AGEDI

مبادرة أبوظبي العالمية للبيانات البيئية

Abu Dhabi Global Environmental Data Initiative

an initiative of

UNEP

هيئة البيئة - أبوظبي

Environment Agency - ABU DHABI

LOCAL, NATIONAL, REGIONAL CLIMATE CHANGE PROGRAMME

REGIONAL ATMOSPHERIC MODELLING

Technical Summary

Climate Change Research Group

NCAR

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

This Technical Report has been prepared by David Yates, Principal Investigator from the National Center for Atmospheric Research (NCAR).

This report was prepared as an account of work sponsored by the Abu Dhabi Global Environmental Data Initiative (AGEDI). AGEDI neither makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, nor usefulness of the information provided. The views and opinions of authors expressed herein do not necessarily state or reflect those of EAD or AGEDI.

Published by: Abu Dhabi Global Environmental Data Initiative (AGEDI), 2016.

Recommended Citation: AGEDI 2016.
Technical Summary Regional
Atmospheric Modelling.
LNRCCP. CCRG/NCAR.

AGEDI and EAD promote environmentally sound practices globally and in their own activities. This publication is printed on ecological paper. Our distribution policies aim to reduce our carbon footprint.

Local, National and Regional Climate Change Programme 2013-2016

Socioeconomic Systems	Regional Climate Change	Environment	Coastal Zones	Water Resources
Public Health Benefits of GHG Mitigation (L)	Atmospheric Modelling (R)	Terrestrial Ecosystems (R)	Coastal Vulnerability Index (N)	Al Ain Water Resources (L)
Food Security (N)	Arabian Gulf Modelling (R)	Marine Ecosystems (R)	Sea Level Rise (R)	Water Resource Management (N)
Desalinated Water Supply (R)				Transboundary Groundwater (R)

L=Local N=National R=Regional

5 Thematic Areas 3 Spatial Regions 12 Sub-projects

12 Sub-projects
Assess the Impacts, Vulnerability & Adaptation to Climate Change in the Arabian Peninsula

Introduction

Background

This goal of this Regional Climate Modelling Activity was to develop projections of regional climate for the Arabian Peninsula at fine spatial and temporal scale, that reflect the large-scale features and temporal trends from Global Climate Model (GCM) simulations (AR5), but also the historical patterns of climate variables at the regional and local scale (Fowler et al. 2007; Wood et al. 2004). To achieve this, a regional climate model (RCM) was deployed that dynamically downscaled the climate of the Arabian Peninsula using GCM data for lateral boundary conditions.

Improved topographic representation across the domain reflects the taller topographic features of the region, which potentially increases and re-distributes precipitation due to enhanced lifting. The taller topography also provides a cooler environment for precipitation over places like the Oman Mountains as compared to smoothed topography, which will not resolve warm season convection. The data can be used in support of the other climate change impact, vulnerability and adaptation assessments.

The climate and hydrometeorological data from this study can be used to explore questions surrounding groundwater recharge and water demand questions; explore renewable energy prospects, especially solar and wind; as changes in wind-patterns, cloudiness, and how changes in aerosol concentrations due to industrial activity or dust from the vast Arabian Desert could impact these resources; understand how potential impacts of climate change and variability on terrestrial ecosystems (Activity #13, "Key terrestrial ecosystems and species" and human health related impacts of climate (Activity #6, "Public health and greenhouse gases"). Projections of future climate change from this sub-project will provide insights into the vulnerability of these sectors and potential adaptation options.

It should be noted that the data archive from this regional climate modelling experiment is quite large. We estimate a data archive of nearly 110 Terra-Bytes. Because of this large size, we believe it makes more sense to demonstrate the datasets that can be developed, and then work with our stakeholders to derive specific datasets that they might need for their studies. In this way, we hope other researchers can identify specific derived products that they might find useful, and that such a process would provide an opportunity to influence and/or directly affect subsequent research activities.

NASA Astronaut photograph ISS038-E-1633

Acknowledgments

Many individuals provided invaluable support, guidance and input to this Modelling project.

The authors would like to express their sincere and heartfelt gratitude for their review by providing comments, feedback, data as well as the opportunity to present multiple deliverables within the project process. These individuals include but are not limited to the below list:

Dr. Abdulla Al Mandoos, National Centre of Meteorology and Seismology

Dr. Omar Abdullah, National Centre of Meteorology and Seismology

Dr. Fred Launay and the Environment Agency- AbuDhabi (EAD) team

Dr. Holger Hoff, Stockholm Environment Institute

Dr. Mansour Al Mazroui, Centre of Excellence for Climate Change Research (CECCR)

Mr. Mufleh Alalaween, IUCN ROWA

Ms. Naoko Kubo, UAE Ministry of Climate Change and Environment (MOCCAE) and team

Dr. Paola Ferreira and the Emirates Wildlife Society (EWS) – WWF team

Dr. Rachael McDonnell, International Centre for Biosaline Agriculture (ICBA)

Dr. Robert Baldwin and Dr. Simon Wilson, Five Oceans

Dr. Saeed Al Sarmi, Research Centre from Public Authority for Civil Aviation (PACA)

Dr. Sultan Al Yahyai, Sultan Qaboos University

Dr. Tarek Sadek, UNESCWA

A very special thank-you to the academic scientific research teams of Khalifa University (KU), MASDAR Institute of Science and Technology (MIST), New York University (NYU) for your data expertise and scientific feedback, support and opportunities for further research.

We are additionally thankful for the participation, time and effort that multiple stakeholders across the region who participated in the multitude of meetings and dialogue.

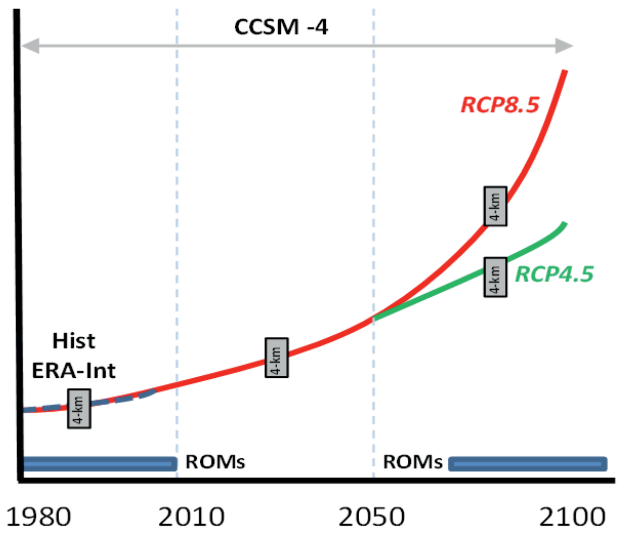
Overview of Experiment

To quantify 21st century climate change over the UAE and Arabian Gulf region, we performed simulations using version 3.5.1 of the Weather Research and Forecasting Model (WRF, Skamarock et al. 2008). WRF is a fully compressible conservative-form non hydrostatic atmospheric model with demonstrated ability for resolving small-scale phenomena and clouds (Skamarock and Klemp 2008). Here, WRF is employed to dynamically downscale climate fields from NCAR's comparatively coarse-scale gridded global climate model (GCM), the Community Climate System Model- Version 4 (CCSM4) which covers the global domain. The WRF simulations are comparatively fine-scale, covering the regional domain of the Arabian Peninsula, which is relevant for assessing climate change impacts at regional-to-local scales.

Figure 1 summarizes the nature of the regional climate model experiments that were conducted. WRF benchmark simulations were performed over a historical period to best estimate the true state and dynamics of the atmosphere. The benchmark simulations in this study derive their initial and boundary conditions from the European Centre for Medium-Range Weather Forecasting (ECMWF) Interim Reanalysis (ERA-Interim; Dee et al. 2011). ERA-Interim is considered to be the most accurate atmospheric reanalysis available at the present time (e.g. Lorenz and Kunstmann 2010).

We then used data from the bias-corrected CCSM4 output, for the contemporary period (20-years at 12 and 36 km) and the RCP8.5 future period (20-year at 12 and 36 km); and for 2, 10-year periods at the 4km resolution.

Figure 1. The Experimental Design. WRF was run for 20 and 10 years for the contemporary period and the future period at 12 and 36 kilometers; and 4-kilimeters, respectively.



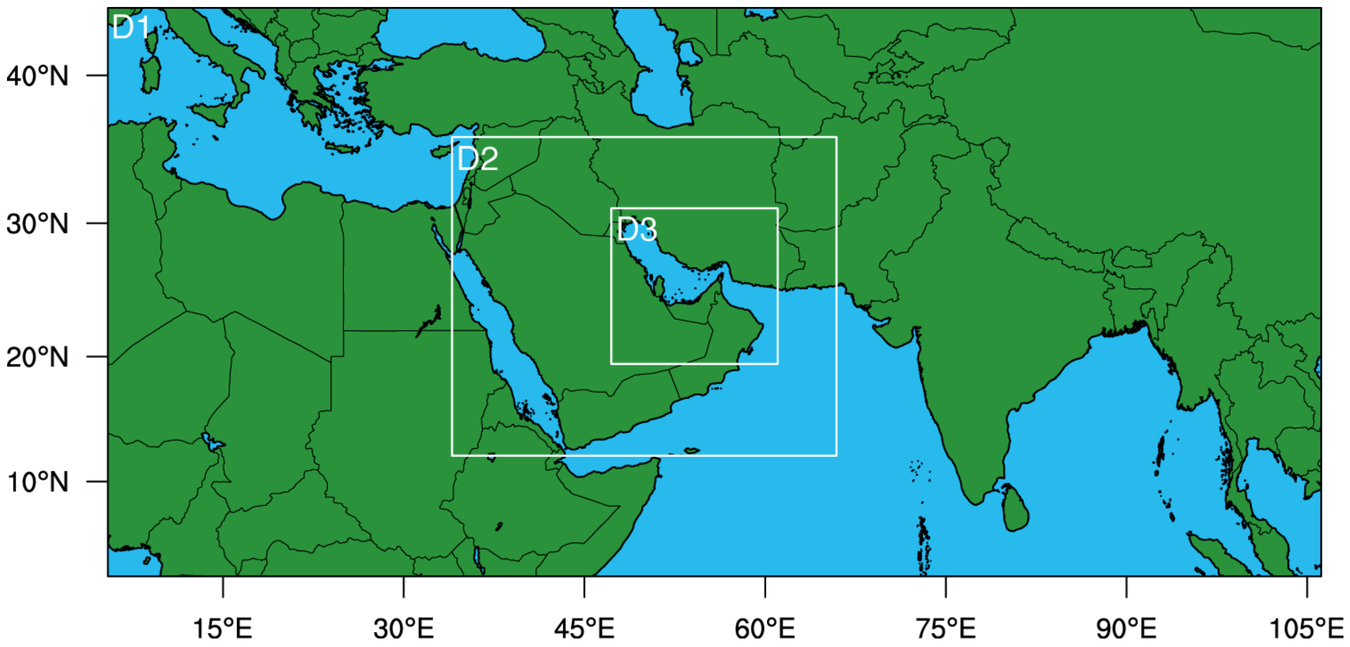
NASA image by Jeff Schmaltz, MODIS Rapid Response Team.

In summary for this study, the following dynamic downscaling simulations were performed with WRF and are summarized in Figure 1:

1. A 30-year ERA-Interim driven WRF benchmark simulation for the historical period spanning 1981-2010 (36- and 12-km domains)
2. A 20-year bias-corrected-CCSM4-driven WRF climate simulation for the historical period spanning 1986-2005 (36- and 12-km domains, referred to as 20THC). The 4-km domain was run for the 1990-1999 sub-period.
3. A 20-year bias-corrected-CCSM4-driven WRF climate simulation for the RCP4.5 period spanning 2060-2079 (36- and 12-km domains)
4. A 20-year bias-corrected-CCSM4-driven WRF climate simulation for the RCP8.5 period spanning 2060-2079 (36- and 12-km domains). The 4-km domain was turned on for the 2065-2074 sub-period.

WRF Setup

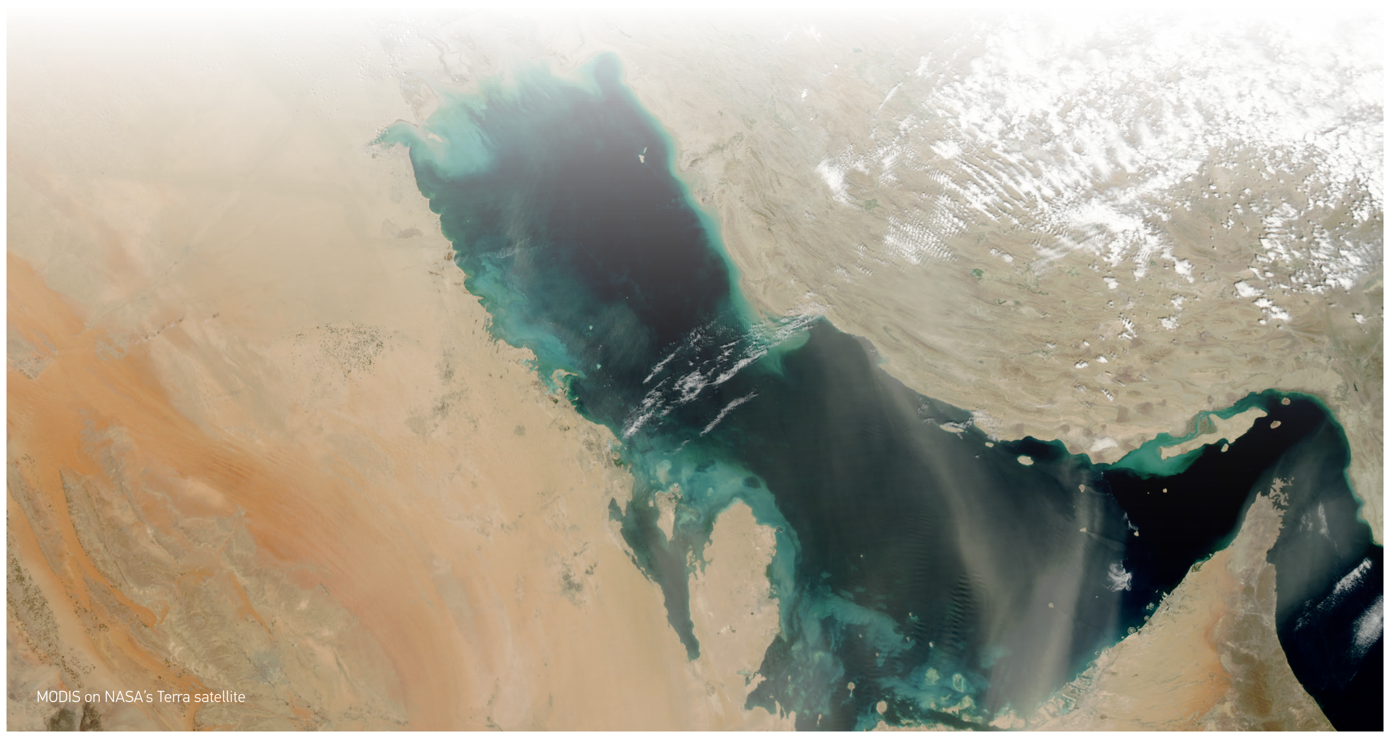
Figure 2. Domains used in WRF simulations.



Configuration and the Climate Change Experiment

The WRF computational domains are shown in Figure 2. The outer domain with a grid spacing of 36-km resolution ("D1") covers much of the eastern hemisphere. Nested inside the 36-km domain is a 12-km domain ("D2") covering the Arabian Gulf region. The innermost 4-km nested domain ("D3") covers the UAE and vicinity.

The WRF simulations feature 40 vertical levels from the surface to 10 hPa (about 30 km above the surface). The WRF simulations are reinitialized every eight days, and each eight-day period is preceded by a 12- hour period that allows the WRF hydrological fields to spin up, and which is subsequently discarded. Throughout the simulations, four-dimensional data assimilation (FDDA, Stauffer and Seaman 1994) - i.e. "grid nudging" – is employed on the 36-km domain to keep the model solution from diverging from the large-scale global boundary conditions, which are described in detail below. Physical parameterization schemes, which simulate the sub-grid scale processes in WRF empirically, include the Lin microphysics scheme, the RRTM longwave radiation scheme, Dudhia shortwave scheme, MM5 surface layer scheme, Noah land surface model, YSU PBL scheme, and the Grell-Devenyi convective scheme (36-km and 12-km domains only). These parameterizations are chosen because they yielded optimal WRF performance over UAE when compared to in situ precipitation and temperature fields for the July and December 1995 case study periods. The global domains providing the initial and lateral boundary conditions for the WRF dynamical downscaling simulations come from two sources depending on whether they are "benchmark" simulations or "climate" simulations, which are described next.



MODIS on NASA's Terra satellite

WRF benchmark simulations with ERA-Interim

The ERA-Interim fields employed here for the benchmark simulations, have an ~0.7° grid spacing on 38 vertical levels. Sea surface temperature (SST) data at the lower oceanic boundaries of these benchmark simulations are from version 2 of the National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation (OISST) 0.25 degree product (Reynolds et al. 2007). Figure 2 and 3 demonstrate the simulations with WRF driven by the ERA-Interm reanalysis data. These simulations represent real meteorological events in the summer and winter of 1995, resecptively; where simulated rainfall is compared to measured rainfall across the UAE. In December, positive biases surround the coastal areas, while the largest negative biases are again clustered along the large rainfall gradients over the steep terrain.

© Niyas Nasirudeen

Results

WRF climate simulations with CCSM4

WRF climate simulations were performed over both historical and future periods, and derive their initial and boundary conditions from an atmosphere-ocean global climate model (AOGCM). The purpose of performing the AOGCM-driven WRF climate simulations for the historical period is to:

1. Generate a dataset that can be used to validate the AOGCM-driven WRF simulations against the reanalysis-driven WRF benchmark simulations described above for some common historical period, and
2. Provide a baseline dataset against which future AOGCM-driven WRF climate simulations can be assessed.

Figure 2. WRF rainfall biases (color-coded dots), WRF rainfall (mm, color shading), and WRF terrain height (gray contours) for July 1995 for subset of domain in Fig. 1

WRF Results - Rainfall

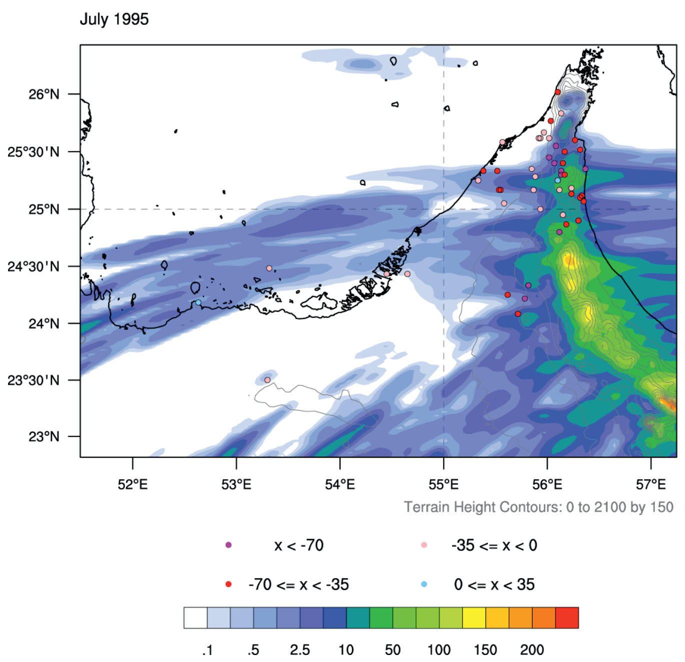
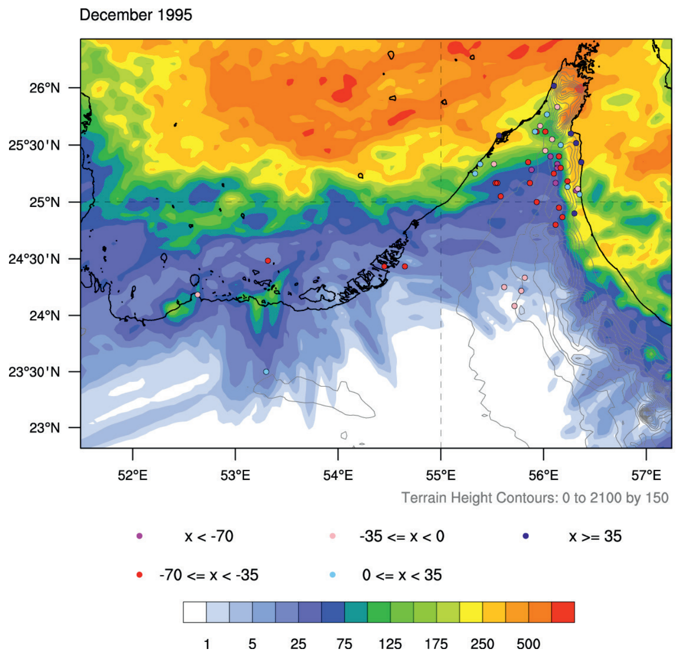


Figure 3. Same as (a) except for December 1995.

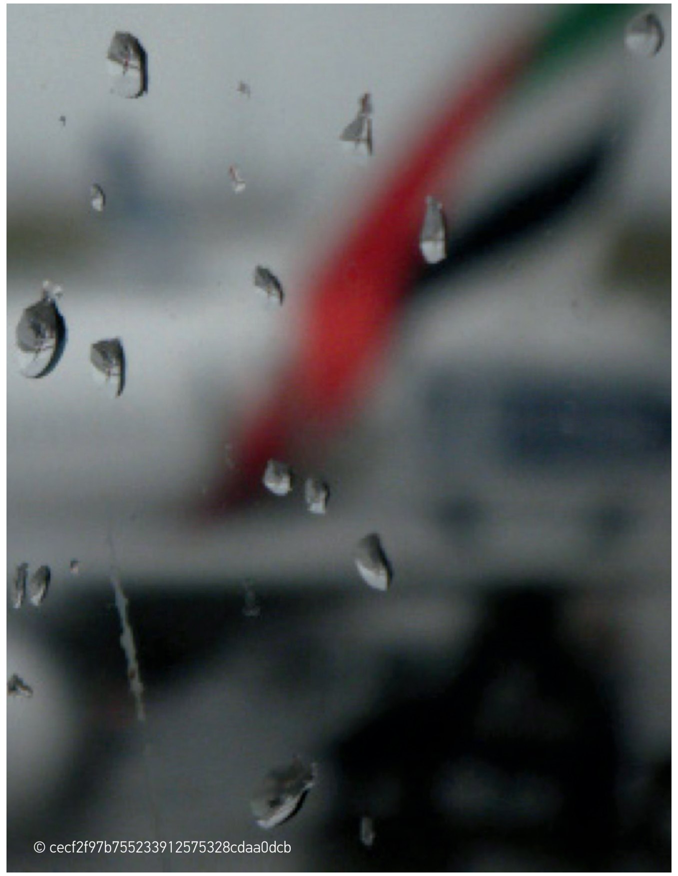


The purpose of performing the AOGCM-driven WRF climate simulations for the future period is to provide a projection for the future state of the atmosphere in some latter portion of the 21st century. The WRF climate simulations in this study derive their initial and boundary conditions from version 4 of the Community Climate System Model (CCSM4; Gent et al. 2009), which is described in the next paragraph. Figure 5 compares the terrain from the CCSM4 AOGCM to that from the WRF 4-km domain. It is clear that CCSM4, with a spatial resolution of 0.9 degrees latitude x 1.25 degrees longitude (approximately 100 km), cannot adequately resolve the topography of the Oman mountains and other important topography in the region compared to WRF, demonstrating the necessity of performing the WRF dynamical downscaling simulations in order to provide a dataset that is appropriate for assessing climate change in the region.

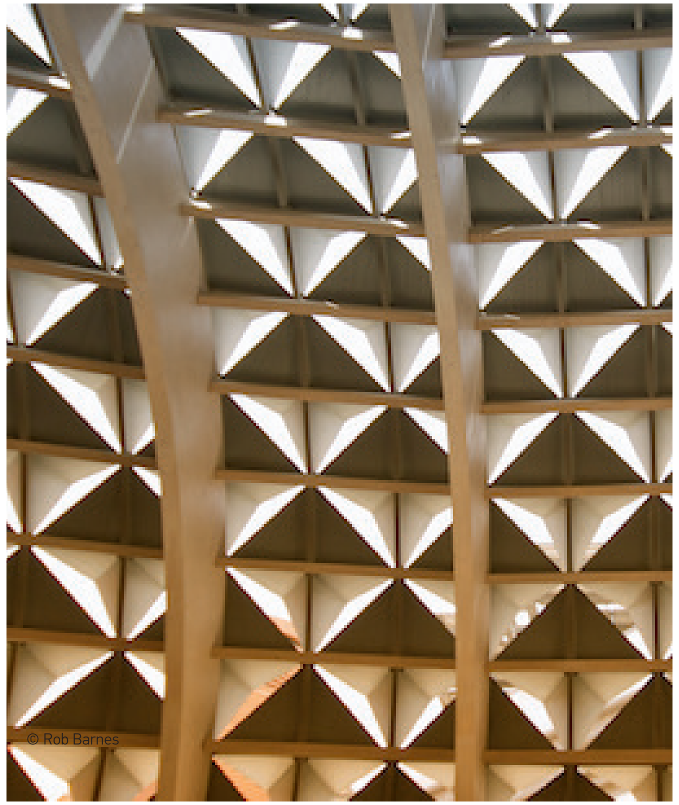
The CCSM4 simulations that provide the initial and boundary conditions for the WRF climate simulations were performed in support of the Coupled Model Intercomparison Experiment Phase 5 (CMIP5; Taylor et al. 2012) and the Fifth Assessment Report of the Intergovernmental on Climate Change (IPCC 2013).

CCSM4 ranks at the top of all CMIP5 AOGCMs in its ability to simulate observed temperature and rainfall globally (Knutti et al. 2013). Model fields were obtained from the National Center for Atmospheric Research and are also available from the Earth System Grid - Programme for Climate Model Diagnosis and Intercomparison (ESG-PCMDI) gateway at Lawrence Livermore National Laboratory, http://pcmdi3.llnl.gov/esgcet/home.htm.

CMIP5 model scenarios used in this study include a historical simulation and two future projections. The historical simulation was forced by observed natural and anthropogenic atmospheric composition changes spanning 1861-2005. The future projections are the Representative Concentration Pathway (RCP; Moss et al. 2010) 4.5 and 8.5 scenarios, which span 2006-2100. RCP4.5 is a low-to-moderate emissions scenario with GHG radiative forces reaching 4.5 W m-2 near 2100.



It represents a trajectory that may be plausible (and desirable) if, for instance, GHG emissions pricing were introduced in order to limit radiative forcing (Thompson et al. 2011). RCP8.5 is a high-emissions scenario with greenhouse-gas (GHG) radiative forcing reaching 8.5 W m-2 near 2100. It represents a plausible trajectory if little is done to curb greenhouse gas emissions (Riahi et al. 2011). Ensemble Member #6 of the historical, RCP4.5 and RCP8.5 CCSM simulations were used, as that is the only member that has available 6-hourly intervals the full three-dimensional fields required to force WRF.



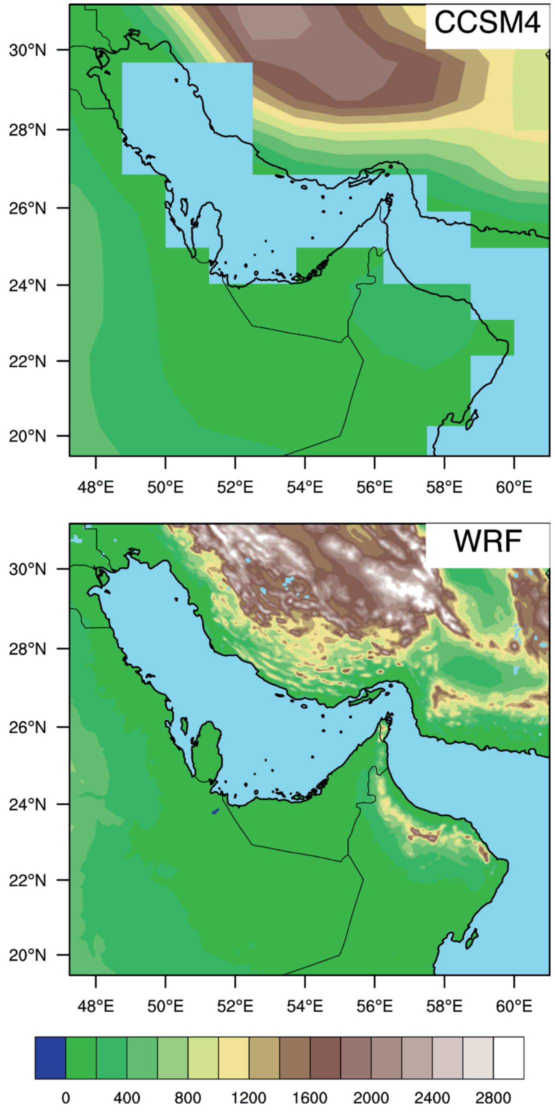


Figure 5. Terrain height (m, color scale at bottom) and land/ sea mask for CCSM4 (top) and 4-km WRF (bottom). Actual coastlines and political boundaries shown in black

Like all AOGCMs, CCSM4 contains regional-scale biases due to having coarse spatial resolution and a limited representation of some physical processes. Such biases can adversely affect the dynamical downscaling process and contribute to uncertainty. To remedy these biases, it is common to bias correct the climate model output before using it to drive regional-scale models like WRF (e.g. Rasmussen et al. 2011).

In this study a recently-developed bias correction method was applied which corrects for the mean bias in the CCSM4 3-dimensional temperature, geopotential height, wind, and humidity fields, as well as the SST, skin temperature, and soil temperature and moisture fields. Although the bias in the mean state is corrected, the methodology still allows synoptic-scale and climate-scale variability to change in the future as simulated by CCSM4 (Xu and Yang 2012; Done et al. 2013; Bruyére et al. 2013). The bias-corrected CCSM4 output is produced by summing the average 6-hourly annual cycle (the Reynolds averaged mean term) from ERA-Interim (1981-2005) and a 6-hourly perturbation term (the Reynolds averaged eddy term) from CCSM4:

$$CCSM = \overline{CCSM} + CCSM'$$
$$ERAINT = \overline{ERAINT} + ERAINT'$$
$$CCSM_R = \overline{ERAINT} + CCSM'$$

To place the CCSM4 climate simulations for the Arabian Peninsula in the context of the larger ensemble of GCMs run for the IPCC AR5 assessment, we show the precipitation anomaly for the region for the ensemble mean from more than 15 GCMs with many of those models including multiple ensemble members. The "take-home" message from Figure 6 is that the ensemble of all the climate models generally suggests an increase in precipitation for the region, with an upward trend beginning around the year 2000 (Figure 6). In similar fashion, the CCSM4 AR5 simulations show generally more precipitation for the region, with a generally upward trend (Figure 7).

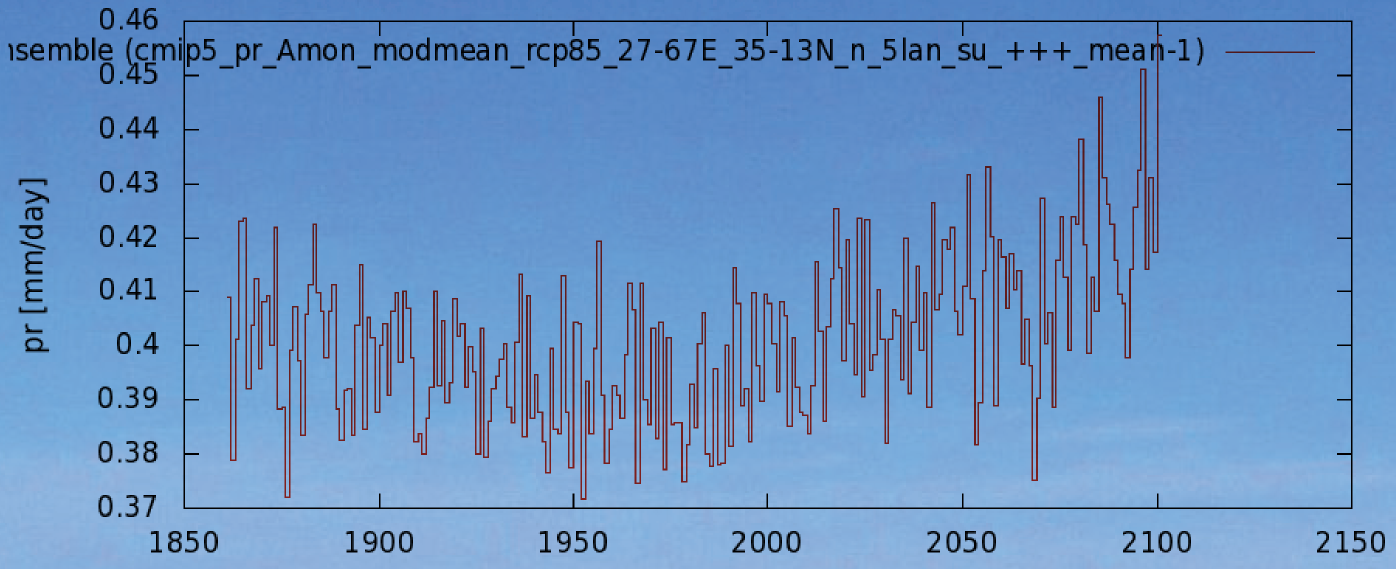


Figure 6. Mean precipitation anomaly from the full suite of GCMs from the IPCC AR5 experiment for the Arabian Peninsula region.

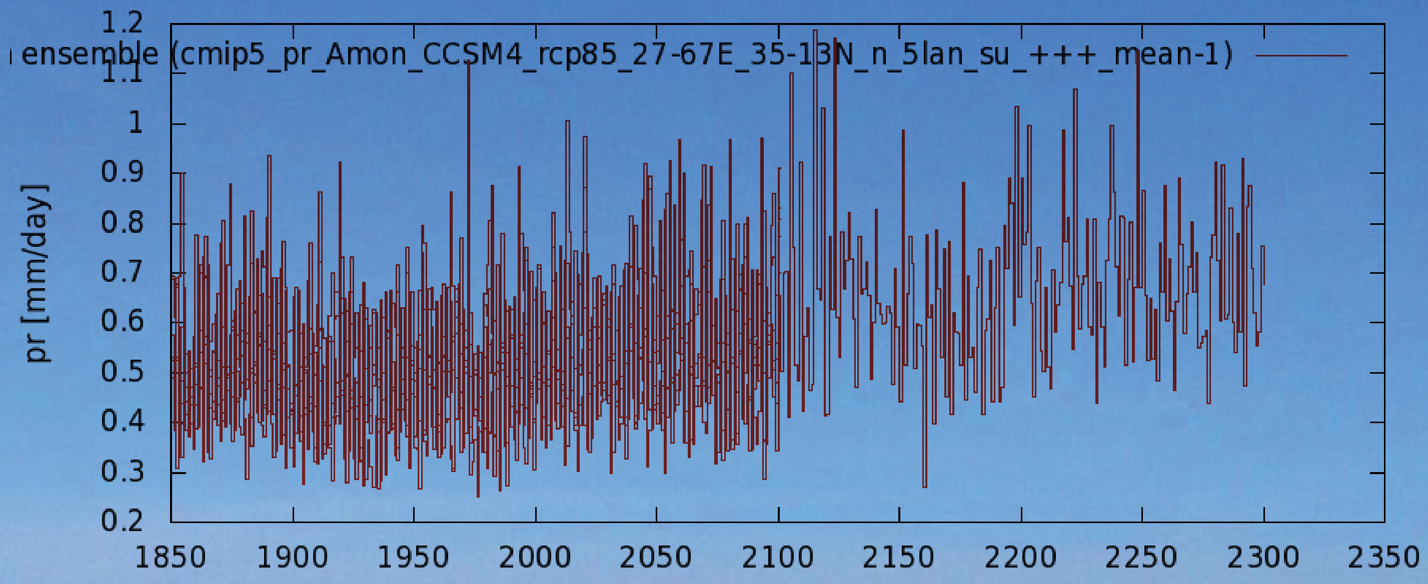


Figure 7. Projected change in the precipitation anomaly for the CCSM model, which includes multiple ensemble members. Some ensemble members included runs past 2100 and is why the graphs extend to 2300, with some ensemble members run out that far.

Regionally, it would appear that the CCSM4 is relatively "wet" in comparison to the ensemble mean of all the AR5 climate models, with a mean daily precipitation for the region for the contemporary period of about 5 mm/ day; while the ensemble mean is slightly less than 4 mm/day.

To estimate the projected precipitation changes over the UAE and Arabian Peninsula, WRF simulations were run (using the bias-corrected CCSM4 variables as input) for two time periods: present-day conditions (1986-2005, denoted as "20THC"), and the RCP 8.5 scenario (2060-2079, denoted as "RCP8.5").

Precipitation

Figure 8 shows the projected rainfall amounts for 20THC (left column), RCP 8.5 (center column), and the percentage difference (right column), averaged annually (top row), winter (December-January-February, middle row), and summer (June-July-August, bottom row). In total (top row), rainfall is projected to increase over much of the UAE, the Hajar Mountains, and Qatar. Increases of 50-100% from current amounts are projected for portions of Dubai, Sharjah, and northern Abu Dhabi emirates, with increases averaging around 25% over surrounding regions. Increases are also projected over the Arabian Gulf and Gulf of Oman.

Decreasing rainfall is projected over much of Oman and eastern Saudi Arabia. Winter (DJF) is the dominant season for rainfall across the region (middle row), and the projected rainfall increases over the Arabian Gulf and north of the Hajar Mountains primarily occur during this season. Interestingly, during the dry summer season, rainfall increases over much of the UAE are larger than during the wetter winter season, in both absolute value and percentage change.

The rainfall increases over the Hajar Mountains and the eastern UAE primarily occur during summer as well. The annual decreases over much of Oman and eastern Saudi Arabia occur during and winter and spring (March-April- May, not shown).

Despite the projected increases in rainfall over much of the UAE, the number of wet days is actually projected to decrease in the future climate scenario. Figure 9 shows the Wet Days Index for each scenario and the differences. The Wet Days Index is simply the number of days (per year, averaged over the respective 20-year periods) with rainfall greater than 1 mm. Increases in the Wet Days Index are only projected over the northern coast of Oman.

With precipitation increases projected to occur over relatively wet portions of the plotted region, the projected decrease in the Wet Days Index, strong precipitation increases during summer, and the projected temperature increases (see next section), a thermodynamic explanation for the rainfall increases is suggested. This simply involves the increase in saturation vapor pressure with increasing temperature (the Clausius-Clapeyron equation). Larger amounts of rainfall would occur during comparatively fewer rainfall events than currently observed.

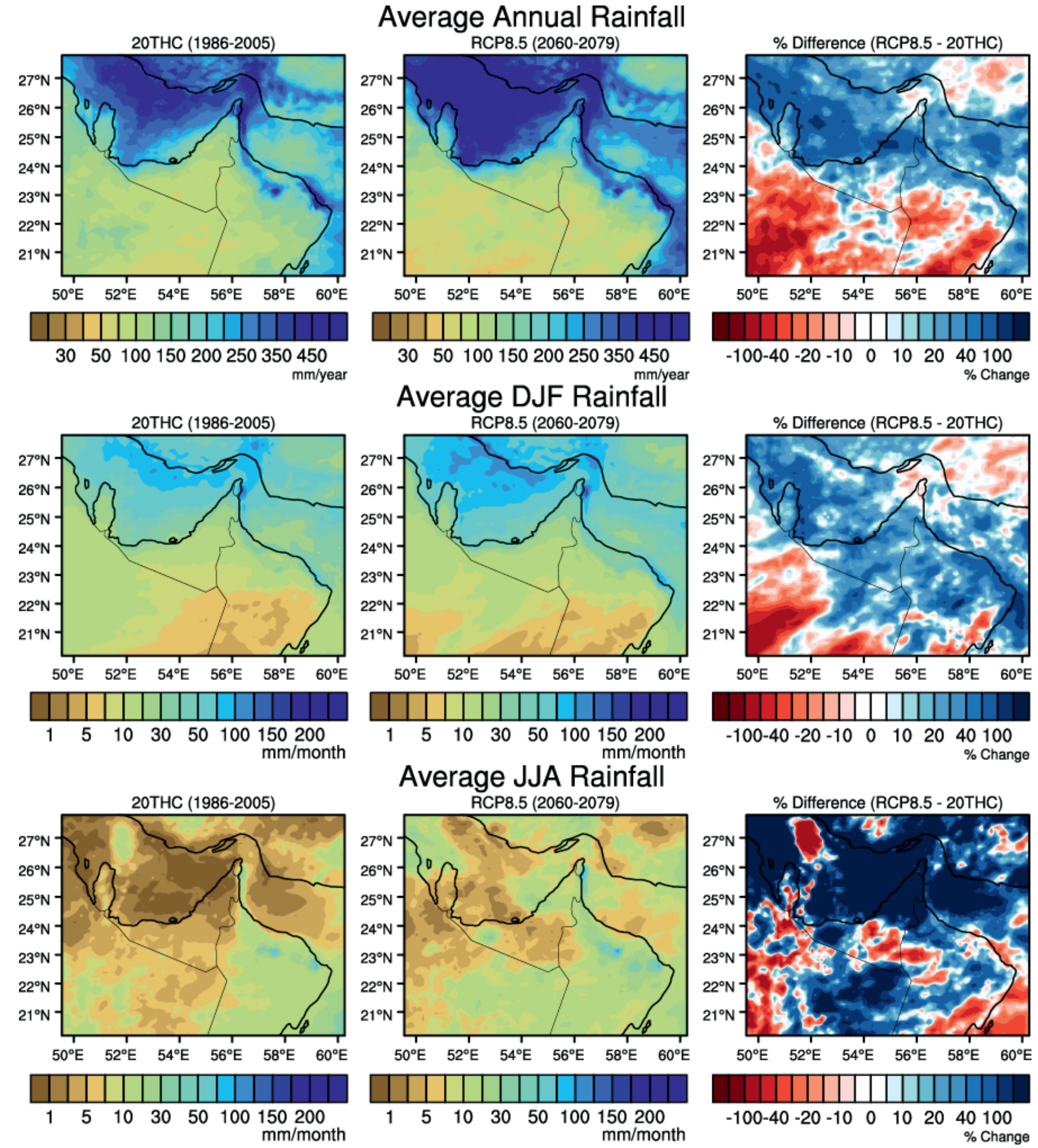


Figure 8. WRF rainfall estimates for the 20THC simulation (left column), RCP 8.5 simulation (center column), and the difference (percentage change of RCP 8.5 minus 20THC; right column), averaged annually (top row), winter (middle row), and summer (bottom row).

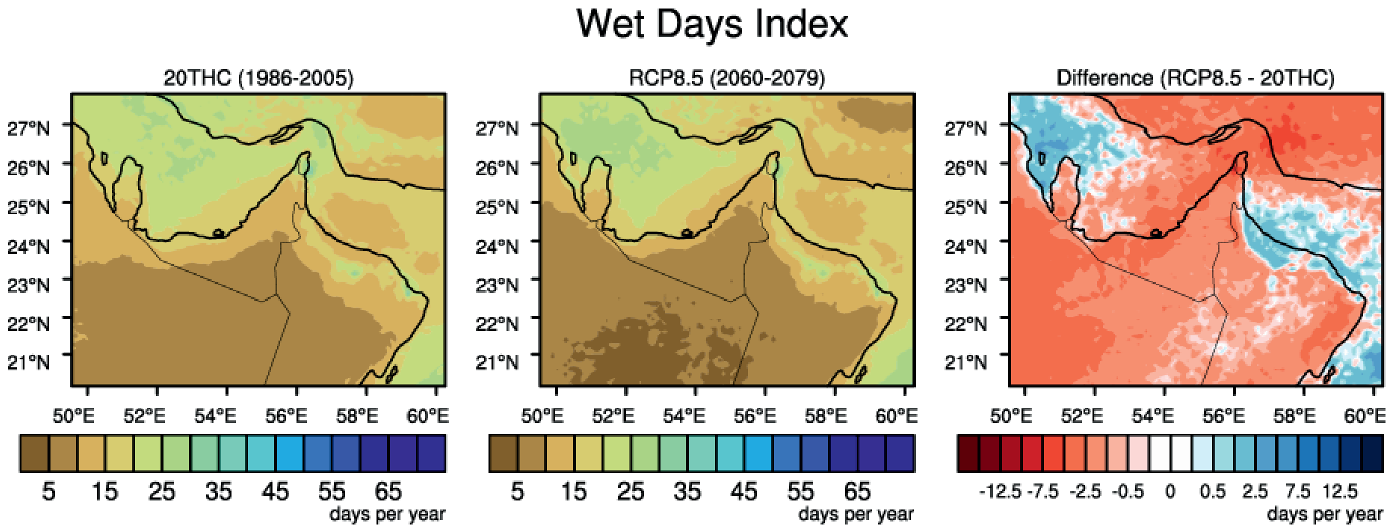


Figure 9. Wet Days Index values (the number of days with rainfall greater than 1 mm, summed over the 20-year time periods), for 20THC (left), RCP 8.5 (center), and the difference (RCP 8.5 minus 20THC; right).

Temperature and Humidity

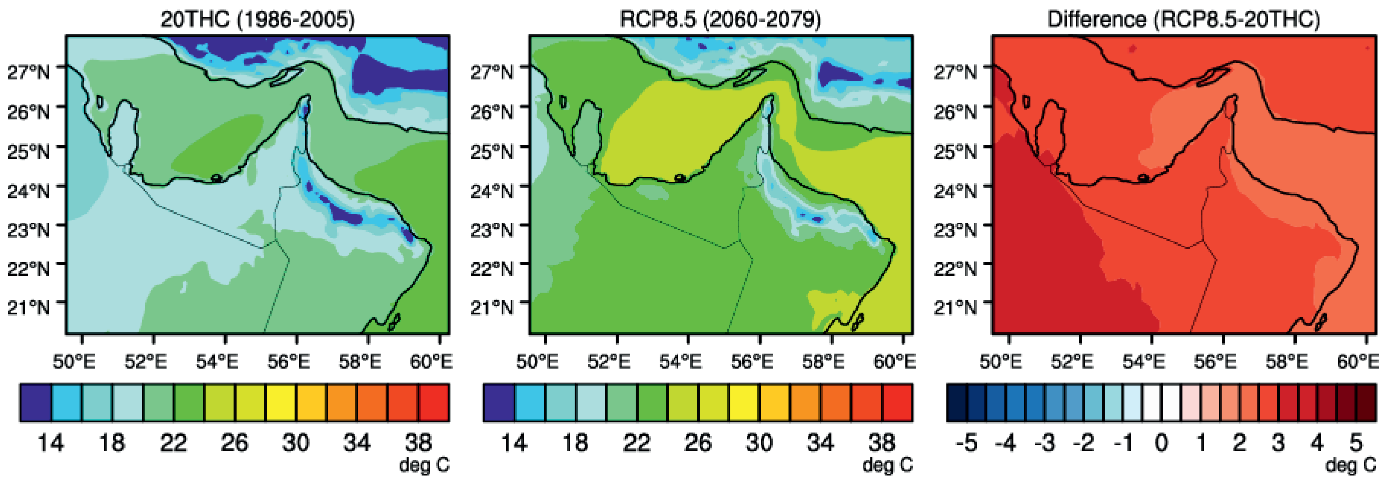
The projected daily average 2-m air temperature and 10-m specific humidity changes are shown in Figure 10 for the winter (December, January, and February) and summer (June, July, and August). Average future temperature increases are unanimous across the plotted domain, on the order of 2°-3°C over land areas (top row). Increases are slightly smaller over many coastal areas. These changes are consistent across winter and summer.

Humidity changes are greater in the summer months, associated with greater water holding capacity of the warmer atmosphere and are about 10% greater over the Arabian Gulf, with higher humidity across most of the UAE and proportionally more in the northeastern corner of the country associated with greater humidity over the Arabian Sea.

Future projected changes in temperature are expressed as the Heat Wave Duration Index (HWDI) in Figure 11. This metric is defined as the number of days, in intervals of 6 days, that the daily maximum temperature is greater than 5°C above a reference value. In this case, the reference value is the respective 20-year average of the daily maximum temperature for each calendar day.

HWDI values are small for 20THC, likely reflecting the relatively small year-to-year variance in temperature across the region, as the day-to-day variance in temperature in region is relatively low (e.g. in the summer, it is nearly always very warm). When HWDI is calculated for the RCP 8.5 future climate scenario, using the corresponding RCP 8.5 averages as reference, there is a marked decrease in HWDI across most of the UAE, the Hajar Mountains, and portions of eastern Saudi Arabia. Increases in HWDI are restricted to a few coastal areas around the plotted domain. The decrease in HWDI may be explained by the projected increase in average temperature (Fig. 10) restricting the number of relatively hot days in the future climate scenario. These are the kind of indices that we would like to discuss with the stakeholders to determine their needs and interest.

Average DJF 2-m Air Temperature



Average JJA 2-m Air Temperature

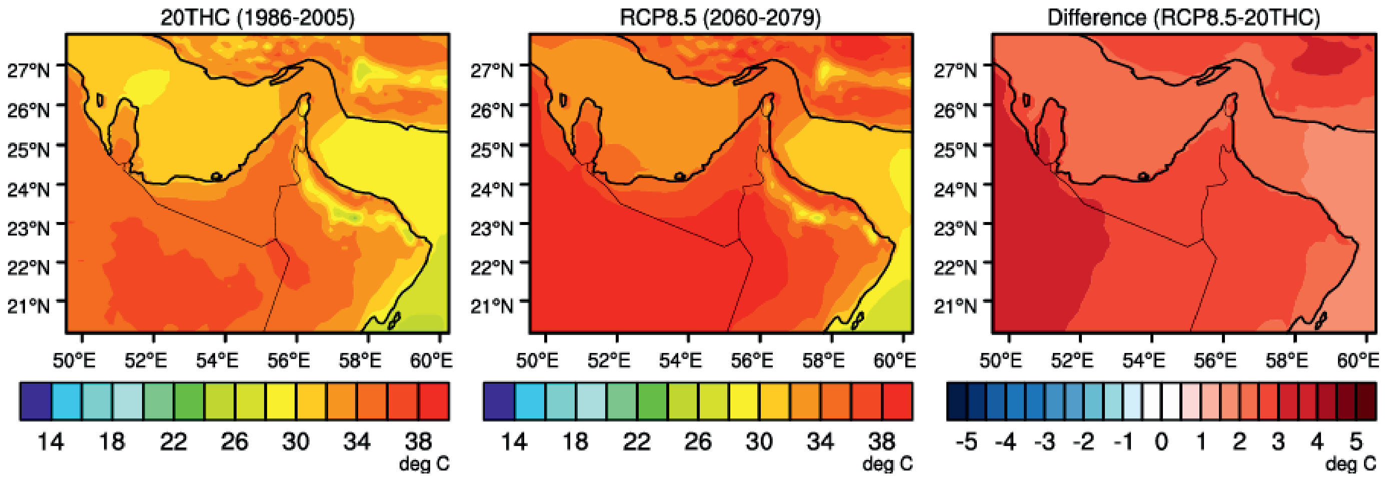
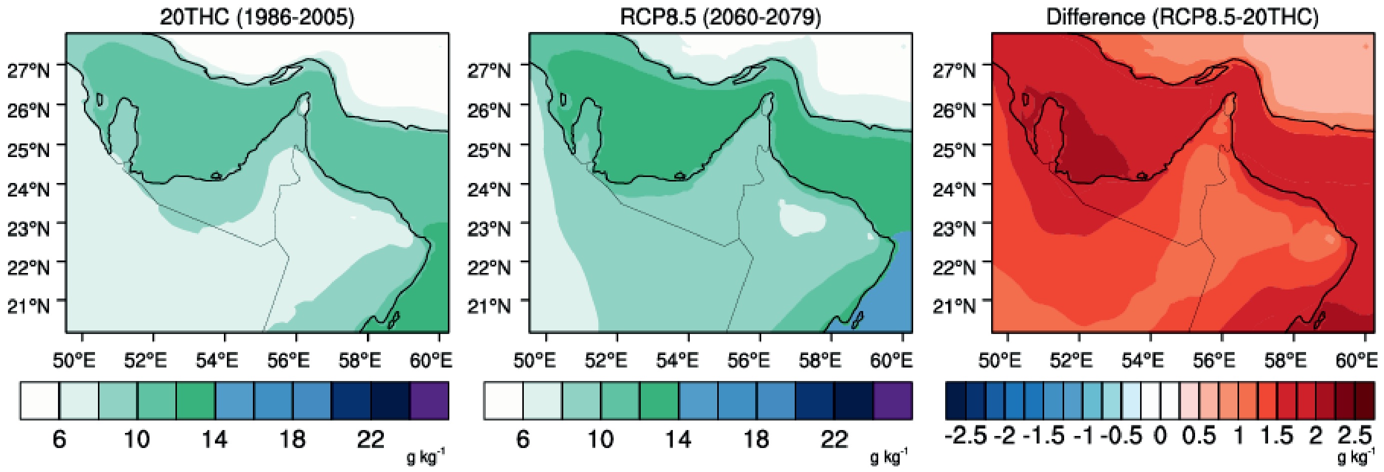


Figure 10a. Seasonal changes in 2-m air temperature (°C) and 10-m specific humidity (g/kg)

Average DJF 10-m Specific Humidity



Average JJA 10-m Specific Humidity

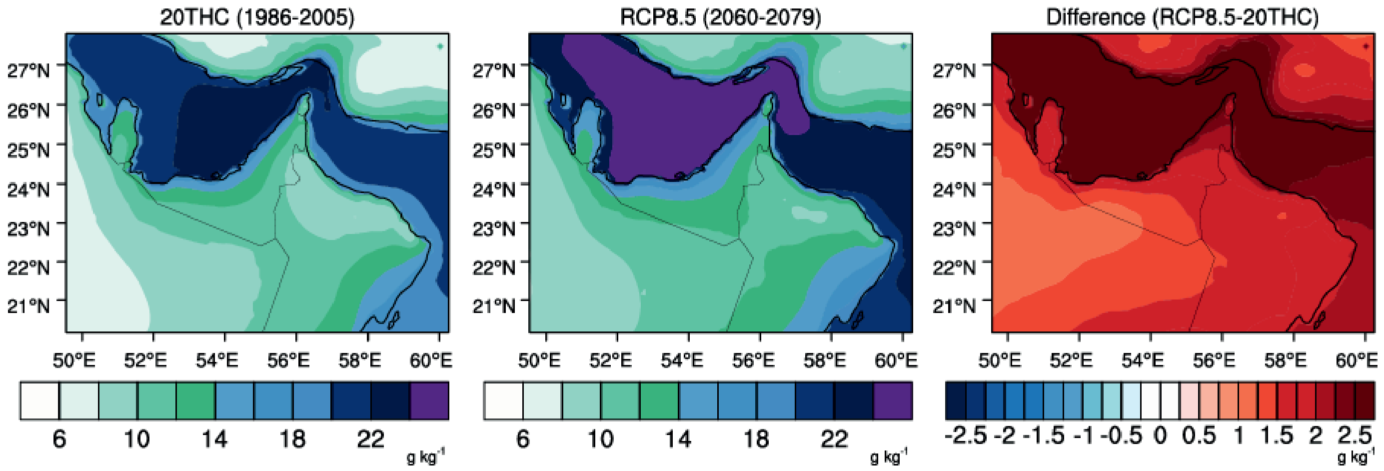


Figure 10b. Seasonal changes in 2-m air temperature (°C) and 10-m specific humidity (g/kg)

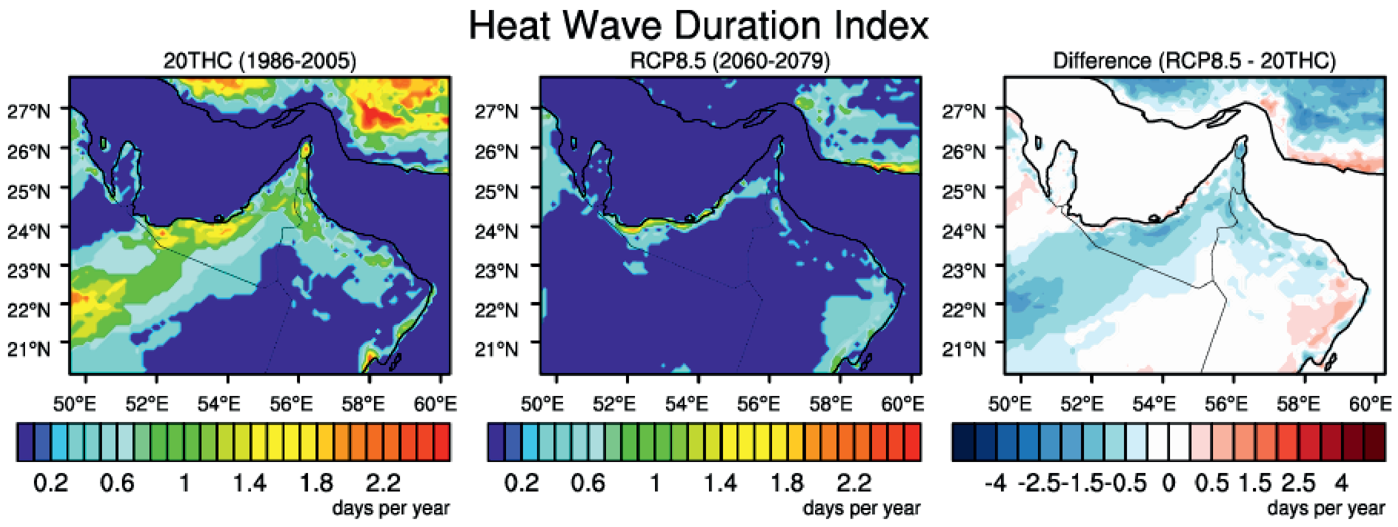


Figure 12. Heat Wave Duration Index values (the number of days, in intervals of 6 days, that the daily maximum temperature is greater than 5°C above a reference value), for 20THC (left), RCP 8.5 (center), and the difference (RCP 8.5 minus 20THC; right).

Changes in Wind around Abu Dhabi Island

Figure 12a,b shows the December-January-February (DJF) mean morning (0600 local) and early evening (1800 local) 10-meter winds for the current 20th century climate (20THC) and the future climate for the RCP8.5 CCSM projection from the 4-km, 10-year simulations.

The far-right panel in both plots their difference. Note that in the early morning, DJF, the wind is from the northeast off of the Arabian Gulf Coast, and under the current climate conditions (20th THC), the wind from interior of the UAE is considerably weaker than in the future climate; resulting in a net change in early morning wind from the east to the west or outward into the Arabian Gulf.

This could be the result of persistently warmer, interior land-surface that results in a more northwesterly near surface wind (needs confirming). The evening wind fields (1800) are similarly strong under the current and future climate, with a generally southwesterly change in flow.

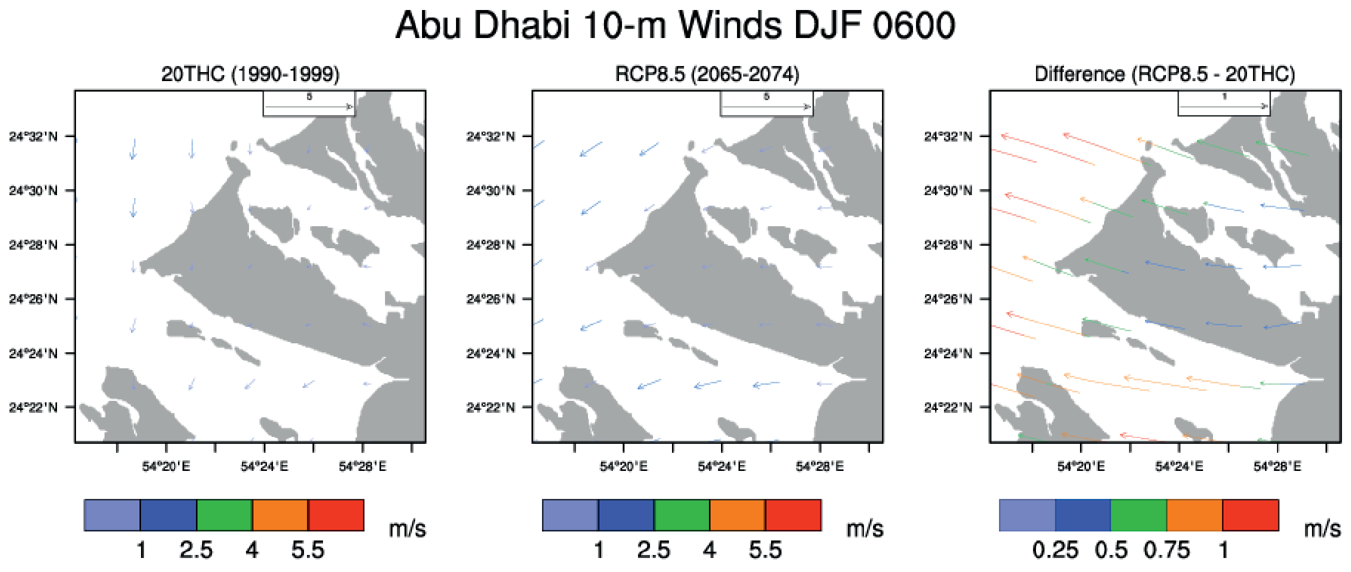


Figure 12a. Mean 10-m winds around Abu Dhabi Island for DJF, early morning local time (0600).

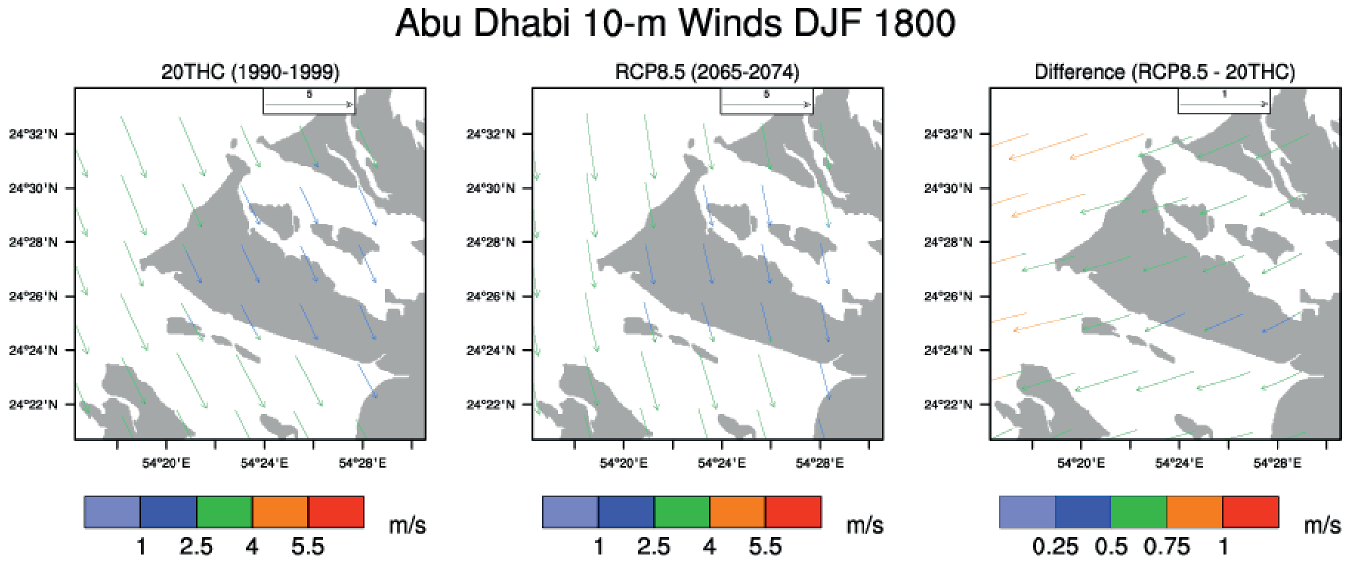


Figure 12b. Same as Figure 12a, except for the early evening (1800 local)

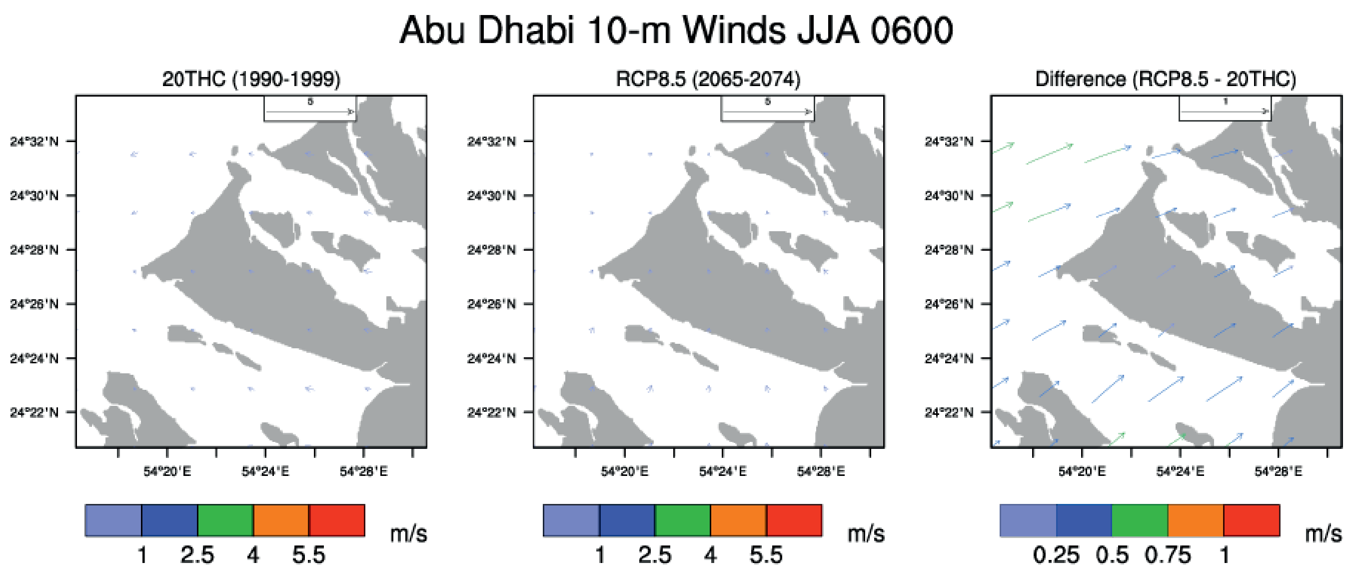


Figure 13a. Mean 10-meter winds near and around Abu Dhabi Island for JJA, early morning local time (0600).

Figure 13a,b is similar to Figure 12a,b, except that the mean wind field is estimated for the months of June, July and August (JJA). Figure 13a is the meaning, morning hour (0600), 10-m wind, while Figure 13b is for the evening hour (1200). Summertime, morning hour winds are weak in both the current and future climate simulations, with a net change of flow to the north-east. A relatively strong, on-shore sea-breeze develops in the evening hour, with a net change in wind similar to the morning hour, with a slight in magnitude to the northeast.

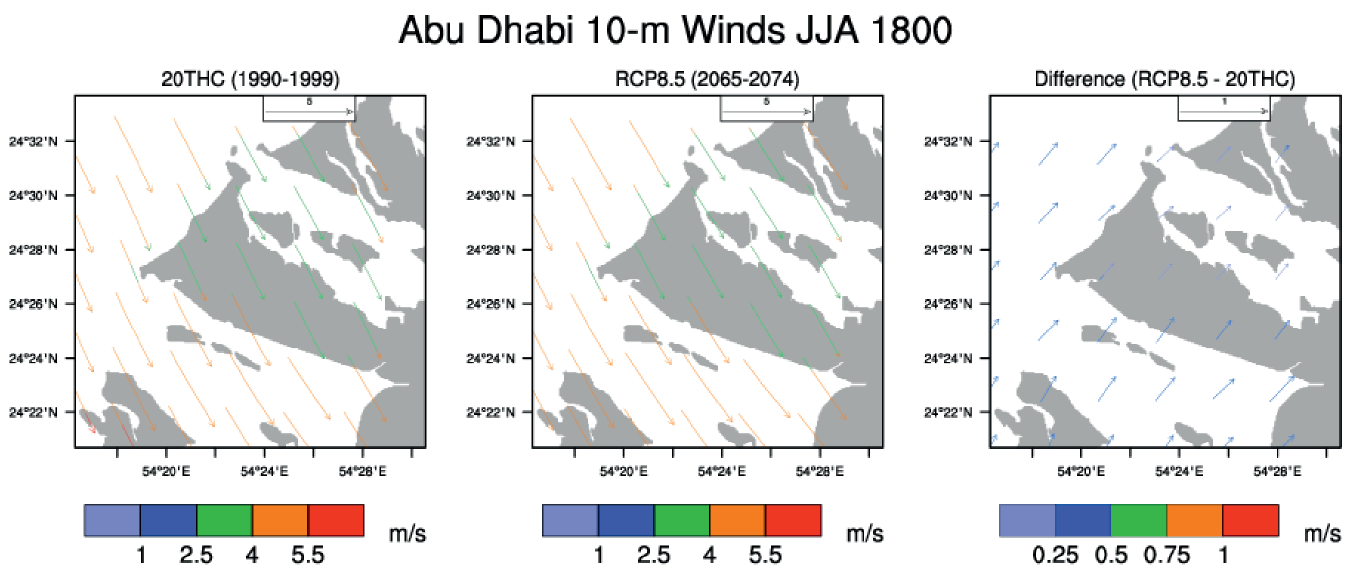


Figure 13b. Same as Figure 13a, except for the early evening (1800 local)

Summary

This Regional Atmospheric Modelling sub-project demonstrated the development of a novel, bias-corrected global climate model dataset, based on NCAR's Community Climate Systems Model (CCSM4). The CCSM4 was one the IPCC AR5 global climate models, which was bias-corrected to be statistically similar to the European Centre for Medium-Range Weather Forecasting (ECMWF) Interim Reanalysis (ERA-Interim; Dee et al. 2011) dataset. The ERA-Interm is considered to be the most accurate atmospheric reanalysis available at the present time (e.g. Lorenz and Kunstmann 2010).

The bias-corrected, CCSM4 dataset was then used as the boundary and initial conditions, for simulating the NCAR Weather Research Forecast (WRF) to dynamically downscale the climate of the 20th century and the future climate based on the RCP8.5 emission pathway. The WRF model was run at spatial resolutions of 36, 12, and 4-km that included a large portion of the Arabian Peninsula. The 12 and 36 KM domains were run for a longer period, 2006 to 2100, while the 4-km domain (D3) was run for two shorter, 10-year periods. Nearly 500,000 "core-hours" on the NCAR supercomputer were used for these analysis. A core-hour is essentially the number of processor cores used multiplied by the duration of the job, so had a single quad-core personal computer been used, the runs would have taken more than 14-years to complete.

The results show that the WRF simulations adequately captured the regional climate of the Arabian Peninsula for the 20th century period, with more validation to be presented in the full final report. The CCSM4 projection of the future climate indicates generally wetter and warmer conditions in the region, with the CCSM4 projected trends similar to the ensemble average of all the GCMs used in the IPCC AR5 experiments (e.g. warm and wet). Most of the increased rainfall is associated with wetter conditions over the Arabian Peninsula that extends across a large portion of the UAE. We demonstrated some tailored climate indices that can be developed from the WRF dataset (Wet and Dry indices), and demonstrated possible changes in wind fields around and near Abu Dhabi Island.

Future Research

The results point to several promising areas of future research. Building off the datasets generated by the study, these include:

- Addressing uncertainty. Additional WRF runs using multiple Coupled Atmosphere Ocean Global Circulation Models to generate a large ensemble of future projections
- Projecting tropical storm frequency. Additional WRF runs using its "simple ocean" representation to simulate tropical storms, including surface flux/drag formulations for high-winds an approach to capture the impacts of sea surface temperatures on cyclones.
- Coupling atmosphere and oceans. Running experiments in a coupled fashion would allow a fuller understanding of how atmospheric and Gulf dynamics work together. As the ocean modelling found, circulation and salinity are quite sensitive to the state of the atmosphere.
- Projecting weather extremes. There are some extraordinary cyclonic events in the CCSM4 GCM data out towards the end of the 21st Century. Exploring if other GCMs produce these kinds of events would be valuable.
- Optimizing modelling configurations. Because the WRF model has multiple configurations, it would be beneficial to conduct more experiments to ensure that an optimal configuration has been achieved for a multitude of meteorological events.
- Sandstorm/dust modelling. Given the importance of dust, it would be valuable to explore how changing climate might impact dust formation, transport and deposition in the region.

Acronyms

AOGCM	Coupled Atmosphere Ocean General Circulation Model
AR5	The 5th Assessment Report of the IPCC
CCSM4	The NCAR Community Earth System Model Version 4
CMIP5	Climate Model Intercomparison Version 5
EAD	Environment Agency - Abu Dhabi
ECMWF	European Center for Medium Range Forecast
FAR	Fourth Assessment Report (IPCC)
GCM	Global Climate Model
GHG	Greenhouse gas
GIS	Geographic Information System
GoAD	Government of Abu Dhabi
HWDI	Heat Wave Duration Index
IPCC	Intergovernmental Panel on Climate Change
LNRCC	Local, National, and Regional Climate Change
NCAR	National Center for Atmospheric Research
NWSC	The NCAR-Wyoming Supercomputer or “Yellowstone”
PI	Principal Investigator
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RT	Research Team
SST	Sea Surface Temperatures
TAR	Third Assessment Report (IPCC)
UAE	United Arab Emirates
WRF	Weather Research and Forecasting model
20THC	20th Century Climate Simulations

Glossary

Glossary of Key Terms

Arabian Peninsula: The Arabian Peninsula consists of the countries of Yemen, Oman, Qatar, Bahrain, Kuwait, Saudi Arabia and the United Arab Emirates as well as parts of southern Iraq and Jordan.

Climate inspector: This is a visualization and data extraction tool for viewing the outputs of the regional atmospheric modelling study.

European Centre for Medium-Range Weather Forecasting Interim Reanalysis (ERA-Interim): ERA-Interim is a data compilation project that has assimilated observed meteorological data for the period 1981-2010 using a single consistent assimilation (or “analysis”) scheme. Observed data comes from sources such as satellites and weather balloons. ERA-Interim is one of the most accurate atmospheric reanalysis available and is widely used in regional climate modelling

Fully compressible, conservative-form non-hydrostatic atmospheric model: This refers to nature of the Weather Research and Forecasting (WRF) model, which is a numerical weather prediction system designed for both atmospheric research and operational forecasting.

Historical climate simulations: This is the process of using the regional climate model to simulate the observed climatic record using the ERA-Interm data as the boundary conditions.

Iterative sensitivity analyses: this is a technique to explore the impact of specific variables in a step-by-step manner

Lateral boundary conditions: These refer to the physical atmospheric conditions (e.g. temperature, humidity, pressure) that exist at the lateral, or side, of a 3-dimensional grid cell

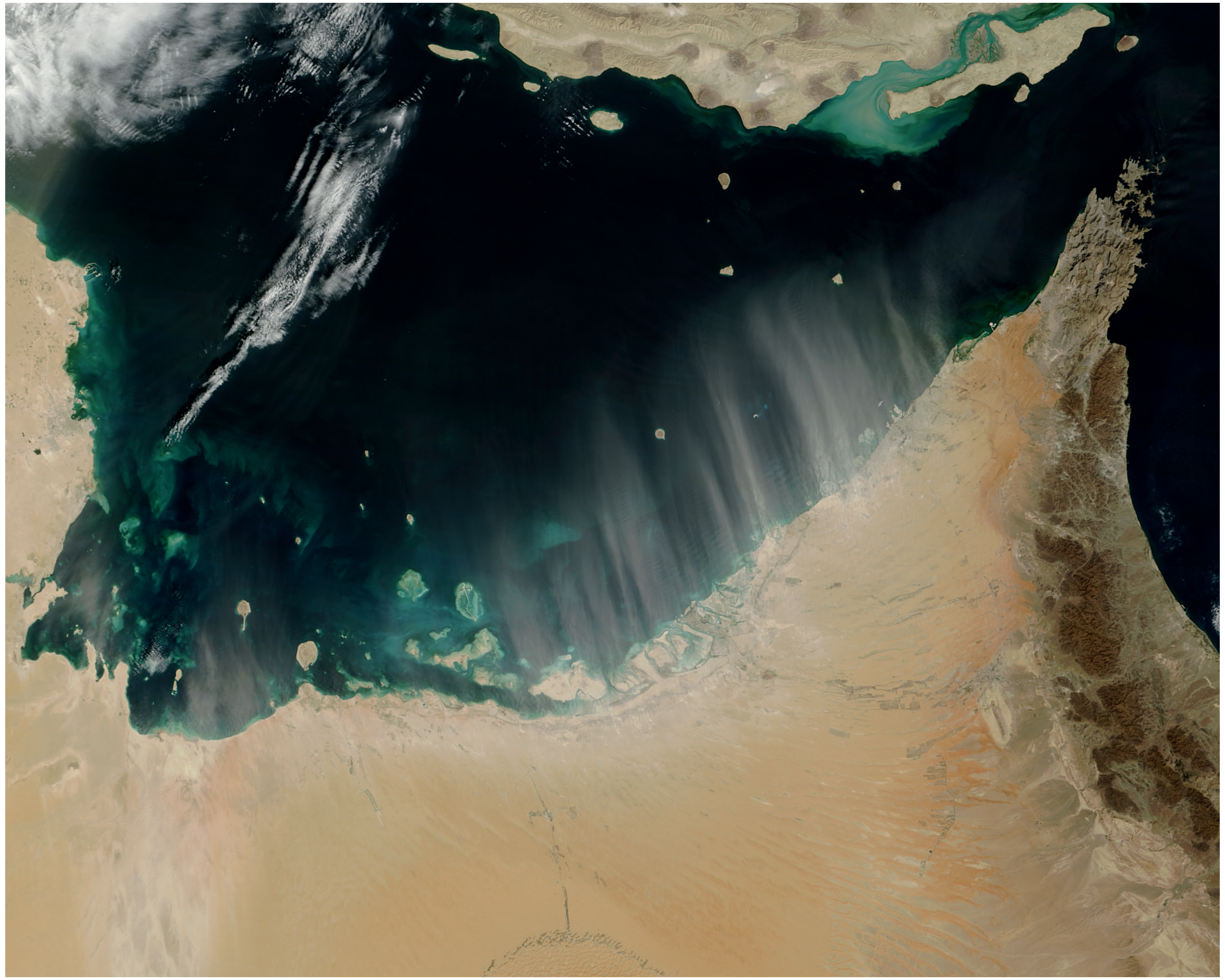
Meteorological forcing outputs: meteorological forcing outputs consist of variables such as temperature, precipitation, wind, vapor pressure, and downward longwave and shortwave radiation, and other variables.

Microphysics parameterization schemes: microphysics parameterization refers to representation of physical process, by deciding and defining the parameters necessary for the relevant specification of factors that control the formation, for example, of cloud droplets and ice crystals, their growth and fallout as precipitation.

NCAR-Wyoming Supercomputer or "Yellowstone": This is a 1.5-petaflop IBM supercomputer. It is one of the world's most powerful supercomputers dedicated to the geosciences.

Orographic precipitation: Includes rain or other precipitation produced when moist air is lifted and moved over a mountain range. As the air rises and cools, orographic clouds form and serve as the source of the precipitation, most of which falls upwind of the mountain ridge.

Radiative Forcing (RF): This is the measurement of the capacity of a gas or other forcing agents to affect that energy balance, thereby contributing to climate change. RF expresses the change in energy in the atmosphere due to GHG emissions.



Representative Concentration Pathways (RCP): Representative Concentration Pathways (RCPs) are four GHG concentration - as opposed to emission - trajectories the IPCC used in its 5th Assessment Report. RCPs supersede the previous GHG storylines (e.g. A1, B1). RCP8.5 can be considered analogous to a business- as-usual scenario. RCP4.5 assumes stabilization of GHG emission concentration in the atmosphere by 2100. Representative concentration pathways" provide time- dependent projections of atmospheric greenhouse gas (GHG) concentrations, with the term pathway meant to reflect the trajectory that is taken over time to reach that outcome. They are representative in that they are one of several different scenarios that have similar radiative forcing and emissions characteristics.

Spatial scale: Denotes the extent or size of a length, distance, or area studied or described

Temporal scale: Denotes the extent of the time period under study, whether in the past or future

References

Bruyére CL, Done JM, Holland GJ, Fredrick S. 2013. Bias corrections of global models for regional climate simulations of high-impact weather. Clim. Dyn., doi:10.1007/s00382-013-2011-6.

Dee DP, and Coauthors, 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Q. J. R. Meteorol. Soc. 137: 553-597.

Done JM, Holland GJ, Bruyére CL, Leung LR, Suzuki- Parker A. 2013. Modelling high-impact weather and climate: lessons from a tropical cyclone perspective. Climatic Change, doi:10.1007/s10584-013-0954-6.

Gent PR, Danabasoglu G, Donner LJ, Holland MM, Hunke EC, Jayne SR, Lawrence DM, Neale RB, Rasch PJ, Vertenstein M, Worley PH, Yang Z-L, Zhang M. 2011. The Community Climate System Model version 4. J. Climate, 24: 4973-4991, doi: 10.1175/2011JCLI4083.1.

IPCC (Intergovernmental Panel on Climate Change). 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschufng J, Nauels A, Xia Y, Bex V, Midgley PM, eds). Cambridge, UK and New York, NY:Cambridge University Press.

Knutti, R., D. Masson, and A. Gettelman, 2013: Climate model genealogy: Generation CMIP5 and how we got there. Geophys. Res. Lett., 40, 1194–1199, doi:10.1002/ grl.50256.

Lorenz C., and H. Kunstmann, 2012: The Hydrological Cycle in Three State-of-the-Art Reanalyses: Intercomparison and Performance Analysis. J. Hydrometeor, 13, 1397–1420.

Moss, R.H., and co-authors. 2010: The next generation of scenarios for climate change research and assessment. Nature, 463, 747-756 doi:10.1038/nature08823.

Rasmussen R, and Coauthors. 2011. High-Resolution Coupled Climate Runoff Simulations of Seasonal Snowfall over Colorado: A Process Study of Current and Warmer Climate. J. Climate, 24, 3015–3048.

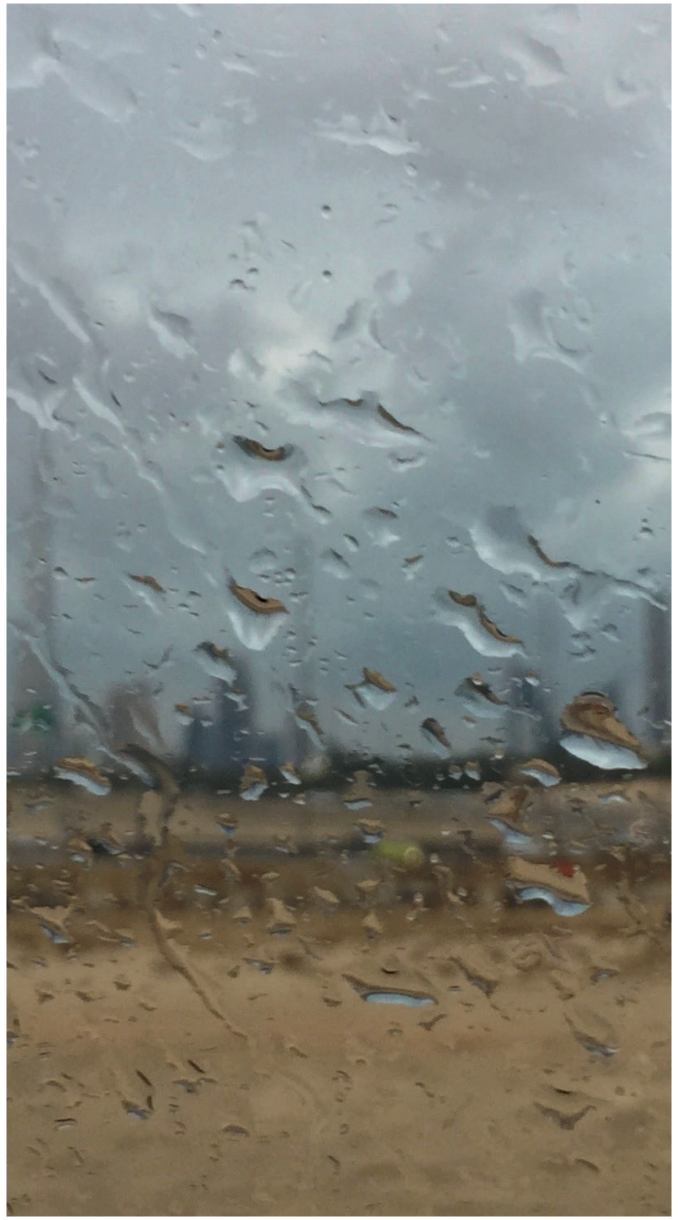
Reynolds RW, Smith TM, Liu C, Chelton DB, Casey KS, and Schlax MG. 2007. Daily high-resolution-blended analyses for sea surface temperature. J. Climate, 20: 5473-5496.

Riahi, K., S. Rao, V. Krey, C. Cho, V. Chirkov, G. Fischer,

G. Kindermann, and N. Nakicenovic, 2011: RCP 8.5 – A scenario of comparatively high greenhouse gas emissions. Climatic Change, 109, 33–57.

Skamarock WC, Klemp JB. 2008 A time-split non-hydrostatic atmospheric model for weather research and forecasting applications. J Comput Phys, 227: 3465-3485

Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Duda M, Huang XY, Wang W, Powers JG. 2008. `A description of the Advanced Research WRF Version 3`. NCAR Tech Notes-475+ STR.



Stauffer DR, Seaman NL. 1994. Multiscale four-dimensional data assimilation. J. Appl. Meteorol. 33: 416-434.

Taylor K.E., R.J. Stouffer, and G.A. Meehl, 2012: An Overview of CMIP5 and the Experiment Design Bull. Amer. Meteorol. Soc., 93: 485–498 doi:10.1175 BAMS-D-11-00094.1.

Thomson, A. M., K. V. Calvin, S. J. Smith,G. P. Kyle,A. Volke, P. Patel, S. Delgado-Arias, B. Bond-Lamberty, M. A. Wise, L. E. Clarke, and J. A. Edmonds, 2011: RCP4.5: a pathway for stabilization of radiative forcing by 2100. Climatic Change, 109, 77-94.

Xu Z, Yang Z-L. 2012. An improved dynamical downscaling method with GCM bias corrections and its validation with 30 years of climate simulations. J. Climate 25: 6271-6286, doi:10.1175/JCLI-D-12-00005.1.

About

AGEDI

Under the guidance and patronage of His Highness Sheikh Khalifa bin Zayed Al Nahyan, President of the United Arab Emirates, the Abu Dhabi Global Environmental Data Initiative (AGEDI) was formed in 2002 to address responses to the critical need for readily accessible, accurate environmental data and information for all those who need it.

With the Arab region as a priority area of focus, AGEDI facilitates access to quality environmental data that equips policy-makers with actionable, timely information to inform and guide critical decisions. AGEDI is supported by Environment Agency – Abu Dhabi (EAD) on a local level, and by the United Nations Environment Programme (UNEP), regionally and internationally.

For more information, visit www.agedi.org.

The Environment Agency – Abu Dhabi

The Environment Agency – Abu Dhabi (EAD) was established in 1996 to preserve Abu Dhabi's natural heritage, protect our future, and raise awareness about environmental issues. EAD is Abu Dhabi's environmental regulator and advises the government on environmental policy. It works to create sustainable communities, and protect and conserve wildlife and natural resources. EAD also works to ensure integrated and sustainable water resource management, to ensure clean air and minimize climate change and its impacts.

For more information, visit www.ead.ae.

All reports and resources are available for download at www.agedi.org and on our Climate Change Inspectors Online Portal, http://www.ccr-group.org/cc-inspectors.

CCR Group

Climate Change Research Group (CCR Group) is a sustainable development research and consultancy firm focused on the intersection of energy, climate and development. Our network of specialists works with international development organizations, national and local governments, as well as non-governmental institutions to formulate policy frameworks, technical assessments and capacity building programmes.

Since CCR Group's founding in 2009, we have lead projects across Africa, the Middle East, Eastern Europe, Asia and the Americas. Because each client faces a unique set of challenges based on local context, we have experience in developing strategies for multiple issue areas within sustainable development. Thematic issue areas and services for CCR Group include: Climate Change Adaptation Strategies; Greenhouse Mitigation Analysis; Climate Change & Disaster Risk Management; Climate Change, Agriculture & Food Security; Climate Change & Water Security; Climate Change & Public Health; Power Supply & Renewable Integration Modelling; Air Pollutant & Greenhouse Gas Emission Scenarios Modelling; and Capacity Strengthening Programmes.

For more information, visit www.ccr-group.org.

NCAR

The National Center for Atmospheric Research (NCAR) is a federally funded research and development center devoted to service, research and education in the atmospheric and related sciences. NCAR's mission is to understand the behavior of the atmosphere and related Earth and geospace systems; to support, enhance, and extend the capabilities of the university community and the broader scientific community, nationally and internationally; to foster the transfer of knowledge and technology for the betterment of life on Earth. The National Science Foundation is NCAR's sponsor, with significant additional support provided by other U.S. government agencies, other national governments and the private sector.

For more information, visit www.ncar.ucar.edu

LNRClimateChange@ead.ae

AGEDI
مبادرة أبوظبي العالمية للبيانات البيئية
Abu Dhabi Global Environmental Data Initiative

an initiative of

UNEP

هيئة البيئة - أبوظبي
Environment Agency - ABU DHABI

Abu Dhabi Global Environmental Data Initiative (AGEDI)
P.O Box: 45553
Al Mamoura Building A, Murour Road
Abu Dhabi, United Arab Emirates

Phone: +971 (2) 6934 444
Email : info@AGEDI.ae

AGEDI.org