2020 population pyramid [20, 27].

TRADITIONAL KNOWLEDGE

Our overall impact depends not only on population, but also on per-capita consumption. 2000 W per capita of energy use has been proposed as the maximum per-capita consumption level [28-30]. Roughly 1000 Watts is able to meet an individual's basic needs for cooking, food, clothing, shelter [8]. Even if we reduce our consumption to 2000 W, when we multiply this estimate by 8 billion people, humanity as a whole is still a 16 TW machine.

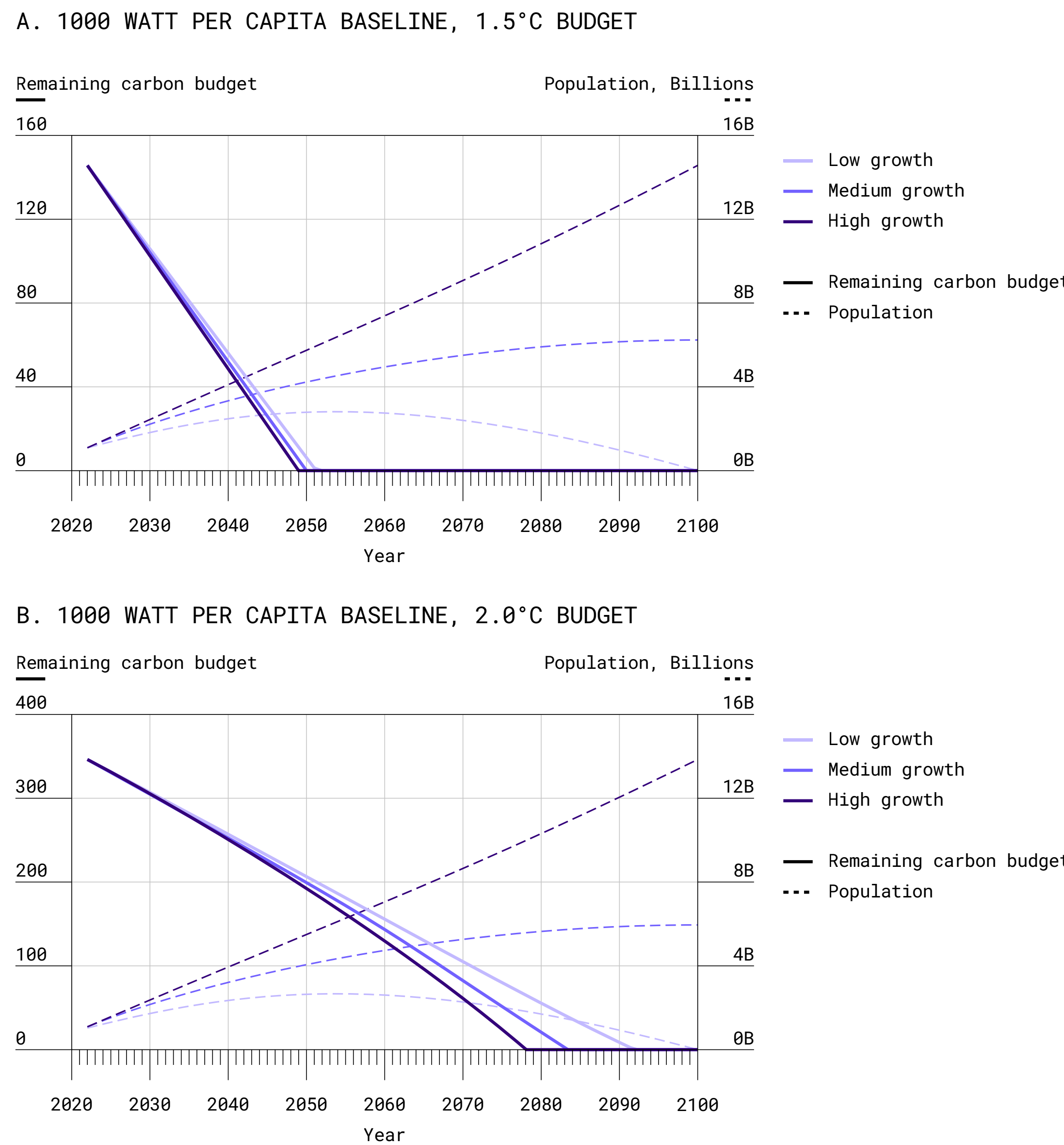
This power consumption curtailment only takes us back to 2010, where we were emitting 8.46 Gt Carbon per year (31.0 Billion tons of CO_2) [9]. At this rate, we will have burned through the 150 Gt carbon budget for 1.5 degrees in 18 years (2040) and the 2 degree (350 Gt carbon budget) in 42 years (2064) [32].

If we then try to minimize consumption to Spreng's 1000 W poverty threshold, we see that this choice doesn't buy much more time FIGURE 5. The population must fall if there is to be any chance of maintaining a livable climate. Additionally, we have assumed that we have the fossil resources to support this population. However, the earth's energy resources are finite, and if humans don't opt to reduce population through humane measures, mass famine will ensue. Given that renewables are at best "repeatable," they will need to be deployed in a way that maximizes well-being and not economic growth ("business as usual").

[8] Spreng and Goldman consider 500 W for cooking and 500 W for other basic needs [28, 31].

[9] This is only considering emissions from energy [33]. If we include land use emissions, the world emitted 10.3 Gt of C in 2010 [32]. Data are located here: https://doi.org/10.18160/gcp-2021 Spreng proposed in 2008 that for climate stabilization, carbon emissions need to be kept below 8 Gt/year by 2050. The latest carbon budget requires much more serious cuts [32].

FIGURE 5 Remaining carbon budget given a 1000W lifestyle under the UN's low, medium and high population growth scenarios.



Source: Mitchell, 2020 [20].

Note: We consider the carbon intensity of economic acitivity as 0.56 kW per tonne C. This value is from 2020 and calculated using total emissions (from land and fossil fuels)in [32] and primary energy consumption in [33].

FIGURE 6 Per-capita power consumption against the 2 KW target.

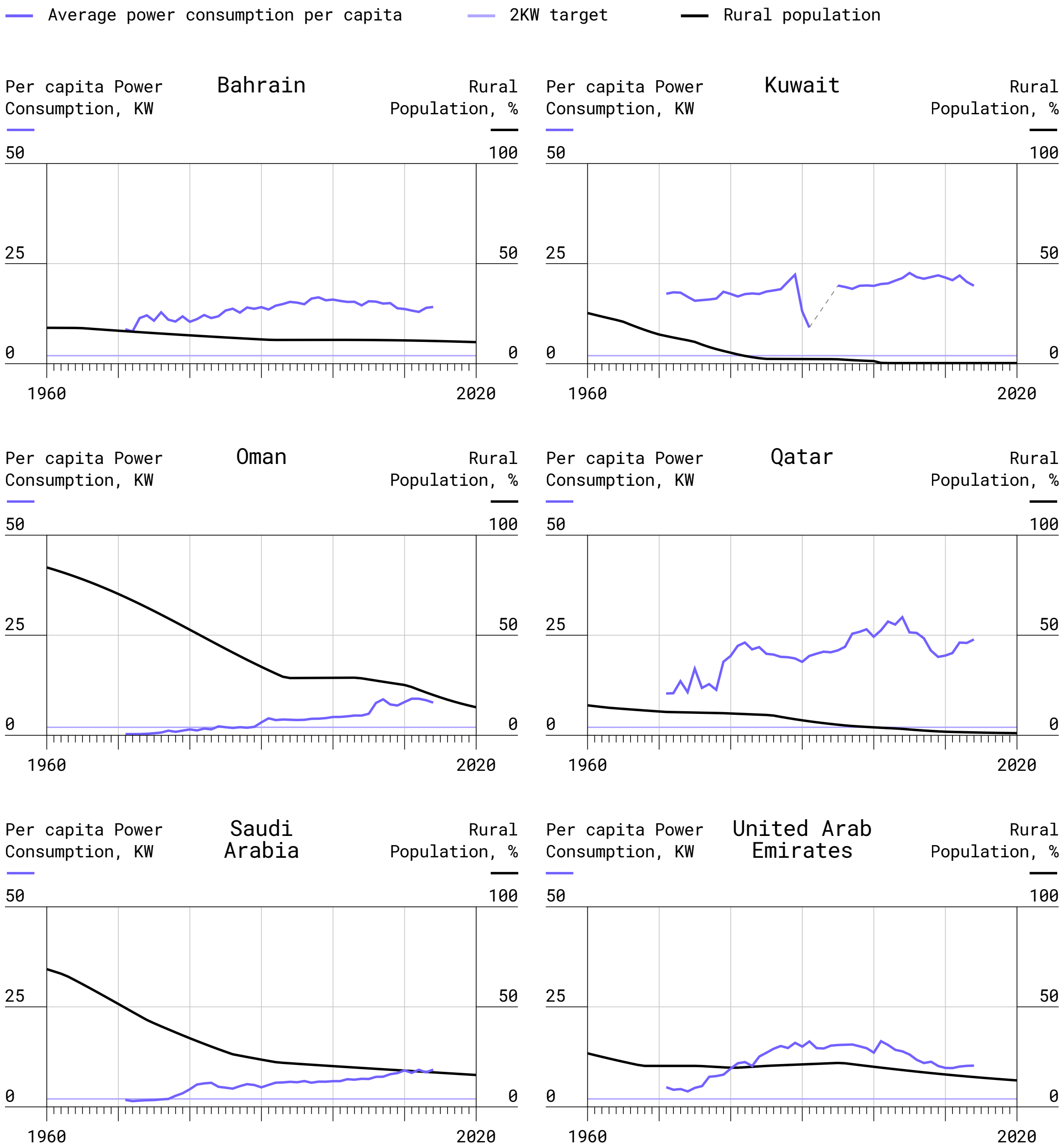
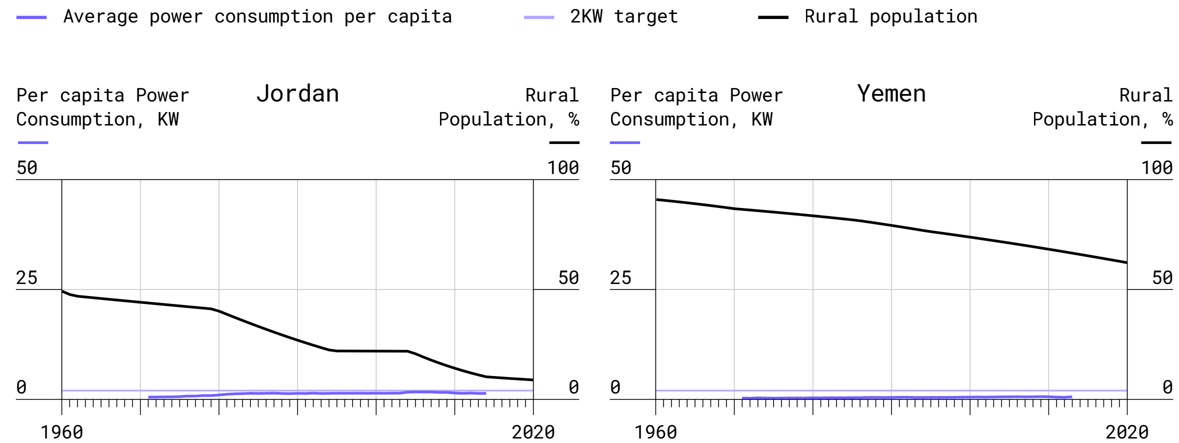


FIGURE 6 Per-capita power consumption against the 2KW target.



Source: Rural population data and energy consumption data are from the World Bank and IEA [27,34].

Note: The limited income distribution data available suggest that the GCC Countries have very high income and energy consumption inequalities [35].

CONCLUSIONS AND RECOMMENDATIONS

→ Empower women in regard to reproductive health and education. This is essential for bringing the population back into equilibrium with the environment.

→ Develop self-sufficiency plans for each major ecoregion on the Peninsula.

→ Prioritize technologies that rely on locally sourced materials with low energy cost.

→ Interview older generations with knowledge essential to navigating low- energy lifestyles need to be interviewed before their knowledge is lost.

→ Advance city planning in the GCC, because most cities are utterly un-sustainable without fossil fuels. The required fossil fuel inputs needed for cooling in the current layout, will only grow with a warming climate.

TABLE 1 Last Year the average primary power consumption was below 2000 Watts.

Country	Last year the average Power Consumption was < 2000W	Notes
Jordan	Current, 2014	2014 last data year
Yemen	Current, 2013	2013 last data year
Kuwait	1991	Gulf War
Oman	1989	
Saudi Arabia	1977	
Bahrain	Pre-1971	
Qatar	Pre-1971	
United Arab Emirates	Pre-1971	

Source: World Bank. Rural population data is from the World Bank [27, [4]] and yearly energy consumption data is from the IEA via the World Bank [34, [23]].

DOUBLING TIMES

Doubling times are calculated using the crude birth rate and crude death rate with the following equation:

$$dt = \frac{100 \ln(2)}{r} \quad \text{where} \quad r = \frac{cbr - cdr}{10}$$

Where cbr is he crude birthrate and cdr is the crude death rate.
To adjust for the disproportionately male migrant worker labor force in some GCC countries, adjusted crude birth and death rates were calculated by conside-ring total population as double the female population.

POWER CONSUMPTION

Power consumption data is from the IEA via the world bank [34]. Top and bottom deciles were calculated using the methodology from [31]. Average income data is from the world bank [36]. Income data is from [35]. The share of income to the bottom 10% was considered one fifth of the bottom 50%.

$$E_{top} = E_{average} + \left(\frac{\Delta I_{top}}{I_{average} 0.8} \right) \qquad E_{bottom} = E_{average} + \left(\frac{\Delta I_{bottom}}{I_{average} 0.8} \right)$$

Where $\Delta I_{top} = I_{top} - I_{average}$ and $\Delta I_{bottom} = I_{bottom} - I_{average}$

Income data in [35] is given as share of income in the top decile T10 for the per capita in the top decile:

$$I_{top} = \frac{I_{total} T_{10}}{0.10 N_{population}}$$

Which simpifies to:

$$I_{top} = \frac{I_{average} T_{10}}{0.10}$$

The bottom decile I_{bottom} is calculated in a similar way.

AREAS OF FURTHER RESEARCH

- → Datasets on income and power consumption disparities are very sparse.
- → Harmonized demographic datasets for the peninsula would make subregional comparisons easier. National demographic and health surveys could also be more comprehensive and include information on desired family size. USAID's Demographic and Health Surveys Program could provide a model.
- → Traditional knowledge regarding resource management, city planning, agriculture, and low-tech cooling solutions should be compiled for each ecoregion.

3

QUESTIONS ARISING:

EMERGING EVIDENCE OF IMPACTS OF CLIMATE CHANGE ON CRITICAL GLOBAL ISSUES

MENTAL HEALTH

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KEY MESSAGES

- → Climate change is worsening people's mental health and well-being.
- → Direct and indirect victims of catastrophic and prolonged weather-related events are at higher risk of experiencing mental health issues.
- → The consequences of climate change will be worse for the more disadvantaged people and communities.

INTRODUCTION

The consequences of climate change for our physical health are well-established. Indeed, climate change is linked with increased respiratory conditions (e.g., asthma, allergies), and increased vector- (e.g., malaria), water- (e.g., cholera), and food-borne diseases. Climate change has also been linked with heat-related morbidity and mortality[1]. The World Health Organization (WHO) predicts that climate change will cause an increase of 250,000 deaths between 2030 and 2050 due to diseases, malnutrition and diarrhoea[2].

In contrast, even though psychological traumas from any form of climate change disaster exceed those of physical injury (40:1 ratio)[3], the consequences of climate change for our mental health and well-being had been ignored until quite recently[4]. To date, mental health has never been discussed at the Conference of Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCC)[5,6]. Moreover, even though COP26 has chosen health as a key area for science, mental health is not mentioned in the programme.

Mental health refers to mental problems, mental illness, and mental disorders. It also includes mental wellness, psychosocial well-being, and emotional resilience[7,8]. The prevalence of mental health issues across the world is extremely high. It is estimated that around a billion people globally suffer some sort of mental illness[9,10].

By 2030, mental health issues will be the biggest cause of mortality and morbidity globally[11]. In 2010 mental health cost the world economy around $2.5 trillion per year in reduced productivity and poor health[12]. This cost is estimated to rise to $6 trillion by 2030. Yet less than 2% of government budgets for health are destined to mental health expenditure[7,8].

Climate change is a threat for mental health. Indeed, it is predicted that climate change will worsen people's mental health and well-being[13]. Extreme weather-related events are becoming more frequent[14,15], therefore it is crucial that we gain an understanding of the interplay between climate change and mental health. Doing so will not only help the environment but will also help our mental health. Action against climate change will reduce associated psychological consequences, and improve human health and wellbeing[16]. Moreover, common actions to tackle both climate change and mental health issues need to be explored[17].

EFFECTS OF CATASTROPHIC WEATHER EVENTS ON MENTAL HEALTH

The connections between climate change and mental health are greatly varied[18-21]. So far, research has mostly examined the effects on mental health of catastrophic weather events[22-30]. These catastrophic events are floods, tornadoes, fires or extreme heat waves. They have been linked with acute mental health issues such as trauma, shock,

post-traumatic stress disorder (PTSD), feelings of abandonment, anxiety, depression, suicide, risk behaviour, poor social relations, increase of community violence, child and domestic abuse, and high-risk coping mechanisms (e.g., alcohol use).

There are many specific examples that illustrate the consequences of such catastrophic events for the mental health of those who experience them. For example, after Hurricane Katrina, 1 in 6 survivors developed PTSD, 49% developed and anxiety or mood disorder, whereas suicide and suicidal thoughts doubled[31-34]. Similarly, after the Haiti earthquake in 2010, the rate of depression amongst the survivors was around 30%[35]. It is estimated that between 25% to 50% of adults and 45% of children affected by a catastrophic weather event will develop an adverse mental health event[36]. Importantly, the impact of such catastrophes tends to be long term. Indeed, 5-8 months after Hurricane Katrina the rate of PTSD amongst survivors was 14.9%, after one year it increased to 20.9%[32,37]. Relatedly, individuals who experience significant floodings reported anxiety whenever it rained from 2.5 to 5 years after the flooding[38]. This is important because support to victims of natural catastrophes is provided in the immediate aftermath of the events, but often no long-term support is offered[4].

EFFECTS OF PROLONGED EXTREME WEATHER EVENTS ON MENTAL HEALTH

Not only people who directly experience catastrophic climate change events are at risk of experiencing mental health issues[39,40]. Exposure to prolonged extreme weather events such as increased temperatures, long droughts, loss of forest and glaciers, rising water levels, and poor air quality have also been linked with long-term mental health effects. These effects tend to be mood and anxiety disorders, low self-esteem, poor interpersonal relations, and eco-anxiety[19].

Although these indirect impacts have yet not received much attention[41], there are many instances illustrating the effect of prolonged extreme weather events on the mental health of those who experience them. Consistent research links temperature increases with negative mental health consequences. Indeed, temperature increases contribute to higher suicide rates and higher levels of violence[42-44]. Visits to psychiatric institutions increase when the temperature is high[45,46]. People with mental health issues are more likely to die because of the heat than those without (2-3-fold increase)[46,47]. This relationship between extreme heat and mental health issues may be explained because heat waves cause heat stress which is directly linked with mood and anxiety disorders, and increased aggression[48]. A shift in monthly temperatures between 25°C and 30°C to temperatures higher than 30°C increases the prevalence of mental health issues by 0.5% points[49].

Prolonged extreme weather events may also force communities and people to migrate. Migrants are more likely to experience mental health issues [50], such as depression, anxiety and increased suicide risk [51-54]. Climate change also increases the risk of experiencing physical health issues such as obesity, cardiovascular diseases, lung diseases or heat strokes [55] which in turn increase the risk of experiencing mental health issues [56]. Climate change may create community conflicts because it affects our access to resources, such as water and food [57-59]. In turn, victims of such conflicts are likely to experience PTSD and mood related issues [60].

EFFECTS OF INDIRECT CLIMATE CHANGE ON MENTAL HEALTH

However, not only people that directly experience catastrophic and long-term effects of climate change are at risk of experiencing mental health issues. This indirect exposure occurs mostly through media representations (e.g., TV, social media) of environmental changes and catastrophes occurring around the world [61, 62]. The scant research examining these relations suggest that these indirect effects are indeed happening [20, 61]. For example, [63] conducted a study across 25 countries and concluded that participants associated climate change with negative emotions, suggesting that it is not necessary to directly experience the negative consequences of climate change to be negatively affected by it. Moreover, in most countries negative emotions related to climate change were linked with sleep difficulties (72% of the countries) and lower self-rated mental health (84% of the countries).

CLIMATE CHANGE, MENTAL HEALTH, AND INEQUALITIES

It is importat to note that the effects of climate change are not the same for everyone. Indeed, it is well documented that climate change worsens already existing inequalities [64, 65]. The most severe consequences will be felt by the most disadvantaged individuals and communities, and those most marginalized [66, 67]. Individuals living in less developed countries, outdoor labourers, racialized people, immigrants, women, young people, and those already suffering from mental health issues will be more affected [1, 41, 68-70]. These groups are more likely to experience mood disorders and anxiety as a result of natural disasters [71, 72]. For example, indigenous groups in Australia are more exposed to the effects of wildfires and drought, which in turn threatens their food and water supplies and their overall economic and social wellbeing, placing them at higher risk of experiencing psychosocial trauma [73-75]. A study conducted in the Netherlands and England found higher concentrations of air pollution in the most deprived neighbourhoods which has been linked with poor mental health outcomes [76] . The climate change crisis has been said to be a racist crisis because its consequences are worse for Black communities worldwide. Indeed, Black people in New Orleans experienced more stress in the aftermath of Hurricane Katrina than other demographic groups even

after controlling other variables, such as demographics, job status, evacuation timing, or income [77].

EFFECTS OF CLIMATE CHANGE ON OUR EMOTIONS

Climate change also affects people's emotions. Increasingly, people around the world report being worried about climate change and its consequences [78, 79]. In 2019, 66% of Americans reported feeling at least a bit worried about climate change [80]. This is relevant because negative emotions affect our mental health and well-being [81, 82].

Indeed, worry about climate change is linked with psychological distress [477] and negative emotions. A wide range of negative emotions have been reported in relation to climate change: sadness, despair, distress, anger, fear, hopelessness, and helplessness [84, 28].

A growing number of scholars warn that negative emotions linked with climate change are likely to have a negative impact on mental health, even among people that do not directly experience negative consequences [85].

Recently, a negative emotion quoted 'eco-anxiety' has received plenty of attention by experts and the popular media [85, 86]. However, eco-anxiety remains poorly understood and there is not a clear definition of the concept [87, 88]. The American Psychological Association defines it as 'a chronic fear of environmental doom'. Eco-anxiety is not yet classified as a mental disorder, but several symptoms have been linked with it, namely: panic attacks, weakness, distress, despair, sleeplessness, irritability, loss of appetite, obsessive thinking, apathy, and learned helplessness [87, 89, 90]. Eco-anxiety also seems to impact certain groups more than others. Indigenous groups, young people, and those who depend on natural resources for their living have been reported to experience higher levels of eco-anxiety [87]. Indeed, it seems that eco-anxiety affects especially young people [91]. A recent study showed that approximately 50% of people aged 16 to 25 report experiencing feelings of anxiety and depression in relation to climate change [92]. This is relevant because 75% of mental illness start before the age of 24, therefore eco-anxiety could worsen young people's mental health. Particularly relevant is the effect of eco-anxiety on children as extensive research suggests that long-term stress and anxiety during childhood and adolescence has a long-term negative impact on children's development [93, 94].

DISCOVERING THE LINK BETWEEN CLIMATE CHANGE AND MENTAL HEALTH

The reason climate change has a negative influence on our mental health is not yet entirely clear [95]. One possible explanation is the biophilia hypothesis [96] which posits that humans are innately connected with the natural world. This connection benefits our general well-being. When we experience extreme climate change weather events the natural spaces that we feel connected to, are damaged, in turn damaging our mental health, resulting in feelings of loss. This phenomenon has been named 'ecological grief' [97]. Ecological grief refers to intense feelings of grief as a result of climate-related losses to valued species, landscapes, and ecosystems [97].

Another possible explanation is The Attention Restoration Theory [98] which posits that interaction with nature has many benefits (e.g., reducing attentional fatigue) and therefore it improves our mental health and our mental cognitive processes. Indeed, exercising outdoors as opposed to indoors improved attentional control [99]. Finally, The Stress Reduction Theory [100] posits that contact with nature reduces stress and improves mental health. Children with more nature in and near their home experienced less psychological distress when facing stressful life events [101]. In general, the more green a person's surroundings, the lower the risk of mortality and morbidity.

The underlying mechanism explaining the connection between mental health and nature may be that proximity to nature activates the parasympathetic nervous system [102, 103] which in turn reduces the release of cortisol, improving sleep, fighting the negative effects of stress, and boosting immune function [104]. Activation of the parasympathetic nervous system has been found after exposure to nature in experimental conditions (e.g., in a laboratory setting) and after long-term exposure to nature (e.g., living in a green area) [105-107]. Taken together, research suggests that although we do not have a clear explanation about the links between climate change and nature, it seems that being connected with nature is beneficial for our mental health and well-being [108, 109].

CONCLUSION

Climate change has been long examined by many different disciplines (e.g., natural sciences, economics, politics), however until very recently the field of psychology did not play a role in climate change research. It is now clear that climate change is directly linked with human behaviour. Not only are humans the main contributors to climate change, but only humans will be able to put an end to it. Psychology must support people adopt a more sustainable way of living, and come up with novel solutions to tackle climate change. Furthermore, psychology must extend our understanding of the impact of climate change on mental health. Existing literature clearly shows that climate change has a negative effect on people's mental health and well-being, increasing inequalities around the world and creating an important economic cost.

However, psychologists must not make the mistake of conducting research on climate change in isolation. It is crucial that we conduct interdisciplinary research to fully understand the impact of climate change on mental health. Multidisciplinary teams must also

work together to design solutions that could improve climate change and mental health at the same time. For example, measures to reduce flooding in high-risk areas, will contribute to avoid mental health issues that would be developed because of flooding. These measures will in turn reduce the economic burden generated by both issues. It is also important to raise awareness of the negative impact of climate change on mental health among the general public, as well as to train healthcare professionals to deal with patients experiencing the negative consequences of climate change on their mental health. First responders must also be trained to consider the mental health of victims of climate change catastrophes, and not to focus only on their physical health. Finally, psychologists alongside professionals from other disciplines must influence policy makers and relevant stakeholders to prioritize climate change mitigation policies.

QUESTIONS ARISING

→ Why must climate change be examined from a psychological perspective? Emerging research shows that psychology has a role to play in the fight against climate change. However, this role is yet not fully understood nor recognized by other disciplines and stakeholders. The GCC could lead the drive to push psychology to the forefront of the fight against climate change.

→ What are the consequences of climate change for mental health? Research is only beginning to understand the direct and indirect effects of climate change on mental health. So far, there is no research in the GCC on this issue.

→ How will climate change affect mental health in the GCC? Limited resources (e.g., water and food), migration and temperature increase are the three main problems associated with climate change in the GCC. These three issues have been linked with poor mental health, intergroup conflict, violence increase, and worsening inequalities. Future research in the GCC should focus on finding solutions to these problems.

→ How can the GCC tackle the effects of climate change on mental health? It is vital to adopt an inter-disciplinary approach. All scientific fields must come together to fight climate change. Solving problems created by climate change will in turn help alleviate mental health problems, saving time and resources.

AREAS OF FURTHER RESEARCH

→ Conduct interdisciplinary research to achieve a comprehensive understanding of the links between climate change and mental health.
→ Examine common actions to tackle climate change and mental health. Such actions could include protecting areas at risk of flooding or improving air quality.
→ Improve our understanding of the barriers and facilitators of engagement in sustainable behaviours.
→ Involve relevant stakeholders in the design of appropriate emergency responses to support the mental health of climate change victims.

3.2

FISHERIES YIELDS & AQUACULTURE PRODUCTION

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KEY MESSAGES

- → Saudi Arabia's Red Sea fisheries are currently based primarily on reef fish, which are vulnerable to degradation from climate change.
- → Impacts of climate change may alter the composition of reef fish communities and, therefore, the composition of species available to fisheries.
- → Ambitious targets for increasing aquaculture developments must carefully consider the potential impacts of climate change, including changes in projected productivity in open-sea aquaculture and fluctuations in costs associated with cooling self-contained aquaculture systems.

INTRODUCTION

Climate change is having a measurable impact in ecosystems worldwide. Saudi Arabia and the GCC region is expected to experience impacts of climate change in many aspects, several of which are treated thoroughly elsewhere in this document. Predicting the impact of climate change on Red Sea fisheries requires an understanding of the somewhat unique factors that influence the local ecosystems and the local industry. Additionally, there are complications in estimating a true value of both the ecosystems and the industry that are worth exploring. Given what we do (and do not) know about the future conditions in the Red Sea, many questions arise. These questions are briefly considered in this section.

The current fisheries industry in Saudi Arabia (and, indeed, most of the Red Sea) is reef-based [1]. Some catch is taken in open waters and some parts of the Red Sea are targeted by trawling operations, but the majority of the fisheries target reef fishes. Various fishing methods are employed, including hand lining, gill netting, trap fishing, and more. While there is a subset of species that are valued higher in local markets (some groupers and jacks, for example), virtually every species that can be caught will be offered for sale [2]. Given that the current composition of the fishery is primarily reef fish, questions about how climate change will impact fisheries are closely linked to how climate change will affect reefs in this region.

Coral reefs are complex ecosystems that may be easier to disrupt than traditional open-ocean systems. Predicting the dynamics of change in such complex ecosystems is a daunting challenge, but one of the clear threats to coral reefs in a warming climate is the increased occurrence of thermal bleaching events. Corals, the animals that build the very structure of reefs, thrive in low-nutrient tropical waters in large part due to an intimate symbiosis with specialized algae. These algae (in the taxonomic family Symbiodiniaceae [3]) share photosynthetic products with their coral hosts, providing the majority of food for most reef-building coral species. When conditions on a coral reef depart from optimal parameters (most notably temperature, but also including salinity, UV exposure, pollutant levels, and others), this symbiosis breaks down and the coral host expels the symbiont algae [4]. Much of the color visible in healthy corals is actually due to the presence of the symbiotic algae in the coral tissue, so if the symbiont is lost, the coral's calcium carbonate skeleton is visible through the transparent coral tissue. The term "bleaching" is used because a coral in this state appears bright white. While the coral animal is still alive in this stage, it has lost the major source of its food (i.e., the photosynthetic product of the algae) and most species of corals will gradually starve. If the stress abates relatively quickly, the corals can recover their symbionts and return to a normal state. (Although there may be some sub-lethal consequences, such as reduced reproductive output [5], the integrity and function of the coral as a part of the overall reefscape is not lost.) Excursions of only 1-2°C above normal summer maximum temperature for a couple of weeks can lead to large numbers of corals on an affected reef bleaching and dying. After several weeks, or if the temperatures reach several degrees above normal, the numbers of corals and reefs impacted may be so large as to be referred to as a mass bleaching event. These mass bleaching events are a major threat to the future of coral reefs worldwide as climate change causes summer maximums to exceed the optimal range for corals with increasing frequency.

Corals are long-lived and slow-growing animals. Lifespans are typically measured in decades and sometimes centuries. Growth rates (linear extension) for most species are in the range of 1-2 cm per year. If large numbers of corals are killed or damaged on a reef, they can recover, but this process can take a long time. Recovery from major coral mortality has been documented in several parts of the world in previous decades, however, the process typically takes 10-25 years [6]. Climate change is causing bleaching events to happen with a frequency that does not allow corals time to recover before the next event occurs. Saudi Arabian reefs in the Red Sea have suffered several bleaching events [7, 8] and the frequency of these events seems to be increasing here as elsewhere in the world [9, 10].

When coral reefs bleach, the associated communities of organisms living in the reef are impacted through a loss of habitat, food, and other resources. Fish, even if not immediately and directly harmed by the bleaching event, eventually can show changes associated with degradation of the habitat. One of the common shifts observed in reef communities following a major loss of live corals is an increase in the amount of macroalgae occupying space on the reef, which can subsequently lead to an increase in the abundance of herbivorous fishes. In severe cases, large amounts of coral loss can lead to a loss of the three-dimensional structure that corals provide. The loss of this structure can have major impacts on the fish community. If climate change will lead to a change in the composition of fish communities or the total fish biomass available in Saudi Arabian reefs, the local fisheries could be directly impacted. A shift for both the fishermen and the consumers may be required [2]. Valuable species may be less abundant or available; some species currently less appreciated or less targeted may become more valuable. Such a shift could introduce new or unexpected vulnerability (both of the fishery and of the reef health). Due to the complex ecology of coral reef systems, a shift to new target species could have unintended impacts on the health (or recovery potential) of a reef – certain groups of fishes, such as herbivores, are often expected to play a major role in helping reefs recover from a disturbance [11].

Determining the true "value" of an ecosystem or the value of the "services" provided by a given ecosystem services is tricky to calculate, but it is commonly done. However, some caution must be applied when applying traditional approaches to this calculation in Saudi Arabia. At present, valuation of the fisheries could be made based on current market prices. In a broader context, reefs themselves could be valued, taking into consideration tourism revenue and the general benefits that these habitats provide. However, it is important to recognize the highly dynamic situation in Saudi Arabia. The value (or perceived value) of a healthy coral reef may increase under a Vision 2030 scenario given the increased importance of tourism among new economies envisioned for the country. Certain groups of fishes that are presently valuable as fisheries targets may have future value as charismatic species that divers and snorkelers would like to see. In other words, some species may become more valuable left alive in the water than they are worth as fished targets. Additionally, healthy ecosystems are a key pillar of plans for some of the GigaProjects, especially the coastal developments such as NEOM or AMAALA. Healthy ecosystems are expected to be major features to attract international and domestic tourists. In the NEOM region, it is recognized that healthy ecosystems are an important component to ensure quality of life for residents. Overall, this is not a direct impact of climate change on fisheries per se, but it is worth considering because it does influence how the impact of climate change may be valued.

Climate change has the potential to disrupt a critical portion of the life cycle of reef fishes. The majority of species targeted by fisheries are broadcast spawners, meaning that they release their eggs and sperm into the water when they reproduce. Successfully fertilized eggs develop into tiny larval fishes which continue their development in open waters away from reefs before settling into a reef and entering the population as a juvenile fish. The stage of development after hatching, known as the pelagic larval stage, varies from species to species and may last from as little as about 1 week up to a few months. Most reef fish have a larval stage that lasts for about one month. During this time, larvae may disperse widely (potentially traveling hundreds of kilometers aided by ocean currents), connecting distant populations. There are many unanswered questions about how climate change will impact larval fish [12]. Increased ocean temperatures may lead to faster development in the larval stage and potentially could result in shorter larval stages. It is not clear how this will impact the success of larval fishes when they arrive at a reef. Existing spatial patterns of connections among reefs may be altered. Climate change may also influence the ocean currents and further alter the patterns of dispersal of larval fish. Management efforts of fisheries, especially for reef fishes, must include some assumptions about the input of arriving larvae and replenishment of local populations. These assumptions may need to be reevaluated in light of potential impacts of climate change. It is worth noting that most reef organisms have some form of pelagic larval de-

velopment, including corals. As mentioned above, fisheries in the Red Sea are largely comprised of reef fishes, so the potential impacts of climate change on larval dispersal for corals or other organisms may impact the overall health of the reef.

Many reef fishes are hypothesized to use seagrass beds and/or mangrove stands as nursery grounds. Juvenile fishes may use these habitats as shelter or feeding grounds until they are big enough to safely migrate into coral reefs (where there are many more larger predators). Climate change has the potential to degrade or reduce the availability of these important coastal habitats. It is very difficult to directly measure the level to which reef fishes depend on nursery habitats, but a reduction in the availability of mangroves or seagrasses could have negative impacts on the availability and population sizes of targeted fisheries species in reef communities.

The growth rate of individual fish may be predicted to decrease under rising temperatures. This is somewhat counterintuitive, but it has often been demonstrated in several fish species with larger latitudinal distributions (e.g., [13]). In these examples, individuals that live further away from the equator have higher growth rates and reach larger sizes as adults than individuals from the same species that live closer to the equator. This phenomenon has not yet been tested in the Red Sea, but it has been demonstrated for some species in the Indian Ocean. It is possible that warming conditions across the whole of the Red Sea could lead to decreases in body size and growth rates for target species (and thus a general decline in productivity of the fisheries). Some forms of aquaculture activities (e.g., closed, recirculating systems) may be able to compensate and regulate internal water temperatures at optimal levels within their systems, but this may require increased energy investment. More open systems, such as sea cages, would not easily be able to regulate temperatures and may thus experience productivity declines if temperatures increase and a counter-gradient temperature/growth rate is experienced.

In general, many of the aquaculture plans for Saudi Arabia need to be carefully evaluated with an eye towards the potential impacts of climate change. Due to the rapidly growing demand for and implementation of aquaculture solutions, several aspects of aquaculture planning rely on untested assumptions or assumptions based on data from very different ecosystems. The unique nature of the Red Sea, with its high temperatures and extremely low nutrient levels, may introduce vulnerabilities into the ecosystem or into the industry, especially if some assumptions are imported from regions with cooler waters, typically high nutrient loads in the environment (e.g., areas with upwelling), and generally different dynamics. This is particularly true for farming in sea cages. Climate change and the expected increase in temperatures may further invalidate the initial assumptions in Red Sea aquaculture plans.

There are clearly many aspects of climate change that are still to be investigated with regards to fisheries and aquaculture in the Red Sea. Some of these aspects involve direct and indirect impacts of climate change on the ecology of the reefs supporting the fishery, while other aspects relate to the unique nature of the Red Sea environment. These are timely questions to be considering as Vision 2030 shifts the potential "value" of both fisheries and the reef systems that support fisheries in the Red Sea.

TO SUMMARIZE SOME OF THE KEY QUESTIONS ARISING

→ How will bleaching affect Red Sea fish communities?
→ Will the fisheries (and consumer markets) adapt to new target species if climate change leads to a shift if reef fish communities?
→ Would a change in fishing targets (e.g., increased targeting of herbivorous fishes) have further impacts on the health of Red Sea reefs?
→ Will the rise of ecotourism change the hypothetical value of healthy reefs (e.g., with fishery management investments) vs. the potential value of fisheries?
→ How will the larval stage of reef fishes be impacted by climate change? How might the resultant patterns of connections among reefs be altered?
→ If climate change impacts the availability or quality of potential nursery habitats, such as mangroves and seagrass beds, would there be subsequent effects on the populations of reef fishes that use these nurseries?
→ Will increased temperatures in the Red Sea result in slower growth rates or reduced maximum sizes for key target species (or for aquaculture species)?
→ Will aquaculture costs increase due to additional energy demands to maintain optimal temperature in fish rearing systems?
→ Will climate change increase the vulnerability of the Red Sea ecosystem with respect to plans for sea cage aquaculture? Will climate change decrease the predictability of the interaction between sea cages and the background environment?

AREAS OF FURTHER RESEARCH

→ How will bleaching affect Red Sea fish communities?
→ Will the fisheries (and consumer markets) adapt to new target species if climate change leads to a shift if reef fish communities? Would a change in fishing targets (e.g., increased targeting of herbivorous fishes) have further impacts on the health of Red Sea reefs?
→ Will the rise of ecotourism change the hypothetical value of healthy reefs (e.g., with fishery management investments) vs. the potential value of fisheries?
→ How will the larval stage of reef fishes be impacted by climate change? How might the resultant patterns of connections among reefs be altered?
→ If climate change impacts the availability or quality of potential nursery habitats, such as mangroves and seagrass beds, would there be subsequent effects on the populations of reef fishes that use these nurseries?
→ Will increased temperatures in the Red Sea result in slower growth rates or reduced maximum sizes for key target species (or for aquaculture species)?
→ Will aquaculture costs increase due to additional energy demands to maintain optimal temperature in fish rearing systems?
→ Will climate change increase the vulnerability of the Red Sea ecosystem with respect to plans for sea cage aquaculture? Will climate change decrease the predictability of the interaction between sea cages and the background environment?

EXTINCTION, CHANGES IN BIODIVERSITY AND THEIR IMPACTS ON HEALTH

Rich Reading,
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— Aeon Collective

KEY MESSAGES

→ The "twin crises" of climate change and biodiversity loss are deeply intertwined.

→ Climate change and related anthropogenic factors, negatively impact biological diversity in numerous ways:

- ↘ Habitat fragmentation and range-shifts.
- ↘ Shifts in temperature, water/humidity, PH or microhabitat lead to loss of local populations.
- ↘ Mismatches in species' temporal and climatic triggers can lead to reproductive failures, disruptions of food chains, etc.
- ↘ Prevalence and distribution changes for pathogens will lead to altered disease patterns.
- ↘ However, concerns over climate change have largely over-shadowed the biodiversity crisis.
- ↘ Both require immediate attention. The world is experiencing changes in climate at an increasing rate since the beginning of the Industrial Revolution in the 1800s. The impacts of climate change affect all aspects of live on Earth, including impacts to biological diversity and the health of all organisms, including humans. Addressing those impacts represents a fundamental challenge to the continuation of life on Earth as we know it.

INTRODUCTION

The world is experiencing changes in climate at an increasing rate since the beginning of the Industrial Revolution in the 1800s. The impacts of climate change affect all aspects of live on Earth, including impacts to biological diversity and the health of all organisms, including humans. Addressing those impacts represents a fundamental challenge to the continuation of life on Earth as we know it.

CLIMATE CHANGE AND RELATED ANTHROPOGENIC FACTORS, NEGATIVELY IMPACT BIOLOGICAL DIVERSITY IN SEVERAL WAYS:

→ Habitat fragmentation inhibits the ability of species to shift ranges in the face of changing climatic conditions

→ For sessile species, shifts in temperature, water/humidity, Ph (aquatic systems) or shifts in microhabitat lead to loss of populations

→ Mismatches in species' temporal and climatic (temperature, humidity, etc.) triggers can lead to reproductive failures, disruptions of food chains and ineffective hibernation/estivation strategies

→ Prevalence and distribution changes for pathogens will lead to altered disease patterns across populations, species and ecosystems

The "twin crises" of climate change and biodiversity loss are deeply intertwined. That said, concerns over climate change have largely over-shadowed the biodiversity crisis in which we find ourselves. Both require immediate attention.

While not the only causal factor, climate change is directly and indirectly impacting species and ecosystems. Direct impacts include the effects of the increasing frequency and severity of droughts and wildfires, loss of habitats and connectivity of those habitats, and the growing number of and population sizes of invasive species. These effects are causing shifts in species distributions, largely causing upward shifts altitudinally and latitudinal shifts away from the equator.

More indirectly, climate change also causes temporal impacts where triggers of certain behaviors or processes do not align with required climatic conditions. This timing mismatch can lead to changes in food/prey availability, hibernation and estivation patterns (among species that engage in those behaviours), the timing of migration, and pattern in reproductive behaviours.

These direct and indirect impacts have resulted in a dramatic loss of biodiversity at several levels. First, the most obvious impacts occur at the species level. More species are threatened and endangered or have gone extinct since the start of the Industrial Revolution than any time since the dinosaurs went extinction some 65 million years ago. In addition to this unparalleled loss of species we are

also losing biodiversity within species at the individual and population levels. This loss of genetic diversity impacts the ability of species to respond to environmental changes such as those associated with climate change. Increasingly, that loss forces species into what conservation biologists refer to as the extinction vortex, in which genetic, behavioural, and environmental factors interact synergistically to force species into a decline that is very difficult to reverse. As our climate changes and we increasingly lose the richness of our biological communities, we are seeing simplification of food chains and food webs that could ultimately result in faunal collapse, or the loss of entire communities of associated species.

Climate change, and related anthropogenic factors are also leading to significant changes in global patterns of health and disease. Changing climatic conditions create new patterns of distribution for certain pathogens, either directly or via impacts on disease vectors. Additionally, as species adapt to our changing climate through movement (altitudinal or latitudinal) the potential for exposure to novel pathogens increases. This new "overlap" between biological sectors leads to increased transmission of pathogens between typical and atypical host species (spillovers). This (potential) increase in prevalence of disease in atypical species often without natural regulatory mechanisms to limit the related morbidity and mortality.

The emerging field of "One Health" recognizes this new global view of health and disease, recognizing the interconnectedness of human health, animal health (domestic and wild) and ecosystem health. As climate change continues to impact the health of ecosystems, animals, and humans globally, this more wholistic approach will be required to identify these new threats to planetary health.

These changes are dramatic and potentially catastrophic and thus deserve immediate attention. Thus, we provide several questions for practitioners to consider when examining the impacts of climate change on biodiversity.

QUESTIONS

→ To what degree does climate change contribute to the current extinction crisis?

→ What are the best ways to mitigate the impacts of climate change on biodiversity?

→ Can we predict how climate change will alter food webs and other species interactions?

→ What are the implications for the combined impacts of climate change and biodiversity loss on humans and human health?

→ What are some likely scenarios for changes in epizootic spillovers into human health given predictions in climate change?

→ Can we predict changes in species assemblages in the face of

climate change?
- How will ecosystems change (restructure) with climate change?
- How will climate change affect food security?
- What ecosystems services (e.g., pollination, soil production, nutrient cycling, water and air purification, etc.) will climate change impact and how?

ADDITIONAL DISCUSSION IDEAS:
- Climate change has increases tree-killing droughts, bug infestations, and wildfire. In two major reports just this spring, the Intergovernmental Panel on Climate Change (IPCC) emphasized again that protecting carbon-storing forests and bringing back degraded ones is essential to curb warming. How do we promote protection and expansion of forests in the face of climate change impacts (above).
- While not directly caused by climate change, associated anthropogenic factors are leading to planetary deforestation, expansion of agriculture, stressed water resources and widespread desertification, all further contributing to climate change. As species respond to climatic change, further overlaps between those species are likely to result in increased spillover of emerging/zoonotic diseases. How do we develop climate change adaptation plans that minimize additional "harm" from health/disease interfaces?

AREAS OF FURTHER RESEARCH
- To what degree does climate change contribute to the current extinction crisis, and how to best mitigate?
- Can we predict how climate change will alter food webs and other species interactions?
- What ecosystems services (e.g., pollination, soil production, nutrient cycling, water and air purification, etc.) will climate change impact and how?
- How will climate change affect food security?
- How will climate change alter epizootic spillovers into human health (emerging diseases)?
- What are the implications for the combined (synergistic?) impacts of climate change and biodiversity loss on humans and human health.

THE LINKS BETWEEN CLIMATE CHANGE, DISPLACEMENT, AND SECURITY

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KEY MESSAGES

→ Despite the global agreement on the climate change impacts that include: sea-level rise, coastal erosion, drought and floods, increasing waves of heat and cold, epidemic outbreak, and consequential disorders affecting both environment and society, this level of agreement can not be applied among those who want to define the potential links between climate change, conflicts, displacement, and security.

→ This chapter presents an integral vision on the links between climate change, security, and conflict and displacement issues. It employs the critical analysis approach and secondary analysis methodology that depends on analysis of data which can be collected from the international and regional reports and relevant studies.

→ Defining and understanding the links between climate change and variability on the one side and migration, displacement, and security on the other side is considered a priority for designing the policies and programs associated with the local social contexts. This will have a positive effect on the plans of adaptation, resilience, and population capacities rehabilitation. Accordingly, the climate change impacts on the human security can be encountered.

→ The state of "uncertainty" is frequently noticed when exploring the direct relationship between climate change, displacement, and security. Therefore, the complicated links between them should be monitored and examined. We can discover these links by classifying the climate change as "a threat multiplier" that affects security in its comprehensive sense inside the regions and countries suffering from weakness and vulnerability in some of their social, economic, and political structures.

→ There are more evidence that climate change may have great impacts on the human security aspects that include: food security, livelihoods security, and health security. These impacts might reduce the communities' capabilities of climate resilience.

→ The local factors (economic, social, political, cultural, and ethnic characteristics of community) seem to be determinants when defining the relationship between climate change, displacement, and comprehensive security.

→ Although there are no accurate statistics on the numbers of migrants and directions of migration and displacement due to climate change in the Arab countries, there is no doubt that climate change and its extreme variabilities have a negative impact on the agricultural production, livestock, or availability of water. Accordingly, many people are compelled to migrate or displace.

→ The climate changes in the Arab world and neighbouring areas can lead to waves of displacement and migration to the rich Gulf countries. This may create external pressures on the Arab Gulf area.

INTRODUCTION

Climate change has a dangerous impact on the human life and health. It threatens the human life's foundations that include: clean air, safe drinking water, food supplies, safe accommodation, and suitable temperatures. According to the Sixth Assessment Report of Intergovernmental Panel on Climate Change (IPCC), climate change resulting from human activities will inevitably occur, regardless any mitigating measures that are currently taken.

Although there is a global agreement on climate change's repercussions and disasters that include: sea-level rise, coastal erosion, drought and floods, increasing heat and cold waves, epidemic outbreak, and consequential disorders affecting both environment and society, this level of agreement cannot be applied among those who want to define the possible links between climate, conflicts, displacement, and comprehensive security.

However, the climate and security speeches have greatly developed during the last few years, and more efforts have been made to explore the nature of links between climate changes on the one side and displacement, conflict, and multiple dimensions of security on the other side. The availability of additional regional and local data on climate has contributed to the development of climate and security speeches.

Therefore, this chapter offers some initial questions to be answered for assisting us in establishing an integral vision on the links between climate change, security, and conflict and displacement issues. It employs the critical analysis approach and secondary analysis methodology that depends on analysis of data collected from international and regional reports and relevant studies.

FIRST: THE CONCEPTUAL FRAMEWORK

→ Climate Change: The United Nations Framework Convention on Climate Change (UNFCCC) has defined the concept of climate change as follows: A change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods [1]. This definition has been slightly modified by IPCC Working Group 1 which defined climate change as follows: Any change in climate over time whether due to natural variability or as result of human activity [2].

→ Climate Variability: This term refers to the variations in the mean state and other statistics (such as standard deviation and occurrence of extreme climatic events) of climate on all spatial and temporal dimensions that exceed the individual climate events. Therefore, climate change leads to long-term shifts in climate patterns and variations for an extended period, whereas climate variability is considered an uncharacteristic climatic activity that can be noticed and measured over a shorter term. Both may result from natural internal processes or external forcings. In line with their IPCC definitions, both terms are used here, often in conjunction, to refer to different but related types of climatic shifts from historical baselines [3].

→ Security (Human Security): This study seeks to go beyond the traditional and minor idea of security by depending on the Human Security term. The term has been used for the first time in the Human Development Report 1994 issued by United Nations Development Programme [4]. The report has defined the "Human Security" as follows: "People's safety from chronic threats which are disseminated over large areas during long periods and threaten his life and freedom [4]. The report has defined seven components of human security: economic security (such as freedom from want), food security (access to food), health security (access to health care and safety from diseases), environmental security (safety from dangers of pollution and congestion), personal security (security from physical torture, crime, and violence), community security (preservation of traditional cultures and ethnic groups), and political security (enjoying the civil and political rights and safety from political repression). This list is long, and it is difficult to identify what can be put aside in the human security definition (UNDP, 1994)(4). In this regard, we will focus on how climate change and variabilities may affect some aspects of human security. Subsequently, exploring the links between climate change and various aspects of human security can be easier.

→ Displacement: Whereas migration involves some level of voluntary agency, displacement sits at the "forced" end of the mobility spectrum. IOM defines a displaced person or group as: one who "has been forced or obliged to flee or to leave their homes or places of habitual residence… as a result of or in order to avoid the effects of armed conflict, situations of generalized violence, violations of human rights or natural or human–made disasters" [3]. The above-mentioned definition offers a broad scope to interpret the situations that may force an individual to leave his home and the levels of hardships, including the environmental adverse conditions, that must be endured by a person before violating his human rights. While displacement includes those who have been forced to flee locally or internationally, only the persons or groups who have fled through the international boarders are classified as refugees. On the other hand, persons who have fled from their countries to avoid the impacts of climate change or variability or natural disasters will not be considered refugees. Accordingly, they will not be granted the same international legal protection stipulated in The 1951 Refugee Convention. However, the UN Environment Program (UNEP) has offered a definition for the environmental refugee as follows: A person who temporarily or permanently leaves the place of his residence due to an environmental disaster (impossibility to live in this place because of drought, flood, or desertification) that threatens his existence or greatly harms his living conditions [5]. It is worth mentioning that the International Organization for Migration (IOM) uses the "Environmental Refugees" term for those people who voluntary or forcibly leave their homes due to the environmental changes that suddenly or gradually occur and have negative impacts on their lives or living conditions. This type of migration may be made locally or to outside of their countries' borders, temporarily or permanently [6].

SECOND: WHAT IS THE RELATIONSHIP BETWEEN CLIMATE CHANGE AND SECURITY?

Recently, many international and regional organizations, mainly the UN, have paid more attention to climate change impacts on struggles and armed conflicts in many areas over the world in a manner threatening security and peace. The Security Council has acknowledged that climate change was considered a basic factor affecting the countries' stability. The Council has invited all concerned parties to prepare more analyses and in-depth studies for exploring the nature of existing or potential links between climate change and security, in general.

Policy discussions about the links between climate and security date back to the mid-2000s but have matured as different governments and international organizations have sought to mainstream climate security concerns. A community of practice that has emerged among think tanks, led by organizations such as: The US-based Center for Climate and Security (CCS), Stockholm International Peace Research Institute (SIPRI) played an important role in forming the community of practice and supporting the speech associated with the relationship of climate change with security [7].

The strategy of the United Nations Department of Political and Peacebuilding Affairs for 2020-2022 deals with climate change as a motivating factor leading to struggle [8]. Moreover, the establishment of a mechanism for climate security by three UN's bodies and integration of climate risks in the UN system from 2018 strongly indicate that climate changes may threaten international security and peace.

Although there is no clear acknowledgement that climate change is associated with specific conflicts, there is a tendency advocated by some people who want to explore how climate changes affect the social and economic dynamics inside countries. There are some examples for such countries that can be indicated as follow:

- → Bangladesh: The studies have examined the basic dynamics of conflict on the land and natural resources in "Chittagong hill tracts and explored how extreme weather led to conflict escalation and threatened the region's security [8].
- → Nigeria and Chad: The impact of variable patterns and rates of precipitation on contestability and dispute over land has been monitored in the regions that witness long-term conflicts between farmers and herders.
- → Syria: We can notice the controversial relationship between drought resulting from climate change that affected Syria in 2006 and 2007 and the increasing levels of displacement and migration locally and across borders. The climate change has increased desertification, destroyed farms, decreased the number of livestock, and displaced many villagers. Moreover, more than two million Syrians have been trapped in the cycle of poverty and obliged to internal displacement to cities or refuge outside the Syrian territories [5].
- → Lastly, some members of international organizations, particularly the UN, have linked the conflict in the Sudanese region of Darfur with climate change. They argued that similar environmental problems have resulted in escalating violence and threatened the security of many African countries [9].

Despite the above-mentioned examples that directly indicate the existing and potential threats resulting from climate change and affecting security and peace, the state of "uncertainty" is frequently noticed when exploring the direct relationship between climate change and security. Therefore, the sensitive links between both should be monitored and examined. These links can be more appraent by classifying the climate change as a threat multiplier that affects the comprehensive security inside the regions and countries suffering from weakness and vulnerability in some of their social, economic, and political structures. Accordingly, the ability of such regions and countries to confront or adapt is limited. When linking the impacts of climate change as a threat multiplier with the aspects of human security, it will be easier to discover the sensitive links between the climate threats and security.

There is a gap in perceiving the human security challenges resulting from climate change. During the informal debate of UN General Assembly in 14 April 2011, Brauch has discussed "the environmental aspect of human security". He suggested a fourth pillar for the human security named "freedom from hazard impact" and said: "Hazards cannot be prevented, but their impacts may be reduced. Such hazards affect not only the national and international security, but also have dangerous impacts on the human security and its various aspects in the most vulnerable communities. They negatively affect water, soil, food, health, and livelihood security". This constitutes the background of the human security's fourth pillar named "freedom from hazard impact" for dealing with environment, sustainable development, disasters, and engagement of organizations, programs, and relevant initiatives in the UN system [10]. Subsequently, the fourth pillar may be considered a tool aiming to "reduce the vulnerability of communities which suffer from natural disasters or man-made hazards".

THIRD: CLIMATE CHANGE AS A THREAT MULTIPLIER FOR HUMAN SECURITY

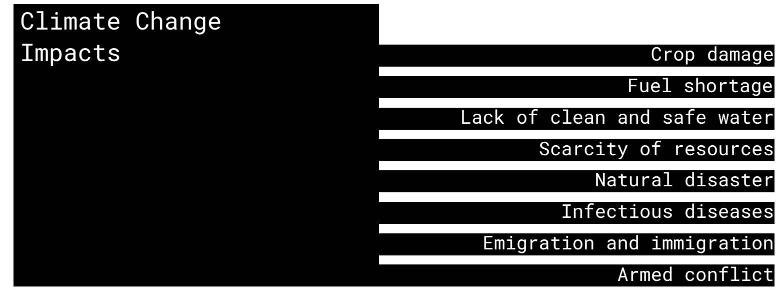
The latest report issued by the IPCC in 2022 [11] affirms that: Human-induced climate change, including more frequent and intense extreme events, has caused widespread adverse impacts and related losses and damages to nature and people, beyond natural climate variability. Some development and adaptation efforts have reduced vulnerability. Across sectors and regions, the most vulnerable people and systems are observed to be disproportionately affected.

Moreover, climate changes lead to erosion of long-term opportunities for human development, undermining of productivity, and weakness of human capacities. Although there is no climate shock attributed to climate change, climate change may result in escalation of hazards and increase of vulnerabilties of the Arab human, particularly who lives in vulnerable regions and under difficult economic and social circumstances. It puts more pressures on the adaptation mechanisms and binds individuals with deprivation and vulnerability restrictions [12]. Hence, climate change impacts restrict the individual capacity to get ride of want and deprivation which represents the human security objective.

Climate change is contributing to humanitarian crises where climate hazards interact with high vulnerability (high confidence). Climate and weather extremes are increasingly driving displacement in all regions (high confidence), with small island states disproportionately affected (high confidence). Flood and drought-related acute food insecurity and malnutrition have increased in Africa (high confidence) and Central and South America (high confidence). While non-climatic factors are the dominant drivers of existing intrastate violent conflicts, in some assessed regions extreme weather and climate events have had a small, adverse impact on their length, severity or frequency, but the statistical association is weak (medium confidence). Through displacement and involuntary migration from extreme weather and climate events, climate change has generated and perpetuated vulnerability (medium confidence) [11].

Based on the FIGURE 1 and the human security components defined by the Human Development Report as follow: Economic security (such as freedom from want), food security (access to food), health security (access to health care and safety from diseases), environmental security (safety from dangers of pollution and congestion), personal security (security from physical torture, crime, and violence), community security (preservation of traditional cultures and ethnic groups), and political security [4], climate change represents serious threats to such seven components.

FIGURE 1 Shows the climate change impacts on the human security aspects.



These threats have been affirmed by some reports issued by IPCC. There is increasing evidence that degradation and destruction of ecosystems by humans increases the vulnerability of people (high confidence). Unsustainable land-use and land cover change, unsustainable use of natural resources, deforestation, loss of biodiversity, pollution, and their interactions, adversely affect the capacities of ecosystems, societies, communities and individuals to adapt to climate change (high confidence). Loss of ecosystems and their services has cascading and long-term impacts on people globally, especially for Indigenous Peoples and local communities who are directly dependent on ecosystems, to meet basic needs (high confidence) [11].

There are more evidence that climate change may have serious impacts on the human security components and affects some aspects such as: food security, water security, livelihood security, and health security. These impacts may also restrict the community capacity to adopt strategies for long-term adaptation or avoid living in vulnerable regions. In this regard, we will present a summary for the most critical impacts of climate change on some aspects and components of human security.

CLIMATE CHANGE IMPACTS ON FOOD SECURITY — Food security exists when all people, at all times, have physical, social, and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life [13]. From this definition, four main dimensions of food security can be defined, according to the FIGURE 2.

FIGURE 2 Dimensions of Food Security.

Food Access	Food Availability
Access by individuals to adequate resources to acquire appropriate foods for a nutritious diet	Sufficient quantities
Resource potential of consumers & market forces	Appropriate quality
	Capacity of agricultural production system
	Sustainability & Resilience capacity of agro-ecosystem

Food Stability	Food Utilization
Round the year accessibility of food to the human population	Ensures the nutritional wellbeing & human wellbeing
	Factors-Cleanliness, clean livable environment, food safety and sanitation

All dimensions of food security are currently vulnerable to threats that originate from climate change, whether directly from variable temperatures and precipitation or indirectly from agricultural land loss due to sea level rise, high rates of wind and water erosion, pests, and diseases. Moreover, changing the land usage by man because of deforestation and desertification has led to reduction of the agricultural capabilities in many areas around the world. The report issued by World Economic Forum in 2015 has indicated the hazards resulting from food insecurity when "access to suitable, good, and nutritious amounts of food is insufficient, unaffordable, or can not be dependable on the wide scale [14].

> FRAME NO. (1)
> CLIMATE VARIABILITY AND EXTREMES
> Are a key driver behind the recent rise in global hunger, one of the leading causes of severe food crises, and a contributing factor to the alarming levels of malnutrition seen in recent years. Increasing climate variability and extremes, linked to climate change, are negatively affecting all dimensions of food security and nutrition [15].

In the wake of a drought that began in late 2010, Somalia experienced an estimated 260,000 excess deaths from famine. Somalia's situation of course was exacerbated by the long-running civil war [7]. From the previous example, we can say that food security is not only one of human security components, but also it is associated with broader issues of countries' national and political security. In addition, climate change and its negative impacts, mainly those affecting the agricultural communities, may create internal conflict threats.

CLIMATE CHANGE IMPACTS ON HEALTH SECURITY — Health security is one of human security components. It refers to endeavores made to free the human from all threats that may negatively affect his physical, mental, or social safety. It is not limited to provision of health care that protects him from only sickness and disability. In other words, health security encompasses all measures taken by a state to ensure the physical, mental, and social safety of its citizens with no discrimination [16].

It is known that climate change greatly affects the human health. The weather and climate extremes result in significant damages, and only floods may cause a large-scale destruction. Accordingly, casualities and economic loss up to billions of dollars resulting from damages affecting property and critical infrastructure of public health may occur. The Sixth Assessment Report of IPCC stated that: Human mortality from floods, droughts and storms was 15 times higher in highly vulnerable regions, compared to regions with very low vulnerability (high confidence) [11], in addition to the health hazards resulting from climate extremes. It is expected that climate change or variability may change the geographical or seasonal patterns of the non-communicable and infectious diseases [14].

A study has indicated that climate changes will increase incidences of severe heat waves, droughts, storms, and floods, and such incidence will become more severe. These changes will bring heightened risks to human survival and will likely exacerbate the incidence of some NCDs, including cardiovascular diseases, some cancers, respiratory health, mental disorders, injuries, and malnutrition. NCDs will likely be affected by climate change in two ways. First, climate change itself may directly and indirectly increase the incidence of NCDs. Second, policy responses to climate change—both adaptation and mitigation—will likely have both positive and negative implications for NCDs [17].

The infectious diseases result in great losses among populations all over the world. Some types of lethal infections are highly sensitive to climatic conditions (temperature, precipitation, and humidity have a great impact on diseases and survival and also affect the life cycles of infectious agents). According to World Health Organization (WHO) and World Meteorological Organization (WMO), weather conditions affect water movement and food-related illnesses, such as Cholera and other types of diarrhea, that kill more than two million people annually. In addition, malaria kills almost one million people, and about 50 million people around the world suffer from dengue fever every year [14].

FRAME NO. (2): CLIMATE CHANGE AND HEALTH
KEY FACTS[18]

→ Climate change affects the social and environmental determinants of health – clean air, safe drinking water, sufficient food and secure shelter.
→ The direct damage costs to health (i.e. excluding costs in health-determining sectors such as agriculture and water and sanitation), is estimated to be between USD 2-4 billion/year by 2030.
→ Areas with weak health infrastructure – mostly in developing countries – will be the least able to cope without assistance to prepare and respond.
→ Reducing emissions of greenhouse gases through better transport, food and energy-use choices can result in improved health, particularly through reduced air pollution.

FOURTH: CLIMATE CHANGE, MIGRATION, AND DISPLACEMENT OF POPULATIONS

Discovering links between climate change, migration, and displacement of populations attracts the interest of policymakers, researchers, and civil society actors. However, knowledge in this field is still limited and dispersed. The available literature on this topic highlights the complicated relationship between environmental factors and migration and indicates that climate change is only one of other factors interpreting the dynamics of migration and displacement. This can be clear by recognizing that any migration movement results from many different and overlapping factors, and environmental stress always mixes with other causes which may include different economic, social, and political dimensions.

For achieving analysis purposes and realizing the desired objective of the study, the researcher commits to assign this part to analyze and examine the nature of links between climate change, migration, and displacement of populations, although such aspects is related to human security dimensions.

Before making the analysis, it is important to indicate that we prefer to link climate change with two basic terms, which are: migration and displacement. Climate Migration in its broader definition refers to the populations' slow movements associated with population mobility after the initial emergence of environmental hazards and climate change impacts. Contrary, Displacement refers to the population groups movement resulting from rapid and sudden climate hazards that force them to flee. We sometime use the term Mobility to be indicative of migration and displacement, but it will not include any other forms of population movement, such as resettlement.

WHY IS LINKING CLIMATE CHANGE TO HUMAN MOBILITY AND SECURITY IMPORTANT? — Although the sensitive relationship between climate change, human mobility, and security is complex and indirect, it is clear, based on what have previously indicated on food security and health security, that climate change and variability often lead to a wide range of human security challenges. Climate-related displacement, food insecurity, and health risks affect millions of people worldwide. The extent of these challenges varies across social groups and is influenced by the interaction of multiple factors, including economic status, gender, age. Women, youth, and ethnic minorities often bear the worst human security consequences of the climate crisis. For example, among cyclone-affected migrants in Bangladesh, poor women were shown to face the greatest hardships, as displacement overlapped with gender-based violence, ethnic discrimination[3].

In some cases, climate-related insecurities can lead to conflict, with migration and/or displacement often playing a mediating role in the process. Illustrating this point, research shows that for every 100,000 people displaced by floods, the probability of conflict incidence rises by approximately 3 percent. Given that flooding drove 10 million people globally from their homes in 2019, and 51 percent of all disaster-related displacements between 2008 and 2018 were flood-related, this threat is far from marginal. While a changing climate and the outbreak of conflict both pose acute risks to human security, the resulting human movements, in isolation, are not an inevitable precursor to violence. Instead, insecurity is mediated through a multitude of political, social, and economic factors that are a greater determinant of violence than climate change and/or variability or mobility on their own[3].

Based on the above-mentioned, we can say that defining and understanding the links between climate change and variability on the one side and migration and displacement on the other side is considered a priority for designing the policies and programs associated with the local social contexts. This will have a positive effect on the plans of resilience and population capacities rehabilitation. Accordingly, the climate change impacts on the human security can be encountered.

WHAT ARE THE LINKS BETWEEN CLIMATE CHANGE OR VARIABILITY ON THE ONE SIDE AND POPULATION MOBILITY AND CONFLICT OVER RESOURCES ON THE OTHER SIDE? — It is historically known through many studies and reports that many linked factors are motivating the population mobility. However, the IPCC's Sixth Assessment Report[11] states with high confidence that there is high agreement and robust evidence that: "climatic conditions, events and variability are important drivers of migration and displacement… with migration responses to specific climate hazards being strongly influenced by economic, social, political and demographic processes".

Nonetheless, when asked their reasons for migrating, individuals most often cite social or economic factors (seeking to earn a living), with climate or environmental factors rarely presented as a primary driver. However, I can affirm that economic and social factors of migration or mobility are based on climatic drivers that are difficult to be identified or articulated.

Migration driven by slow-onset climate hazards tends to be a more complex phenomenon than disaster-related displacement. Slow-onset hazards occur over longer periods and are typified by decaying ecosystem services, increasing temperatures, shifting precipitation patterns, erratic rainfall, prolonged drought, pest and disease outbreaks, rising sea-levels, salination of freshwater sources, and desertification. Slow-onset climate hazards are likely to interact with other, more primary social, economic, and political drivers to push individuals from their homes[3].

In most cases, population displacement or migration for responding to the great environmental stress and scarcity of resources is indicative of community resilience collapse. In fact, moving from one place to another is considered a basic method for responding to difficult circumstances by humans. Similarly, many impacts of climate change will most likely encourage displacement due to emergency or motivate migration as result of long-term changes in climate[14]. However, this will not contradict that the first reaction of communities encountering gradual climate hazards will be adaptation at their place of residence. The continuous deterioration of environmental status and escalation of hazards may lead communities to search for more solutions, such as: internal or external migration Therefore, research stress that families or communities' adaptability plays an in important role in taking decisions for staying in the local environment or migrating.

Even where populations do not migrate and seek to adapt, practitioners worry about the effects on lives and livelihoods, particularly for agriculturally dependent communities, which may face severe food security deficits from growing seasons disrupted by climate extremes and variability[7].

Although labor migration is ostensibly driven by the desire for employment, climatic change and/or variability can play an indirect role in contributing to these flows by damaging livelihood strategies in origin areas. As approximately 80 percent of the world's poor depend on agriculture for livelihood generation, remittances are especially important for households in areas where agricultural productivity is negatively impacted by climatic vulnerability[3].

In few words, although its id difficult to draw maps on how climate changes affect the different forms of migration, displacement, or migration, it is probably that environmental and climatic changes play an indirect role by deteriorating the existing livelihoods and agricultural productivity levels. Although there are no trusted global estimates on the future cases of displacement, there are strong evidence that

planning and increasing mobility may reduce the effects of climate change displacement on human security. However, lack of global estimates and research on the differing weakness points may make it difficult to consider it a part of a national plan or security issue. Moreover, the gradual climate change and potential conflicts are critical research gaps. In this context, the research trends demonstrate four key findings as follow[19]:

→ The rates of displacement and conflicts may increase as a result of climate change and also can be considered a multiplier effect of political instability and poverty, in addition to the uncertainty about climate change and variability.
→ There is evidence on migration from rural to urban areas and other countries. This is attributed to climate change and emergence of conflicts because of community dwellers non-acceptance.
→ There is a minimum level of adaptive mechanisms - or there are no adaptive mechanisms that are really developed or have to be developed - to manage or stop population displacement resulting from climate change and to avoid conflict situations.
→ There is no adequate research on the way that may be empoyed by this link for asking more complex questions in the future by increasing number of weakness points. Accordingly, it will be difficult to predict migration and climate-related conflicts for the most vulnerable countries.

THE NATURE OF LINKS BETWEEN CLIMATE CHANGE AND HUMAN MOBILITY — Although there are some evidence and analyses showing links between the human mobility that is associated with climate factors and violent conflicts, some researchers argue that this topic is complex and sophisticated and no clear or direct links can be established or extracted. In this context, the accurate analyses (the specific case studies or those centered on a specific local context) may be successful tools for understanding whether the conflict-related mobility may lead to conflict, and how/why/and when does this conflict occurs.

Based on that the local factors (economic, social, political, cultural, and ethnic characteristics of community) seem to be determinants when demonstrating the relationship between climate change, displacement, and security, the social and environmental dynamics of community affect conflict and vary across the geographical regions. For example, In Sahel and Horn of Africa, the climate change and variability affect the resources availability by changing the patterns of long-term seasonal migration. Accordingly, contestability will increase between the pastoral or semi-pastoral communities from one side and the farmers who have the resources, grasslands, and water on the other side. Particularly, the studies and reports consider climate change and variability as direct drivers of conflict more than multiplier threats in the Sahel and Horn of Africa. Therefore, such region is named Sahel Climate Conflicts [20].

In addition to what have previously mentioned about the Syrian case, we can mention the situations in Guatemala, Honduras, and Nicaragua where two-thirds of the population rely on agricultural livelihoods, with climate hazards playing an indirect but important role in undermining agricultural productivity and the viability of rural livelihoods. These climate hazards interact with pre-existing, context-specific inequalities and vulnerabilities that are driven, in part, by persistent and largely unresolved legacies of conflict and violence directed toward indigenous communities. The result is an unevenly distributed risk landscape, where indigenous communities face greater risks to their livelihoods and physical security, rendering them more likely to engage in migration or to become displaced by declining agricultural productivity, or as a consequence of rapid-onset natural disasters [3].

According to what have previously mentioned and based on the local studies and reports, we can say that the local context characteristics are highly correlated and define how impacts of climate change, mobility, and displacement affect security. It is important to identify the conflict drivers (such as: drivers related to gender-based discrimination, drivers of conflict over resources, drivers associated with actors, and institutional drivers) within specific geographical contexts instead of being used in general according to inappropriate or false determination. Conflict and threat to security result from many different factors that interact through the geographical, temporal, and societal measures and dimensions. By scrutinizing this contrast and complexity, considering such drivers as amplification factors or threat multiplier will be a precise description.

Hence, regarding the violent conflict outbreak and security threat as dependents on various local variables and don't represent a direct or inevitable result of climate changes-related mobility. Accordingly, a ris-based approach is relied upon to monitor and measure potentials of violent conflict occurrence within a specific context.

FIFTH: CLIMATE CHANGE, DISPLACEMENT, AND SECURITY IN THE MIDDLE EAST: A BRIEF DESCRIPTION AND THE FUTURE FIELDS OF RESEARCH

Although the report focuses on the countries of the Gulf Cooperation Council "GCC", it is difficult to talk about the countries of GCC apart from their geographical borders, particularly their neighbour Arab countries. This geographical dimension includes many countries that are most vulnerable to the climate changes. For example, Those countries are: Iraq, Syria, Yemen, Egypt, Sudan, and the remaining countries of the region. Moreover, the previous countries are considered sources of migration flows to the Gulf countries. Therefore, it is important to present a brief overview on the climate changes in the Middle East in general.

For the Arab world countries which their thermal emissions doesn't represent more than 5% of total thermal emissions, climate change is considered an additional, dangerous, and real threat. It brings many great environmental, economic, political, social, and security challenges for the Arab world in the light of the current situation of its countries that suffer from economic problems, political instability, and armed conflicts. Generally, the future expectations indicate that the natural and unnatural resources (such as: Water) may be sources of conflict and dispute in many areas around the world [16].

The IPCC working group expects that climate extremes, such as: floods, drought, and etc. will be more frequent and severe. This will lead to streams of mass migration in the Arab region. For example, the scenarios designed by the UNEP and other organizations indicate that the sea-level rise of 0.5 meter may lead to displacement of about two million persons in the Arab countries by 2050 [21]. Moreover, the dissemination of drought and desertification can create migration streams from East Africa countries to the Arab world, particularly the Gulf countries. Therefore, it is important to enlarge the national security scope of the Arab countries. It means that regarding the impacts of climate change, displacement, and security, the policies adopted by the Arab countries must put into consideration that part of their regional security is associated with situations in other countries, such as: The countries of the Horn of Africa and East Africa which may bring streams of migration and displacement to the Arab world. This potential influx of large groups of the population attempting to reach the oil states poses extra-systemic stress factors to the Gulf region [22].

Regarding the impacts of climate change in the Lower Gulf, the research on coral reefs in Abu Dhabi, Dubai and Sharjah demonstrate that the local marine ecosystems in the Arabian Gulf are substantially affected by climate change. There are other environmental risks in Qatar. The decrease in precipitation in combination with a projected temperature rise will render even wider areas of the Gulf states unfit for agriculture and inhabitable. It is described with the "desertification in the desert" term. This will raise the stakes for existing water supplies in the region [22]. For the Kingdom of Saudi Arabia, it is expected that climate change will affect water supplies and cropping systems, and it may lead to temperature rise and decrease in precipitation rates [23].

In some Arab countries that witeness local conflicts, the conflict proximity and climate change consequences may lead to emergence of new forms of social vulnerability resulting from climate change impacts on many aspects. The examples of this social vulnerability can include: Shabaab Group and Da'esh, which are two terroristic organizations in Somalia and Iraq, consecutively. Most of their members have come from regions that suffer from shortage of natural resources and high levels of economic and social deprivation and climate change. Some studies affirms that deterioration of food security levels in some Arab regions has contributed to increased deprivation and dissatisfaction which accordingly created an environment motivating protests and social and political disorders. These events sometimes fuel the armed conflicts in the areas of conflict and originate less violent forms of conflict in other regions. The conflicts in Syria, Yemen, and Sudan are good examples as we see that climate change in these countries is a clear factor of conflict. By the middle of 2000, drought forced big number of farmers to stop agriculture activities and migrate to cities with population pressures. Moreover, the water inventory decrease and high prices of food led to social chaos that originated uncontrolled disorders that subsequently turned into the current conflicts [16].

Although there are no accurate statistics on the numbers of migrants and directions of migration and displacement due to climate change, natural resources scarcity, and environmental disorder in the Arab countries, there is no doubt that climate change and its extreme variabilities, such as severe floods, drought, and environmental deterioration that negatively affect the agricultural production, livestock, or availability of water, have compelled many people to migrate. Migration in the Arab world include individuals and groups from various social and economic backgrounds [5].

Therefore, it is important for the Arab countries to consider how climate change is linked to patterns of mobility, displacement, and security in the Arab world. Accordingly, the effect of environmental or climate migrations on the national economies and public policies can be monitored. Moreover, the Arab countries must pay attention to give definitions for concepts of environmental migration and environmental refuge to be included in their systems and pave the way for preparing adaptative policies, strategies, and plans concerning displacement and forced migration. The Arab countries are not decisive in including concepts of environmental migration and environmental refuge when the case is associated with conflict over limited resources or forced migration [5]. The Arab states' migration policies, particularly those concerning migrants to the Arab states of the Gulf, should be integrated in the perspective and plans of adaptation to climate change and environmental hazards.

All the above mentioned procedures should be supported with comprehensive regional and territorial research plans discussing the various issues and topics associated with links between climate change, mobility, and security in the Arab world in general, and in the Arab states of the Gulf in particular. The following schedule, that is not inclusive at all, highlights the research areas and topics that may be most important in the future.

CONCLUSION

The analyses of issues that have been discussed in this chapter affirms that the links between climate change, displacement, conflict, and security seem to be unclear and complicated. However, we can not ignore that climate change and variabilities may lead to insecurity in some cases, particularly what are associated with human security aspects. Subsequently, streams of population displacement and climate migration may occur.

Therefore, more research efforts should be made to monitor, define, and understand the existing and potential links between climate change, displacement, and security in the Arab world. The climate change and variabilities should be considered as threat multipliers affecting the human security aspects. Accordingly, security procedures should be taken, by the countries of the Arab Gulf in particular, to encounter these threats. The climate changes affecting some neighbouring Arab countries and the Horn of Africa may direct streams of displacement and population migration to the Gulf countries. This would create additional pressures other than the potential ones resulting from climate change.

Disagreement on the nature of links between climate change, displacement, conflict, and security can be discussed by preparing more innovative research and studies that present in-depth answers for some questions mentioned in this chapter. Moreover, the regional and case studies on specific local contexts should be submitted on a large-scale, provided the climate security of the Arab world in general, and the Gulf region in particular, is associated with climate security of other regions, such as Horn of Africa, and some Asian countries that are directly or indirectly near to the Arab world borders (ie. Central Asian states).

AREAS OF FURTHER RESEARCH

→ Concerning climate change research: Thanks to IPCC's efforts and various in-depth studies which it conducts, the global and continental impacts of climate change are well known. However, downscaling is still a necessary requirement for establishing plans and national plans, particularly in the Arab region.

→ Links between climate and population mobility: More studies are required to monitor and examine the nature of existing and potential relationships between climate change and population mobility in the Arab countries.

→ Climate change and local conflicts: It is necessary to pay attention for examining the existing conflicts in some Arab regions. Accordingly, climate change impacts on the scope, nature, and regional consequences of these conflicts can be monitored. This particularly applies to streams of displacement or refuge.

→ Climate change and human security aspects: It is necessary to prepare a multidisciplinary and integral research program for tracking the existing or potential challenges and threats associated with climate change and their impacts on the aspects of Arab human security, particularly food security and health security, and climate migration.

→ Human mobility and climate migration: it is necessary to support evidence-based research on internal and international climate migrations and their relationship with security on the national and regional levels in the Arab world in general and in the Arab Gulf in particular. These research should indicate the potential numbers of climate migrants and their legal status and

should present a flow chart on an international or Arab treaty that shows the rights of those migrants and the countries' future obligations. However, the national security requirements of such countries must be considered and the national security scope of the countries of the Gulf Cooperation Council should be broadened. Accordingly, the Arab Gulf countries start to settle the surrounding conflicts then extend their efforts include the Horn of Africa region from which millions of environmental migrants may move to the Arabian Peninsula to flee from conflicts and climate changes.

→ Innovation and cooperation in the climate action: The best practices include supporting the innovative research and cooperative initiatives between governmental agencies, research centers, civil society institutions, and concerned international organizations. Accordingly, programs and plans for reinforcing the climate resilience capacities of community dwellers in the most vulnerable areas in the Arab countries.

→ There are many environmental indications and evidence that climate change may affect most Arab Gulf countries. This can motivate the in-depth examination of local and regional impacts of climate change. Moreover, more research should be submitted for exploring the climate change impacts on the Arab Gulf countries economies, industries, urban centers, and development pans as a whole. The innovative research in this field may be an excellent opportunity for all higher education institutions which have been established in the Arab Gulf countries according to international standards.

POLICY INSIGHTS

GLOBAL EVIDENCE FROM J-PAL OF EFFECTIVE POLICIES ADDRESSING SELECT TOPICS IN LOW INCOME DEVELOPING NATION

BOX 1

INSIGHTS FROM GLOBAL EVIDENCE: CASH AND FOOD TRANSFERS TO SUPPORT LOW-INCOME HOUSEHOLDS | J-PAL Policy Team

Low-income households are particularly vulnerable to food price shocks as they spend a substantial portion of their income on food. Randomized impact evaluations in many countries around the world have shown that cash and in-kind voucher transfer programs can be effective policy tools to support the well-being of low-income households. There are three common ways of delivering social assistance: cash, direct in-kind transfers (like direct distribution of food), and in-kind transfers delivered through vouchers, redeemable for tar- geted goods at merchants.

Evidence finds that cash transfers increase spending on productive, health-enhancing goods, with no evidence of wasteful spending. Evaluations of unconditional cash transfer programs have demonstrated that households receiving transfers are more likely to invest in their priorities, including increasing savings, investing in agricultural inputs, livestock, or durable assets, paying down debt, and increasing their food consumption [1-5]. In Burkina Faso, Kenya, Rwanda, and Zambia, households receiving an unconditional cash transfer prioritized spending on food and often consumed nutritious meals more regularly compared to non-recipient households [2, 3, 5, 6]. Almost without exception, results from Latin America, Africa, and Asia suggest transfers do not significantly increase consumption of "temptation goods" like alcohol and cigarettes [7].

Cash transfers did not discourage recipients from working. Seven randomized evaluations of cash transfer programs, found that the assistance did not affect the number of hours worked or the propensity to work, for either men or women [8].

In Indonesia, moving from in-kind direct food provision to in-kind voucher transfers greatly reduced poverty [9]. A study evaluating the impact of the national transition from an in-kind direct transfer program to a voucher transfer program found that the change from in-kind food transfers to vouchers led to an increase in subsidies received by eligible households, thanks to better targeting. As a result, poverty fell by 20% among the poorest households [9]. Vouchers also allowed households to purchase higher-quality rice, and led to increased consumption of egg-based proteins.

Overall, average rice prices were not affected by the transition, except for in the most remote villages (where rice prices increased by 3.6%) [9]. In short, the vouchers delivered greater poverty reduction than direct food provision at a lower administrative cost.

BOX 2

INSIGHTS FROM GLOBAL EVIDENCE: EFFECTIVE REGULATION TO REDUCE AIR POLLUTION | J-PAL Environment, Energy, and Climate Change team

Technological innovation has improved human well-being in countless ways, but clean air has no substitute. Air pollution is one of the greatest threats to human health globally, causing 4.2 million premature deaths every year [10], and low air quality in large cities in the GCC is a primary threat to public health [11].

The same activities that generate carbon emissions—most prevalently, the combustion of fossil fuels—generate other pollutants such as particulate matter. These co-pollutants have immediate and local effects on health and productivity, cutting the average person's life short by nearly 2 years [12]. Unlike greenhouse gasses, which are global pollutants, local pollutants can be tackled by national or even city and state governments. At the same time, cleaning up local pollutants can lead to climate co-benefits, as is the case, for example, when a coal-fired power plant is replaced by one that burns natural gas.

EFFECTIVELY ENFORCING AIR POLLUTION REGULATION BY IMPROVING INDUSTRIAL POLLUTION AUDITS AND INSPECTIONS

Many countries have strong environmental protections, but limited resources for enforcement. Evidence from randomized impact evaluations in India shows that improving pollution regulation monitoring and enforcement, including by improving the quality of data regulators have on pollution and violations of environmental standards, can significantly reduce industrial pollution.

Evidence from a randomized evaluation in Gujarat, India suggests that improving the quality of third-party auditing, where auditors periodically take pollution readings at industrial plants and report them to regulators, may be particularly important in countries facing high levels of pollution. In many contexts, auditors face a conflict of interest between providing credible reports and maintaining business with their client firms who hire and pay them. Researchers evaluated the impact of a reform to the pollution audit system in Gujarat, India that made auditors more independent, on the truthfulness of their reporting and the behavior of the firms they audited [13, 14]. Increasing auditors' independence made them 80% less likely to falsely report a pollution reading as compliant with the relevant regulatory standard. In response to more accurate audits, industrial plants reduced pollution by 0.21 standard deviations (28%) [13, 14]. In another randomized evaluation with the same regulator, researchers found that giving government pollution inspectors discretion in which industrial plants to inspect, rather than randomly assigning inspectors to industrial plants, was more effective in improving pollution regulation enforcement because inspectors had information that allowed them to target inspections to higher-polluting firms [15].

EMISSIONS TRADING AND MARKET-BASED APPROACHES

Other approaches to pollution reduction may include market-based mechanisms, like cap and trade schemes, where the regulator sets an overall pollution cap and allows individual firms to buy and sell permits to emit pollution up to this cap. Market-based environmental regulations have the potential to abate pollution at a lower cost to firms, but are seldom used in countries where pollution levels are the highest. In a recent randomized evaluation conducted in partnership with the Gujarat Pollution Control Board in India, researchers found that industrial plants randomly assigned to participate in a new emissions trading market reduced particulate matter pollution emissions by 20-30% relative to control plants that remained in the command-and-control status quo regime [16]. Given these promising results, researchers are currently working with pollution regulators in several states in India to adapt, pilot, and scale similar emissions trading schemes.

TECHNICAL ANNEX

WATER RESOURCES IN SAUDI ARABIA: TRENDS IN RAINFALL, WATER CONSUMPTION, AND ANALYSIS OF AGRICULTURAL WATER FOOTPRINT

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KEY MESSAGES

→ The impact of climate change on natural water resources is minimal.

→ Surface water resources do not play an important reole in the kingdom's water supply due to the lack of rainfall and absence of permanent rivers.

→ Freshwater supply in Saudi Arabia relies on non-renewable groundwater and energy-intensive desalination driven by fossil fuels.

→ Increasing temperatures will affect freshwater use in Saudi Arabia due to increased evapotranspiration of crops and demand for irrigation in cities.

→ It takes up to three times more water to grow crops in Saudi Arabia compared to the global average.

ABSTRACT

Saudi Arabia is one of the most arid regions in the world. Average annual precipitation is about 50 mm/year across the Kingdom's territory, and it varies from as low as 20 mm/year in Empty Quarter desert to 500 mm/year in the mountain regions in the southern parts of Saudi Arabia. Limited natural supply does not satisfy the needs of the country in fresh water. Energy-intensive desalination, driven by fossil fuels, meets two thirds of municipal demand for freshwater, while non-renewable groundwater addresses most of agricultural consumption. Climate change has a small impact on water supply in Saudi Arabia, and precipitation did not change significantly over the last seven decades. However, increasing temperatures associated with changing climate greatly intensify the demand for fresh water, on top of the demand driven by the fast-growing population. Increased evapotranspiration of crops and irrigated vegetation in cities are the main contributors to this demand increase. We give an overarching view on the water resources in Saudi Arabia, both in terms of demand and supply. We show the broad picture of the kingdoms water use and its vulnerabilities. The analysis of the efficiency of water consumption is given with particular attention to agriculture that accounts for 67% of total freshwater consumption in the country.

INTRODUCTION

Several previous studies reported water resources and consumption trends in Saudi Arabia [1-5]. However, an updated analysis is necessary, because during the past several years Saudi Arabia has initiated significant changes in resource use, and various incentives have been introduced by the government [6,7]. Also, new datasets on precipitation and water use have been released [8,9], and consideration of the most recent data is crucial to produce relevant results. To our knowledge, there are no recent public reports that summarize water consumption at the country-scale in Saudi Arabia, with particular focus on agricultural sector, which is responsible for two-thirds of freshwater use in the kingdom [10]. Such studies are particularly needed nowadays, when groundwater resources have decreased in the region, and the impacts of climate change and associated temperature extremes drastically exacerbate with each decade [11,12]. A warmer climate increases demand for agricultural fresh water, changes thermal limits, and decreases yields of various crops [13,14].

There are multiple publications that focus on evapotranspiration of crops in Saudi Arabia [15-17]. There are also studies that show total water requirements of various crops, mainly focusing on date palms, a major non-forage crop in Saudi Arabia. Estimates of date palm tree water requirements vary from roughly 53 m^3 year in Qatif [18], to 136 m^3 in Najran [19], and 195 m^3 in central region [20]. Assuming date palm tree produces roughly 50 kg per year [21], this equates to 1-4 m^3 of water per kg of produce. Water use varies depending on a season and irrigation type. Date palm trees require nearly four times more water in August than in January [15]. Traditional surface irrigation method is more water intensive. Subsurface drip irrigation can decrease the water use significantly, to less than 40 m^3/palm tree [22]. However, there are no data available for the average water intensity of agricultural sector and water use per type of crop in Saudi Arabia, and this gap was addressed in our work by inferring the estimate based on available data on global water footprint of crops, and on water use by agricultural sector in Saudi Arabia.

MATERIALS AND METHODS

The dataset we used to extract the precipitation data is the latest fifth generation of the reanalysis of global climate from the ECMWF, or ERA5 [8]. The data are provided on a regular 0.25° latitude-longitude grid. We calculated data across Saudi Arabia [FIGURE 1B] as an average of the data points that fall within the boundaries of the country. We also accounted for the latitude cosine correction, as the distance that one degree latitude covers decreases with an approach to the poles. We compared the ERA5 data with the Ministry of Environment, Water and Agriculture (MEWA) data for 2010-2019 obtained via General Authority of Statistics (GASTAT) [9].

We accessed historical crop production data for Saudi Arabia from MEWA statistical reports 2018 and 2020 [10] for the period 2015-2020 excluding 2019, as no data are available for this year, and the Food and Agriculture Organization of the United Nations (FAO, [23]) for the period 1961-2020. MEWA and FAO statistics have one substantial difference. FAO data do not include forage crops statistics, while MEWA do. Total crop production in Saudi Arabia is reported as 6.1 million metric tons by FAO as opposed to 10.9 million metric tonnes by MEWA in 2020. Forage is the major crop type produced in Saudi, and it accounted for 42% of mass production in 2020. Data on production of non-forage crops between FAO and MEWA are similar, but not identical. For further calculations we used the 2015-2020 MEWA data, because it is a primary source.

METHODOLOGY TO ESTIMATE WATER FOOTPRINT OF CROPS

We calculated both theoretical and actual water consumption to grow crops in Saudi Ara- bia for the period 2015-2020. The theoretical value is based on the MEWA data for crop production and global average total water footprint1 values for these crops; hereafter, water footprint, obtained from [24, 25, EQUATION 1]. Actual water consumption for crop produc- tion is based on the MEWA data for agricultural water use. It is important to mention that total agricultural water use includes both regenerated and non-renewable water use. MEWA statistics for 2010-2019 reports only the non-renewable water use. To get the total value, we assume that regenerated water accounts for 20% of total agricultural water use, and this fraction is obtained from the 2020 data, FIGURE 3, 10. Next, we factored out water non-associated with crop production. This includes water for fish, meat, dairy, and eggs production. KAPSARC[2, 26] estimates it as 6% of total agricultural water use in 2012, or approximately 1570 million m^3. Because we do not have statistics on agricultural water use non associated with crops production on in the following years, we assume this frac- tion to be constant. The obtained value of total agricultural water use associated with crop production is reflected in FIGURE 5B and used to obtain the value of water use per unit of agricultural produce FIGURE 6A. We then compare the actual water consumed in Saudi Arabia for crop production with the average theoretical value. We assume that it takes X times more water to grow crops in Saudi Arabia than on average worldwide. X is the same for each crop, but changes over years. To get the X, we divide annual agricultural water use for crops production by theoretical water footprint EQUATION 2. This obtained number X varies slightly from year to year, and its value is between 2.6 and 2.9 based on the 2015-2018 data FIGURE 6B.

Cumulative global average water footprint of crops grown in KSA, liters =

$$\sum_{i=1}^{N} (\text{water footprint of crop}_i\text{, liters/kg} \cdot \text{annual production of crop}_i\text{, kg}) \quad (1)$$

$$X = \frac{\text{annual agricultural water use for crops production, liters}}{\text{cumulative global average water footprint of crops grown in Saudi Arabia, liters}} \quad (2)$$

RESULTS AND DISCUSSION

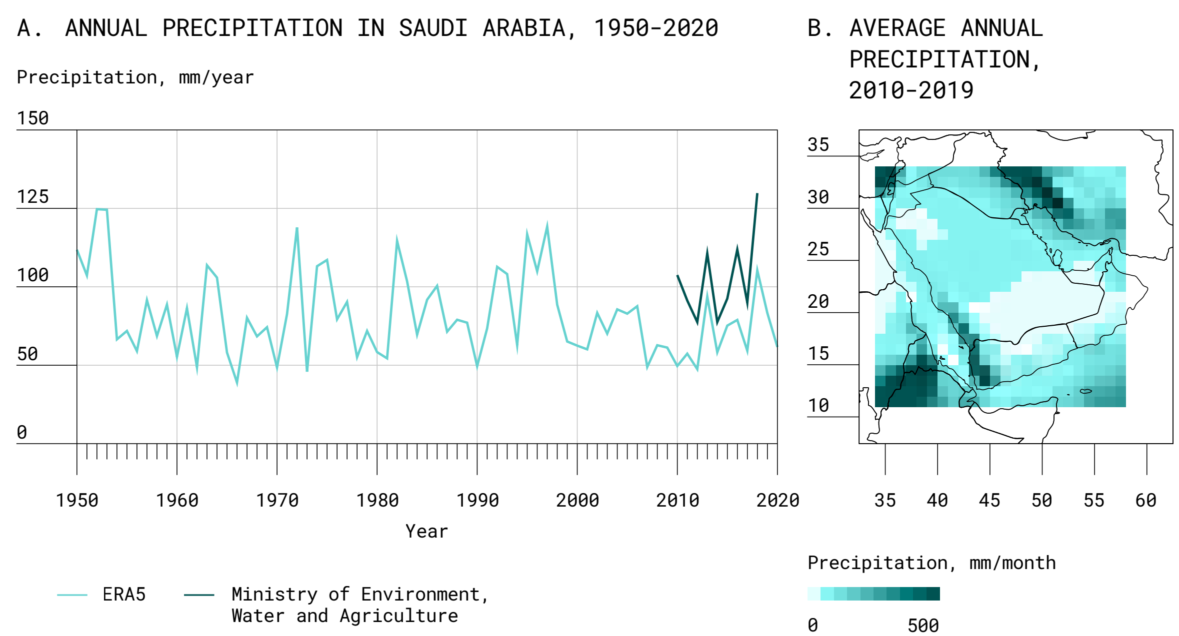
WATER RESOURCES — Saudi Arabia is one of the most arid regions of the world. Average annual precipitation is less than 100 mm per year across the most of country's territory and varies from as low as 20 mm/year in the Empty Quarter desert to 500 mm/year in the mountain regions in the southern parts of Saudi Arabia FIGURE 1. Average annual precipitation over the past 71 years is shown in FIGURE 1A, and precipitation change across that period is insignificant. Over the past decade 2010-2019, average precipitation across Saudi Arabia varied from 40 to 90 mm/year based on the ERA5 data, and from 60 to 130 mm/year based on the MEWA data obtained via GASTAT[9]. The discrepancy between the two datasets is caused by the different calculation methodologies: ERA5 is the global reanalysis data and encompasses the entire territory of the country, including the vast Empty Quarter desert,

while MEWA uses local data from the sparse meteorological stations, with the majority of them located near cities.

WATER CONSUMPTION — With almost no rain, there are no permanent rivers or lakes in the country. Few wadis and water dams cannot support the Kingdom's freshwater needs. Energy-intensive desali- nation driven by fossil fuels meets two thirds of municipal demand for freshwater, while non-renewable groundwater addresses 80% of agricultural consumption. Over the past years, water use has been steadily growing and peaked in 2015 at 24.8 billion m^3 FIGURE 2A, or 30 billion m^3, if regenerated water is included. Water use in 2015 was nearly 150% of that in 2010. In the following years, the total consumption started to decline due to the substantial decrease of agricultural water use, particularly after 2019, when the governmental program to stop forage cultivation has been initiated[10]. However, while water use in agricultural sector is declining, the municipal and industrial demand is accelerating each year due to the vast economic development and fast

[1] *Total footprint includes green, blue, and grey water footprint[24].*
[2] *King Abdullah Petroleum Studies and Research Center.*

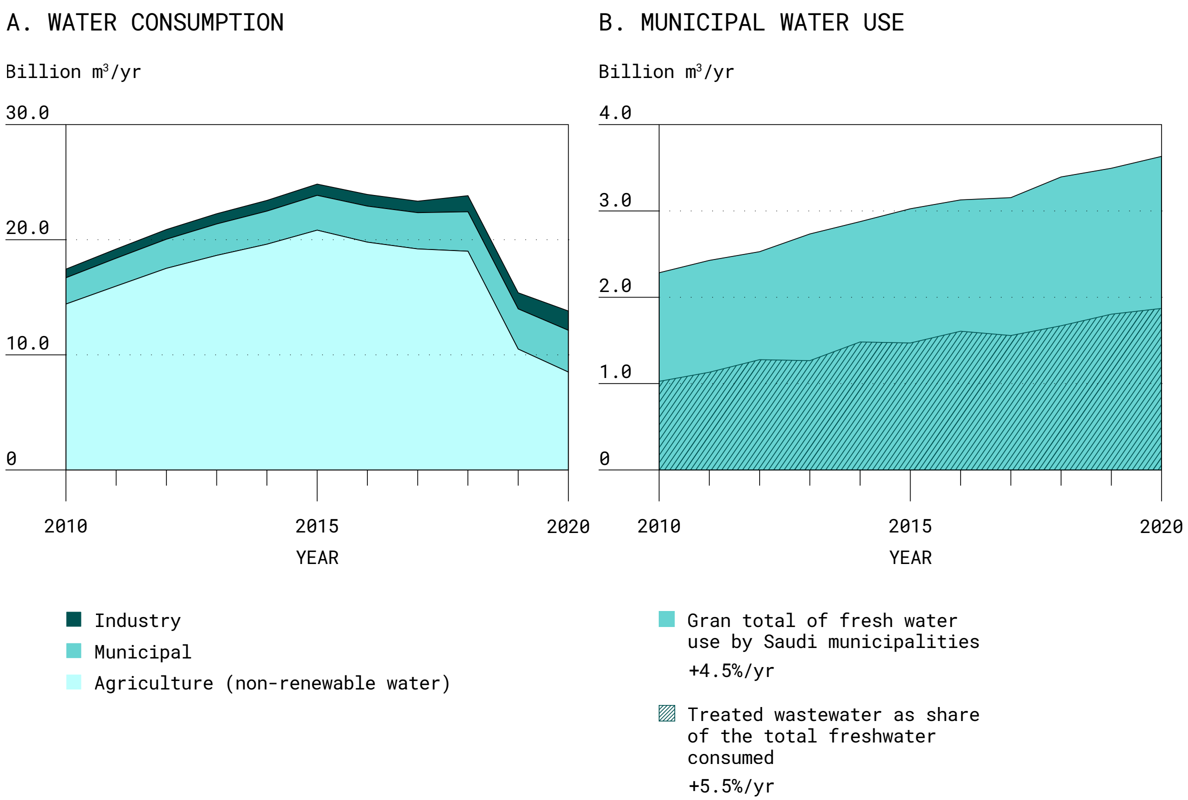
FIGURE 1 The 1950-2020 annual precipitation in Saudi Arabia and the 2010-2019 average precipitation.



Source: ERA5, MEWA.

Source: ERA5.

FIGURE 2 Water consumption by sector, exluding regenerated water use in agricultural sector and wastewater treatment share of total municipal water use.



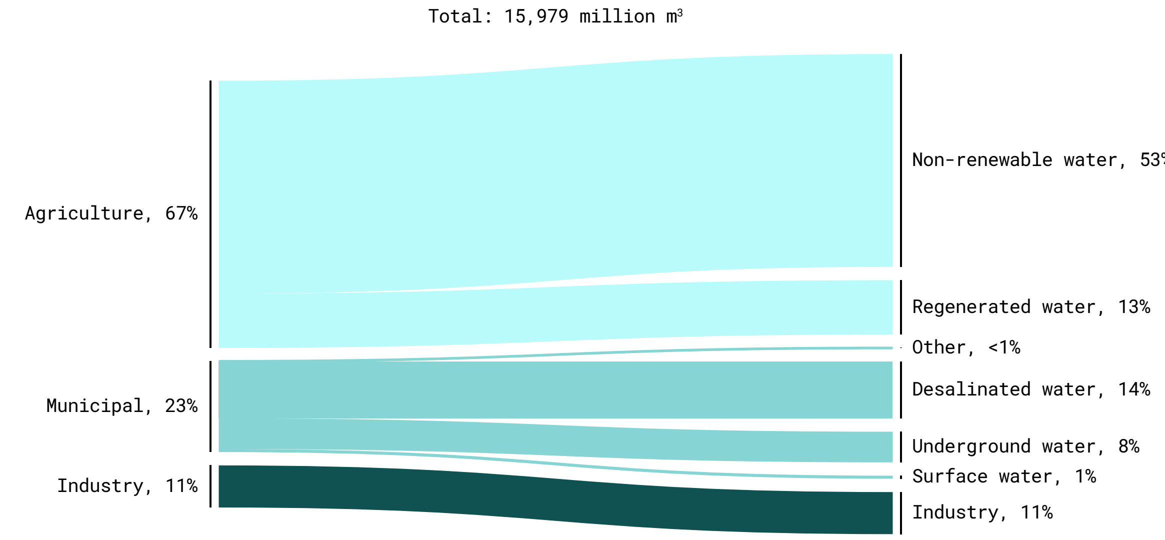
Source: MEWA

population increase. The water use by Saudi munici-palities has been increasing by 4.5% per year, while the volume of treated wastewater has been rising at a faster rate of 5.5% per year.

However, at present, only a half of the total volume of water used by municipalities is treated. The share of treated water was 52% of total domestic consumption in 2020 compared with 45% in 2010, see FIGURE 2B. It is important to emphasize that only 18% of treated wastewater is further reused (2020, [10]).

Presently, the total amount of water consumed in Saudi Arabia is nearly 16 billion m³ (2020), or 459 m³ per capita per year [1]. Of this volume, 11% is attributed to industrial consumption, 23% to municipal, and the rest is agricultural consumption FIGURE 3.

FIGURE 3 Water use breakdown in Saudi Arabia, 2020.

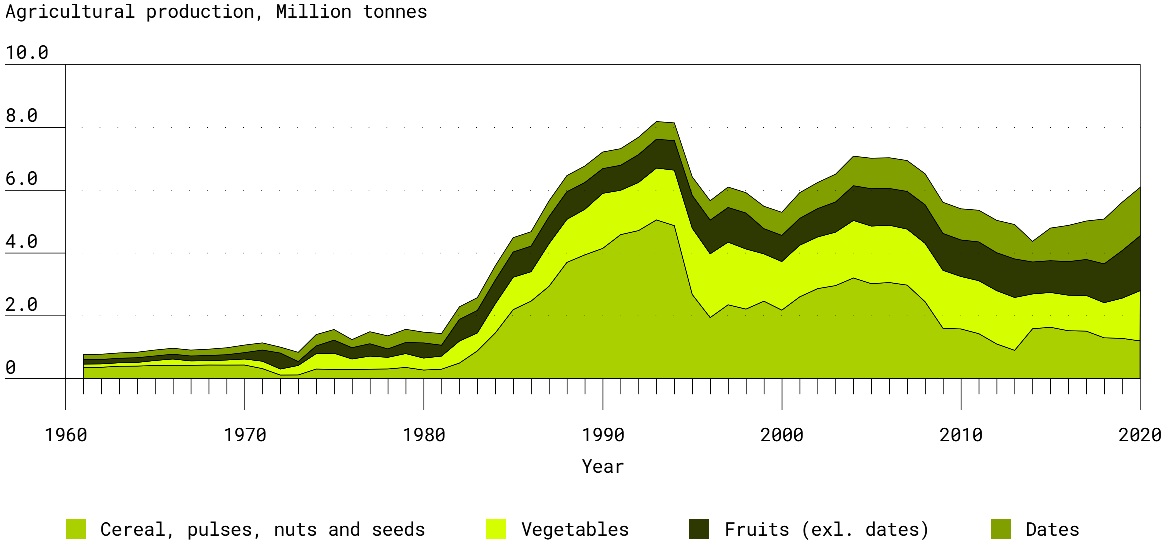


Source: MEWA

AGRICULTURAL WATER USE, PRODUCTION, AND EFFICIENCY — Despite having a hot desert climate, Saudi Arabia has a strong agricultural industry, owing to the rich non-renewable underground water resources [28]. At present, agriculture accounts for 67% of total kingdom's water use, or 62% if regenerated agricultural water is excluded. 80% of agricultural water consumption comes from nonrenewable underground resources, or 8.5 billion m³/year FIGURE 3. The remaining 20% is regenerated water, or 2.2 billion m³/year (2020, [10]). In previous years, agricultural water use was nearly twice as much as in 2020, reaching 20.8 billion m³/year in 2015 with 84% share in the total kingdom's water use (excluding regenerated water). The sharp decline in the non-renewable water use is due to the program of stopping fodder cultivation, which started in 2019.

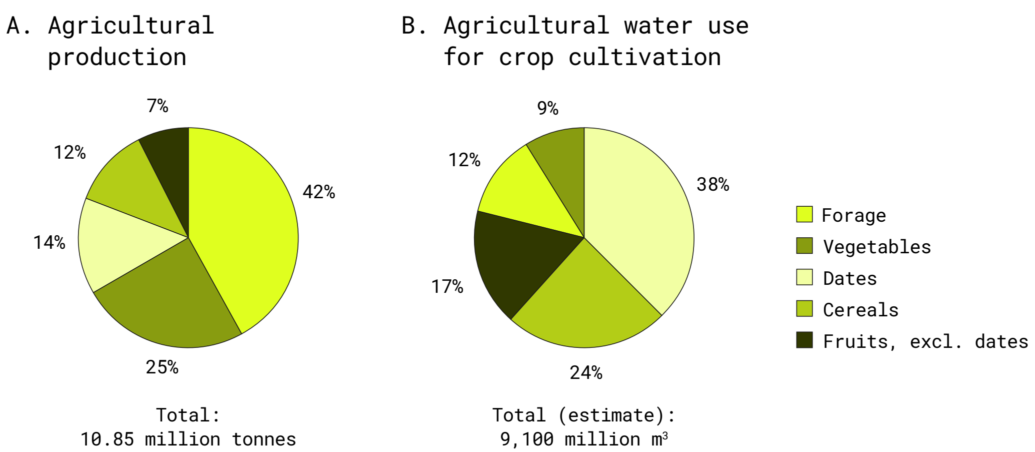
Agricultural production in Saudi Arabia started to grow rapidly since the early 1980s and peaked in 1994 at at 8.2 million tonnes for non-forage crops, mainly dominated by cereals. After a decline in production, the second peak was observed in the mid-2000s at about 7 million tonnes. 2020 is marked as the third historic peak: the production was 6.1 million tonnes, the highest value since 2008. Since 2010s, the production of water-intensive cereals has declined while the production of vegetables and fruits increased FIGURE 3. In 2020, according to MEWA [10] data, vegetables is the major non-forage crop type, followed by dates, cereals and other fruits. Forage is the major crop type

FIGURE 4 Agricultural production.



Source: FAO, excluding forage crops.

FIGURE 5 Agricultural production and water use in Saudi Arabia.



Source: Based on MEWA data (including forage crops).
Notes: Water use values are based on footprint estimates from [24,25]

that accounts for 42% of mass production FIGURE 5A, 6. However, mass production values do not represent the water use per crop type, as different crops have different water footprint. For example, forage has smaller water footprint compared with non-forage crops per unit of mass, and it accounts only for 12% of total annual agricultural water use. Cereals and dates have a relatively high water footprint. Date production is associated with 38% of agricultural water use, and cereals with 24%, while their share in mass production is 14% and 12% respectively FIGURE 5B. FIGURE 7, 8 Summarize top 15 crops grown in Saudi Arabia with the highest water intensity and total theoretical water use respectively. Actual water consumption is higher because of the hot desert conditions. In order to get actual water consumption, theoretical one is multiplied by a factor X FIGURE 6 for a given year, and discussed in the next paragraph.

Theoretical water footprint of agricultural sector in Saudi Arabia based on global average values [24, 25] was about 600 liters/kg of produce between 2015 and 2018. As mentioned in the previous section, in 2020, the production of forage crops decreased while production of vegetables and fruits increased, that led to an increase of average footprint value to 860 liters/kg FIGURE 9A.

FIGURE 6 Top 15 produced crops by mass in Saudi Arabia, 2020.

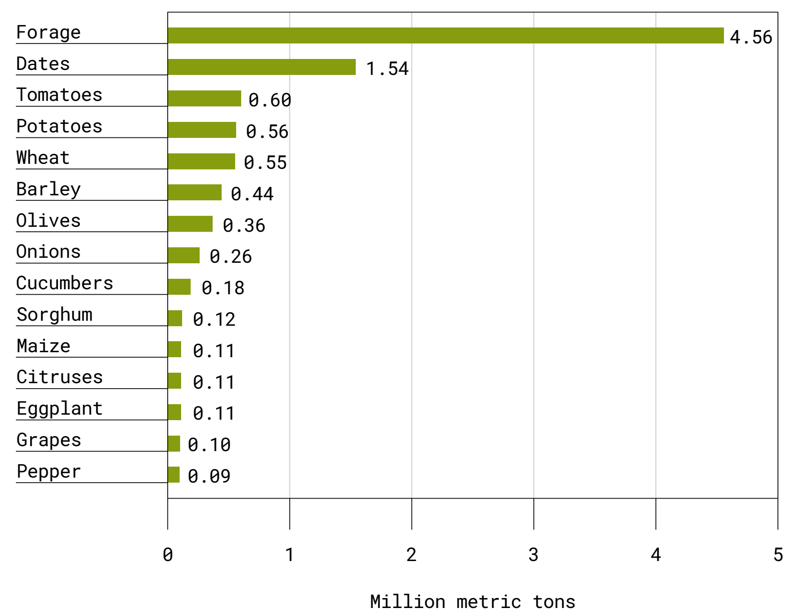


FIGURE 7 Top 15 crops by water intensity in Saudi Arabia.

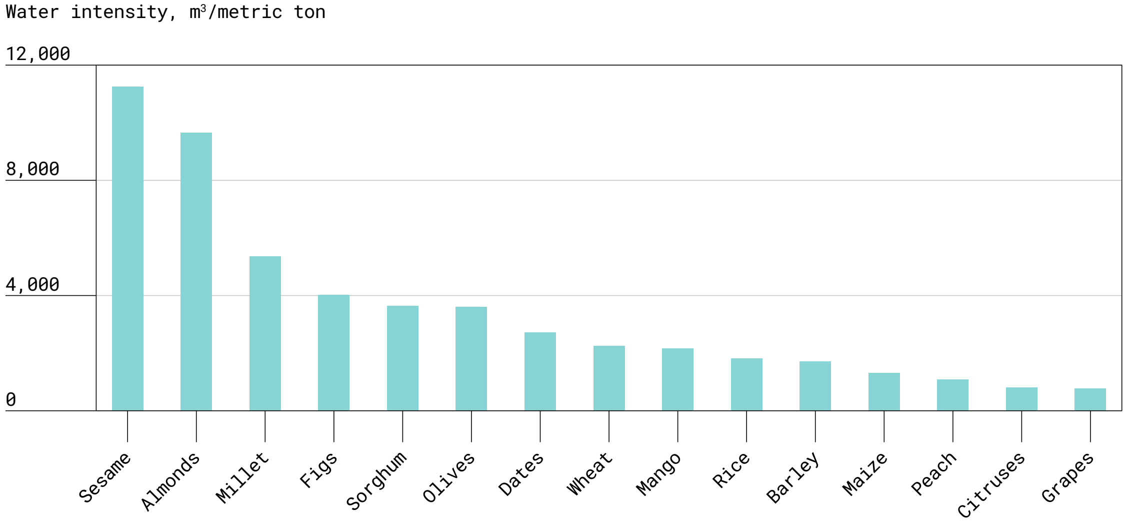
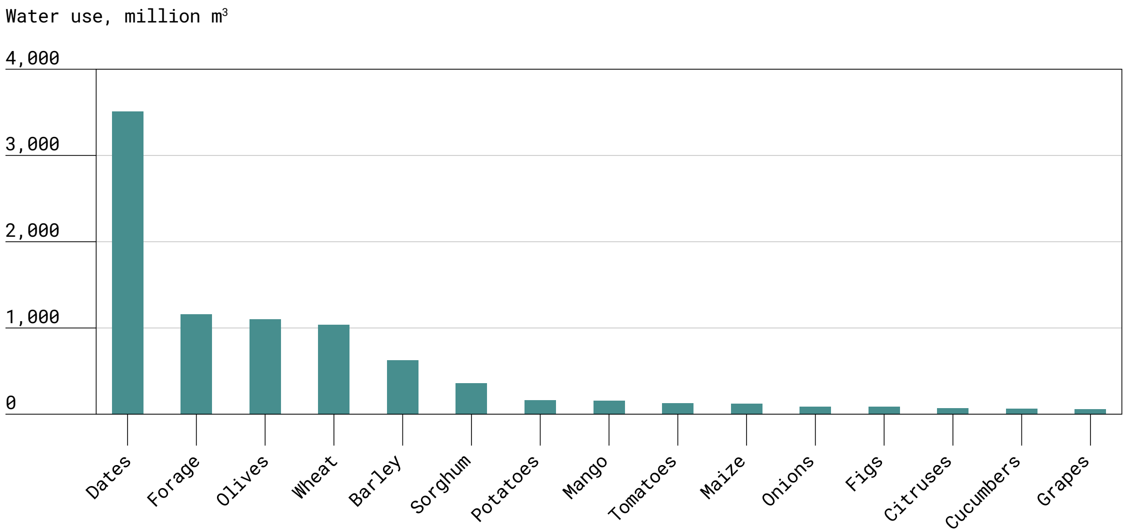


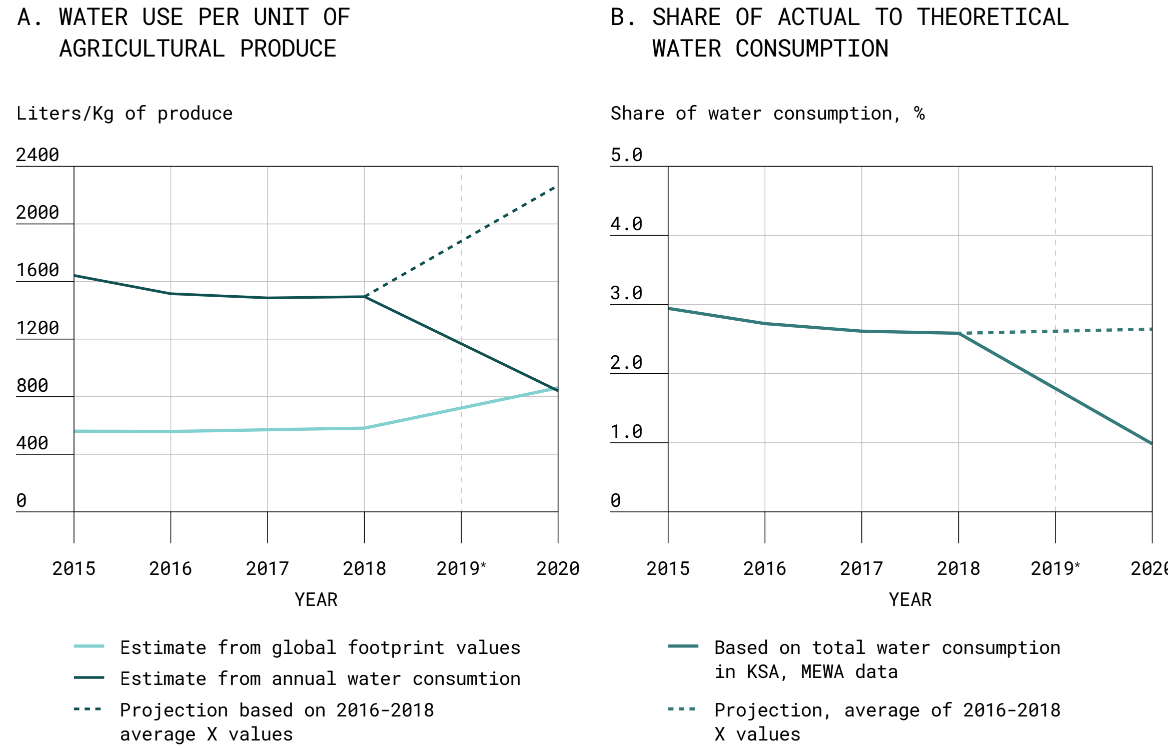
FIGURE 8 Top 15 crops by water use in Saudi Arabia, 2020.



Source: MEWA 2020 data for crops production and [24] data on global footprint of crops.

Note: Values are for theoretical water intensity based on global average values. Actual water intensity can be obtained by multiplication by a factor X for a given year, Figure 9B.

FIGURE 9 Efficiency of agricultural sector in Saudi Arabia: water use per unit of agricultural produce and share of actual to theoretical water consumption.



Note: 2019 data not available.

Actual water consumption which is based on data for annual water consumption associated with agricultural production varies between 1450 and 1650 liters per kilogram of produce between 2015 and 2018 FIGURE 9A. Share of actual to theoretical water consumption X was between 2.5 and 3 over the same time FIGURE 9B. Interestingly, the value of actual water footprint drops drastically in 2020, almost down to the theoretical consumption. This may be due to the underestimation of actual water use in 2020, that dropped significantly after 2019 FIGURE 2. We estimate the projected actual water footprint for 2020 as 2265 liters/kg based on 2016-2018 average X value.

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We would like to acknowledge the Copernicus Climate Change Service (C3S), a part of the Copernicus Earth Observation Programme of the European Union, and the European Centre for Medium-Range Weather Forecasts (ECMWF) for providing to us the open access, high-quality ERA5 hourly data on temperature and other weather parameters. Finally, we acknowledge FAO for their open source data on the production of the agricultural sector in Saudi Arabia, and open source publications on the global average water footprint of crops[24, 25]. This research was funded by the KAUST baseline research funds to Professor Patzek.

AREAS OF FURTHER RESEARCH

- → Role of wide scale application of smart watering techniques and meters in agriculture. Examples include subsurface irrigation, drip irrigation, hydroponics. Expansion of production of low-water intensive and salt-water tolerant crops
- → Evaluation of policies to increase the share of treated municipal wastewater and its further reuse

IMPACT OF TEMPERATURE ON ENERGY SECTOR IN SAUDI ARABIA

Natalia Odnoletkova,
Tadeusz Patzek

KEY MESSAGES

- → Future temperature increases due to global warming will elevate demand for electricity in Saudi Arabia beyond the increases due to other driving factors such as growing population.
- → For days when cooling is required, one degree of temperature is associated with a 4.5% and a 5.4% rise in electricity generation in the Central region and more humid Western region respectively.
- → Rising temperatures negatively affect thermal power plant efficiency, which increases primary fuel consumption.
- → Daily temperatures above 40°C, may induce rolling power blackouts.

ABSTRACT

Saudi Arabia is one of the warmest places on Earth, already setting new records in summer maximum extremes beyond the human adaptation abilities. In addition to the already hot climate, the country is experiencing severe heating trends that surpass the rate of global warming. The assessment the impact of climate and temperature in particular on energy sector is of vital importance, because energy is sustaining the lives of more than thirty million residents of the Kingdom of Saudi Arabia by providing life-essential cooling and desalinated fresh water in a hot desert climate. We show that power generation in the Kingdom is very sensitive to outdoor weather conditions. Average daily summer generation is almost two times that in winter. One degree of temperature increase is associated with a 4.5% rise in electricity generation in the Central region and 5.4% in the more humid Western region for days when cooling is required. Without continuous access to electricity, city-dwellers will perish in the ever-hotter environment. It is vital to ensure stable and robust electrical power supply to make Saudi Arabia more resilient in the face of supply limits and disruptions.

INTRODUCTION

The Kingdom of Saudi Arabia is characterized by a desert climate[1] with average yearly temperatures above 26°C. Average June-August temperatures are above 35°C with daily maxima reaching 45°C in most regions of the country. In addition, the country is subject to a severe impact of climate change. The rate of temperature increase across Saudi Arabia is 50% faster than over Northern Hemisphere land and almost 3 times the rate of average planetary warming. Summers are warming faster than winters in Saudi Arabia, driving a surge in humidity[2] that puts additional load on the air conditioning systems. This increase of thermal discomfort will continue in the future[3,4], putting at risk the ability of people to adapt to outdoor conditions without continuous access to air-conditioning.

Hot conditions are responsible for the high cooling load, which accounts for two-thirds of all electricity use in households in Saudi Arabia[5]. However, there is a lack of studies that document the sensitivity of power use to ambient conditions in Saudi Arabia, which is an important factor in assessing the quantitative impact of rising temperatures on energy demand. [6] conducted such an analysis using hourly power generation data and hourly temperature across a period of one year and for each of the four seasons of the year separately. The use of hourly data provides some advantages, such as a large statistical sample size. However, it is difficult to account for a lag of one or two hours due to delayed power consumption response to ambient conditions. Our approach is different and based on weekdays' daily temperatures and power generation. Instead of using seasons, we segregated days using a threshold 20°C daily average temperature to

disaggregate days when cooling is required. This allows us to improve the sensitivity prediction.

In this work, we show the influence of ambient temperature on demand for electricity. The current assessment should help the Kingdom to prepare better for the inevitable future impacts of climate change and to avoid possible catastrophic disruptions of vital commodities such as cooling.

MATERIALS AND METHODS

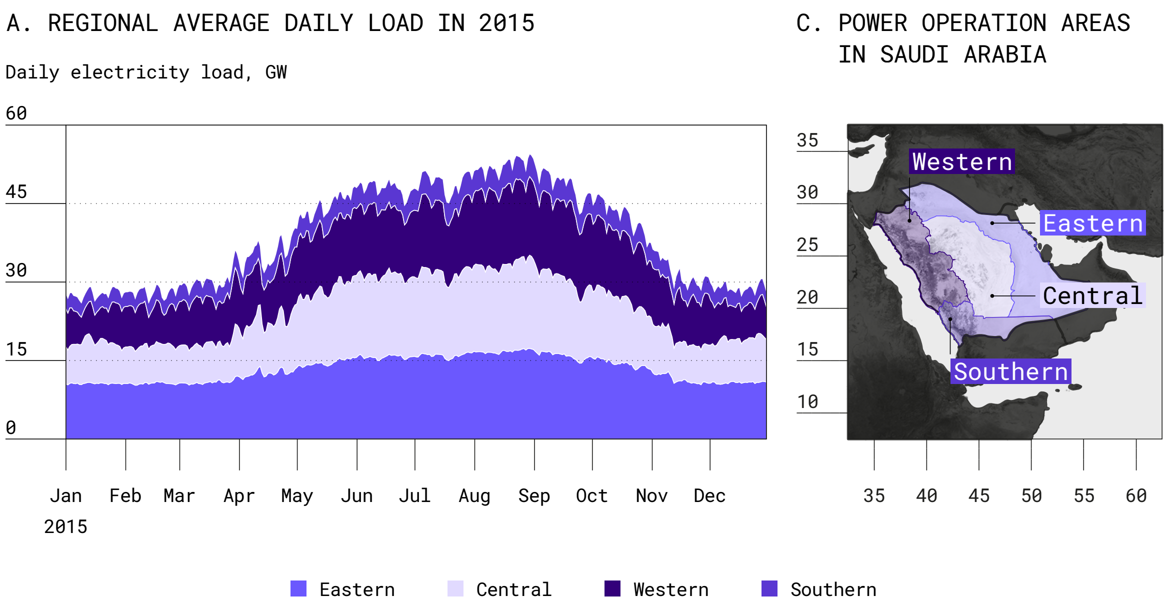
The dataset we used to extract the temperature data is the latest fifth generation of the reanalysis of global climate from the ECMWF, or ERA5[7]. The data are provided on a regular 0.25° latitude-longitude grid. To obtain data for Riyadh and Jeddah we used 24.75N 46.75E and 21.50N 39.25E coordinates, respectively. Linear trends in temperature-electricity dependence are obtained using the "fitlm" function in MATLAB. We use Pearson's correlation coefficient ("corrcoef" function in MATLAB) to study the relationship between power consumption and temperature.

Data on electricity generation in the Western and Central regions of Saudi Arabia in 2015 are obtained from the Saudi Electricity Company (SEC), the major electricity provider in the kingdom[8,9]. Data do not include transmission and distribution losses.

RESULTS AND DISCUSSION

Saudi Arabia is divided in four regions by power generation [FIGURE 1]. Eastern, Central and Western regions have relatively similar level of consumption, while less populated Southern region has the smallest share of total electrical consumption. Average daily electricity load across a year is 39 GW (2015). The load is very sensitive to weather conditions and varies from as low as 23 GW in winter to almost 60 GW in summer. Daily load curves averaged for each month are presented on [FIGURE 2]. Variations are the highest in summer, when the difference between off-peak and peak consumption reaches 13 GW, or 20% of total SEC capacity for that year (2015). In summer the peak is observed at 3 pm, while in winter it shifts to 6-7 pm due to the decrease in cooling demand.

FIGURE 1 Regional average daily load in 2015 and power operation areas in Saudi Arabia.



IMPACT OF TEMPERATURE ON POWER GENERATION

Climate change has a two-sided impact on the energy sector: 1) increased demand for electricity due to increased need for cooling, and 2) decreased efficiency of thermal power plants (which produce all electricity in the Kingdom [8]) as a result of an increase in ambient temperature.

Efficiency of a thermodynamic cycle depends on the difference between the maximum and minimum temperatures between which this cycle operates. Conventional power plants utilize gas or steam turbines to generate electricity, and maximum temperature is at the inlet of the turbine, while minimum temperature is either ambient temperature (gas turbines) or temperature of cooling water (steam turbines), which is also a function of ambient temperature. Studies suggest that the average loss in electrical output is about 0.3-0.7% per 1°C of air temperature increase [10–15]. Unfortunately, nothing can be done to decrease this loss of efficiency attributed to an increase in ambient temperature. It is not only conventional fossil-power plants that are negatively affected by rising temperatures. The similar decreases of efficiency impact nuclear, solar thermal and PV plants [16–19], which are set to play an important role in the future energy supply in the Kingdom [20]. Lack of data limits our understanding of the impact of ambient temperature on the efficiency of power plants in Saudi Arabia.

To illustrate the influence of temperature on electricity demand, we show the scatterplot of daily temperature and daily electricity generation in the most populated Central and Western operation regions [FIGURE 3]. The Central region includes Hail, Qassim, and Riyadh provinces with more than 50% of the region's population concentrated in the capital, Riyadh, which is home to 7.3 million people (estimate for 2021 [21]). Western power operation region includes Makkah, Madinah, and Tabuk provinces, with 71% of the population living in Makkah province (based on the estimated data for 2017 from [21]) with Jeddah and Makkah being the second and third largest cities in Saudi Arabia (4.7 and 2.1 million residents respectively, estimated for 2021 [21]). We use Riyadh and Jeddah as representative cities for the Central and Western regions, respectively, to obtain temperature data.

There is a strong positive correlation ($r > 0.95$) between temperature and electrical generation for warm days with daily temperature exceeding 20°C. This correlation highlights the fact that power demand is very sensitive to ambient weather conditions. In the Central region, during warm days, each 1°C of daily temperature increase is associated with a 13.8 GWh increase in daily electrical generation, or 4.5% from an average value for warm days (306 GWh). For cold days with the average daily temperature below 20°C, there is a negative correlation between temperature and electricity due to the demand for heating, although this correlation is weaker than the one for warm days ($r = -0.80$). Each 1°C of daily temperature decrease is associated with an increase of daily electrical generation by 4.3 GWh, or 2.3% from an average daily value for cold days (185 GWh), see [FIGURE 3A]. In the more humid Western region, power generation is even more sensitive to outdoor conditions. Based on the linear trend, an increase of 1 °C adds 15.3 GWh to the daily electricity production, or 5.4% from an average value for warm days (255 GWh). However, the shape of the scatterplot suggests that an exponential rather than linear plot describes better the observed relationship between temperature and power generation [FIGURE 3B].

New buildings should be designed and built according to the best energy efficiency standards to minimize the demand for cooling and decrease peak power consumption. Sustainable off-grid energy production will help to further decrease the grid load variations and ensure the reliable supply of energy for cooling. Examples of such solutions that minimize the intake of electricity from the grid include solar air conditioners and heaters, and rooftop/neighborhood PV arrays. In case electricity supply must be curtailed, community heat emergency centers should be established in shopping malls with redesigned restroom facilities.

FIGURE 2 Daily load curve averaged for each month, 2015.

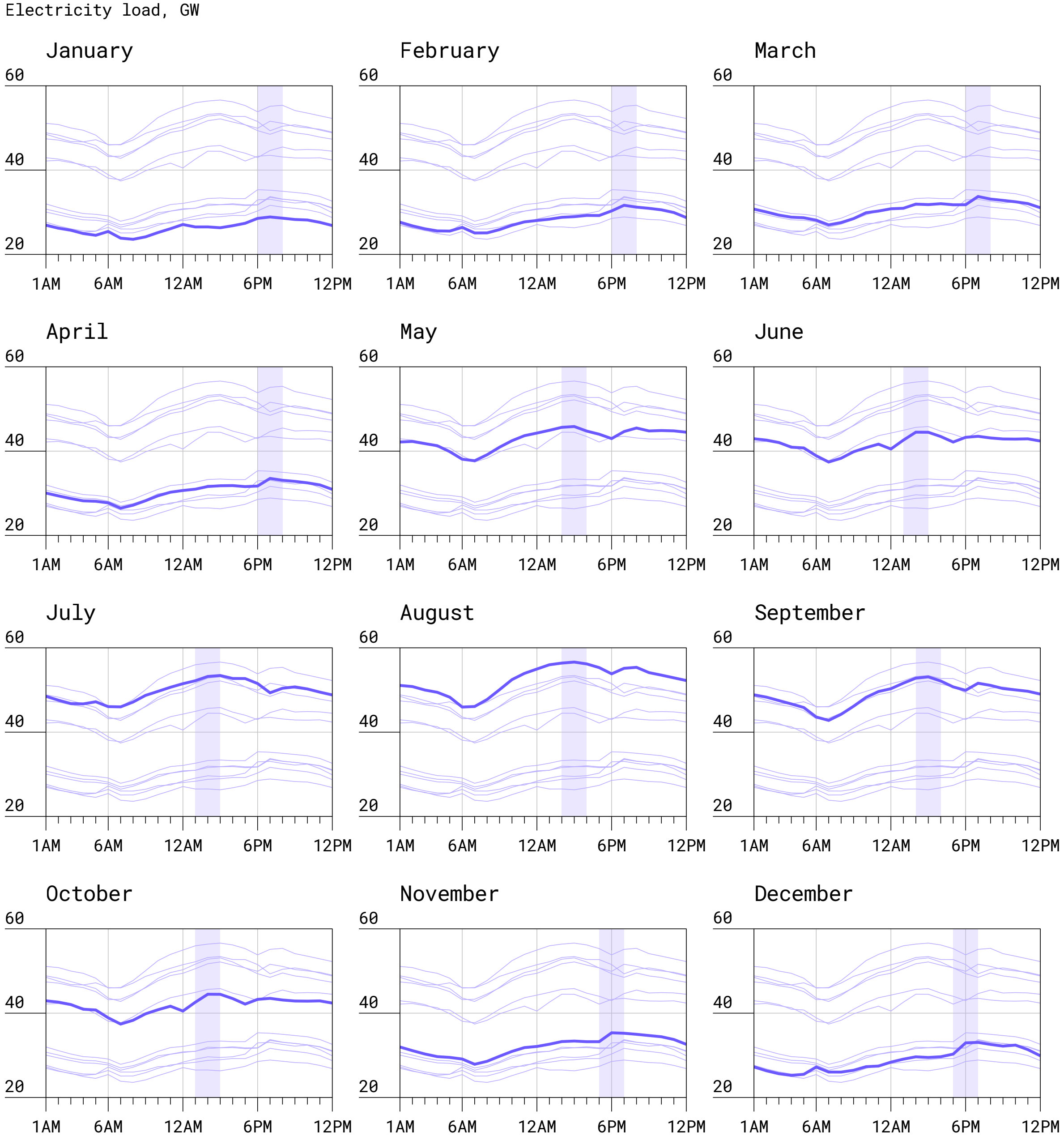
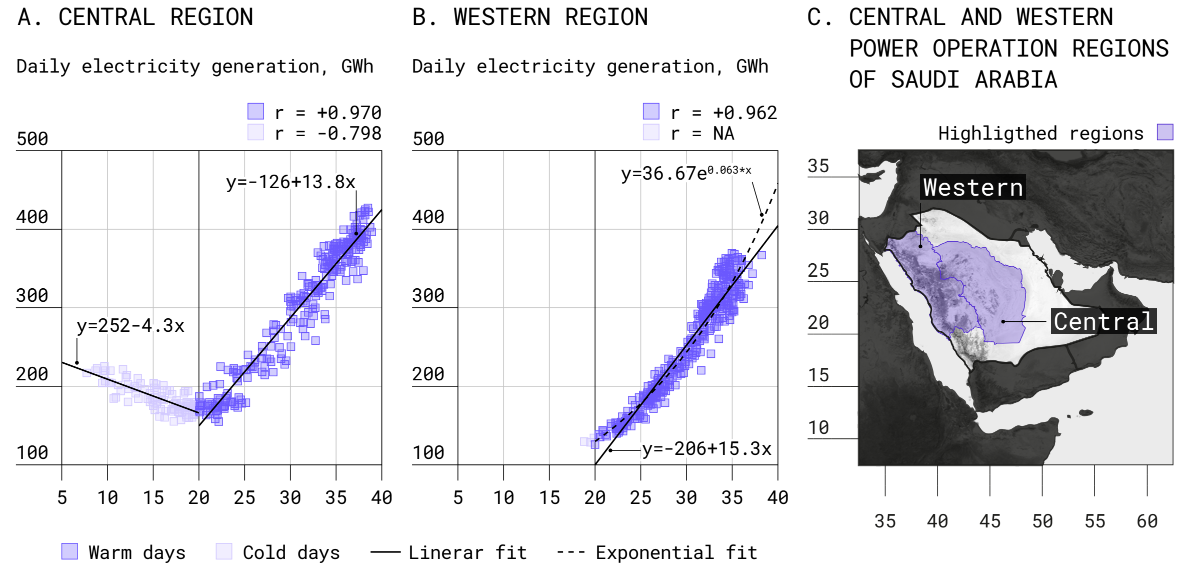


FIGURE 2 Daily temperature in Riyadh and electricity generation in Central power operation region and daily temperature in Jeddah and electricity generation in Western power operation region.



Note: Data are shown for 2015 and exclude weekends and holidays. Notice that should temperature exceed 40°C, electricity demand in the Western Region will surpass 0.45 TWh/d, and rotating blackouts be likely introcoduced.

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AREAS OF FURTHER RESEARCH

→ Evaluation of incentives aimed to decrease peak consumption.

→ Assessing the application of high-efficient AC units applicable for local climates, centralized cooling systems, and improvement of energy efficiency standards in buildings.

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2.6 POPULATION GROWTH’S MULTIPLIER EFFECT ON CLIMATE IMPACTS

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3 QUESTIONS ARISING: EMERGING EVIDENCE OF IMPACTS OF CLIMATE CHANGE ON CRITICAL GLOBAL ISSUES

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3.4 THE LINKS BETWEEN CLIMATE CHANGE, DISPLACEMENT, AND SECURITY

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TECHNICAL ANNEX

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ARTS & CULTURE CAN BE HEALING — THE GOOD NEWS IS: ARTS AND CULTURE ARE NOT REDUCED TO A “NICE TO HAVE” ANYMORE!

In these difficult times that are still marked by the pandemic, war and other fundamental issues like climate change and health risks, the position of arts and culture has increasingly become central in today’s troubled world. Not only have artists the ability to make the world a more beautiful place with their esthetical creations and build bridges among different cultures and religions around the globe. They are also able to find varied forms of expression to facilitate communication on worrying issues like climate change or mental health, breaking it down to transmitting messages in different ways without though staying light or shallow on their deep messages about these complex issues. Sometimes their statements in their art works are stronger than words and touch immediately the senses and emotions of the viewers; one can argue that the messages get understood on a different level than political statements by some political or financial leaders.

These often also critical creative minds have also the ability to put their finger in an open wound, trying to shake us all up on how things going in the wrong direction in our world. What maybe have been put aside as some isolated “agents provocateurs” in the art scene in the past, today’s artists are not willing to shut up, nor to stay inactive on these themes anymore; they have recognized the urgency to denounce and act in order to save what has remained of the planet. The theme of health has obviously become a central theme in all public discourses and especially in artistic circles the sensibility towards health and climate change are very high. Artists and culture creative workers seem to have a more focused sensitivity towards these complexities and also a strong will to express this through their work. Taking for example the question of physical well-being in the arts, this theme has been present since ever and it is as old as the arts themselves. For very long the intuitive interpretation and different expressions in arts & culture has been able to dissect intrinsic systems like the body, sickness, recovery, effects of medicine or climate factors that show in the works of creatives.

In order not to stay a small or isolated group of people, the entire cultural humus needs to adapt and support concrete actions against climate change or delicate health. It is not enough that some creatives do beautiful or denouncing works for specific shows, the entire arts sector has to walk the talk itself and become more sustainable and integrated in the powerful world of decision makers.

With a certain degree of optimism, we have observed in the past few months that health risks and climate change have accelerated the recognition that arts and culture can have a healing factor in the different distresses present today. Not only scientists doctors or exponents of the creative sector have put forth the positive effects of arts and culture on mental and physical health, but also a broader group of people got a heightened alert around topics of climate change thanks to the emotional messages in the arts. This growing recognition of many leaders of the beneficial outcome of these humanistic disciplines on the overall health of society has also led to a positive and accelerated creation of entire arts and culture sectors within important international organizations such as WHO, the ICRC or WEF. In order to show today’s leadership the beneficial effects of the well functioning creative sector for the well-being of the entire society. These may only be the first baby steps in showing the world how arts and culture can have a positive influence in order to raise awareness around urgent crisis and give some instrument of soothing and to maybe overcome such times of trouble.

Of course the exact scientific effects have still not be proven a 100% but the actual positive and sometimes alarming vibes coming from the creative world in relation to climate change and health aspects have been registered by many. It is too early to be totally optimistic on the beneficial effects of culture overall and many open questions remain. But the time is ripe to at least raise some questions that might become more central in the near future in a similar report as the present one. The aim is therefore to spark off an open debate on the possible positive effects of arts & culture on the actual well-being of entire societies and our planet as a whole. Even if it remains an inexact science or intangible concept in regards to complexities as discussed in this report, the sheer recognition of a growing community who believe in the power of arts and culture for a better world, might be enough for now but will spark off an essential dialogue for a sustainable future.

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