

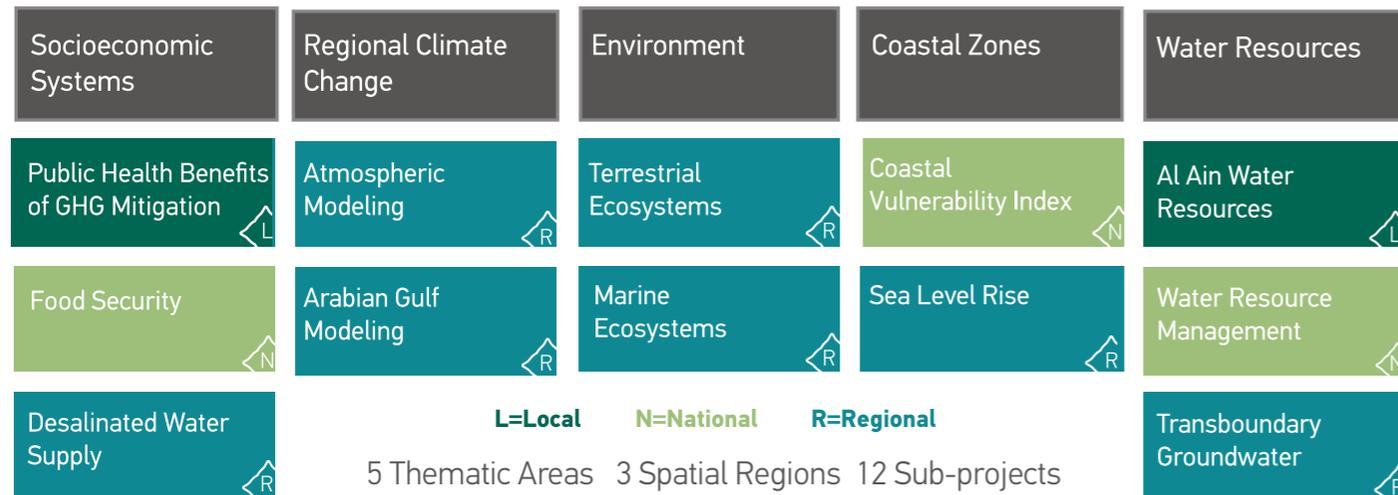
AGEDI | THE ABU DHABI GLOBAL ENVIRONMENTAL DATA INITIATIVE

CLIMATE CHANGE PROGRAMME

REGIONAL CLIMATE CHANGE ATMOSPHERIC MODELLING



Local, National and Regional Climate Change Programme 2013-2016



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Background

This goal of this Regional Climate Modeling 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 modeling 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.



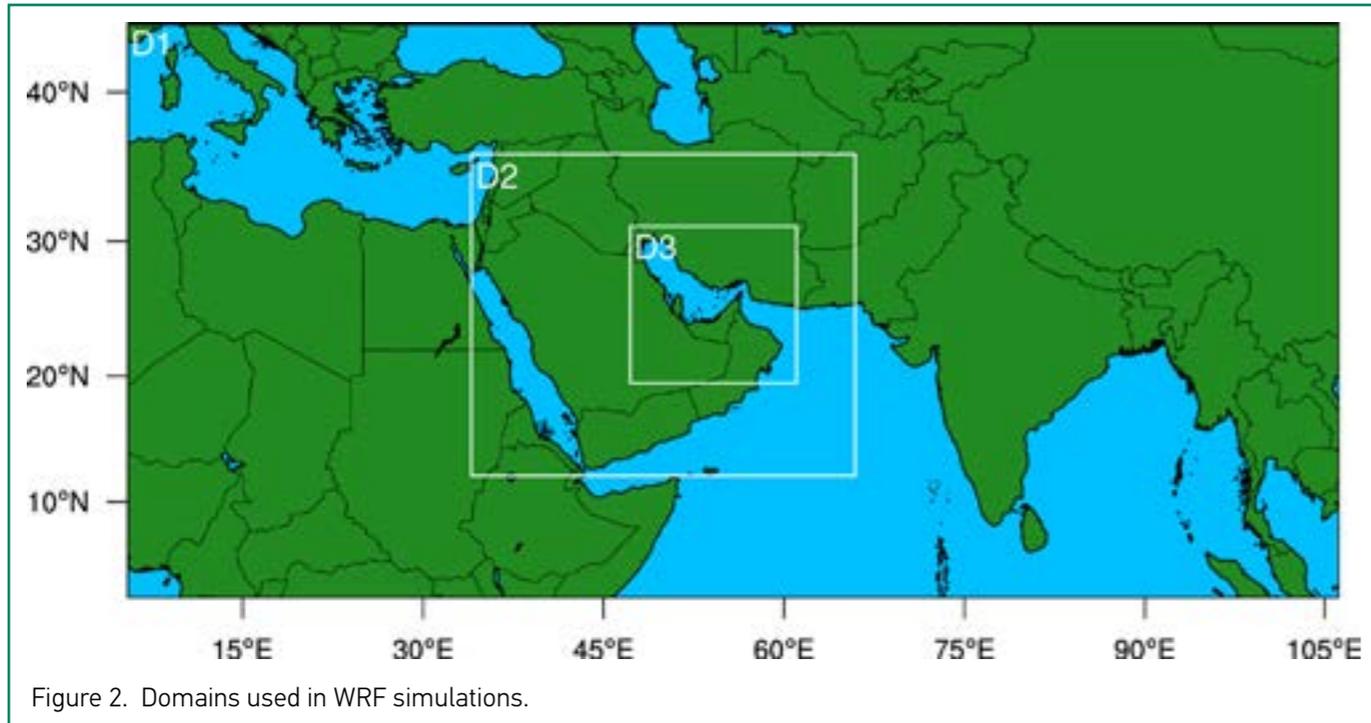


Figure 2. Domains used in WRF simulations.

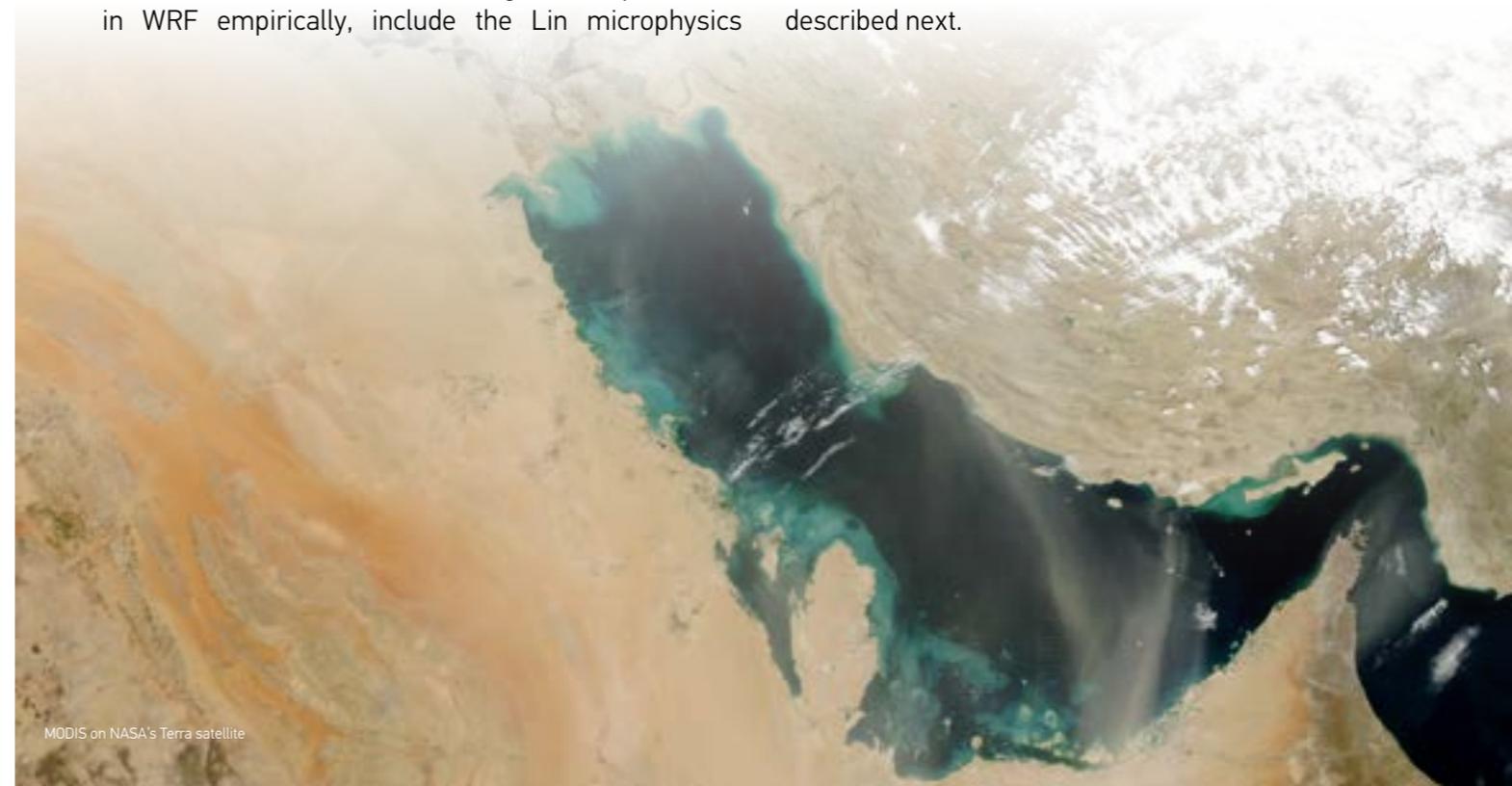
Configuration and the Climate Change Experiment

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.





WRF benchmark simulations with ERA-Interim

The ERA-Interim fields employed here for the benchmark simulations, have an $\sim 0.7^\circ$ 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 from the

simulations with WRF driven by the ERA-Interim reanalysis data. These simulations represent real meteorological events in the summer and winter of 1995, respectively; 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.



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WRF Results - Rainfall

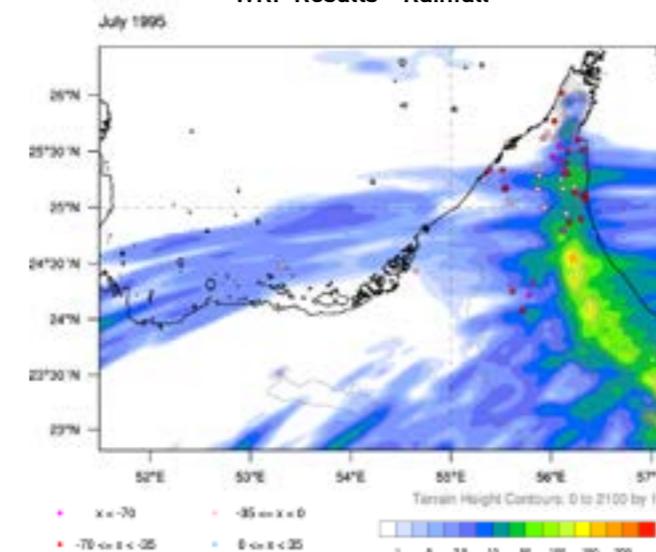


Figure 3. WRF rainfall biases (color-coded dots), WRF rainfall (mm, color shading), and WRF terrain height (gray contours) for July 1995 for subset of domain in Fig. 1

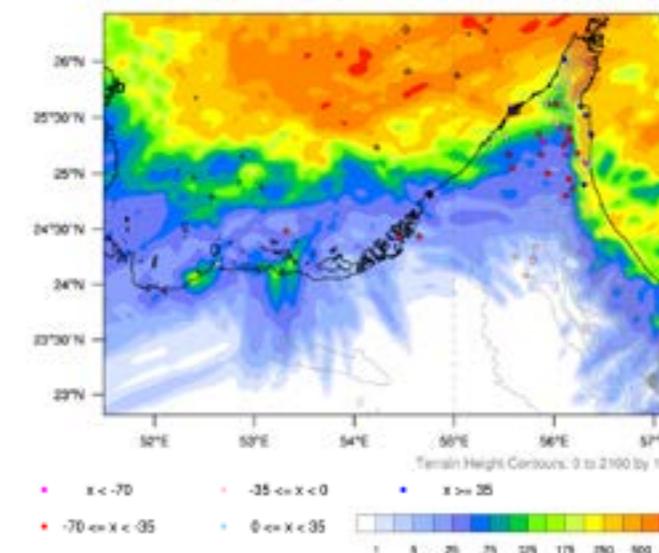


Figure 4. Same as (a) except for December 1995.



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.

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 orography 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 - Program 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 forcing 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 was used, as that is the only member that has available at 6-hourly intervals the full three-dimensional fields required to force WRF.



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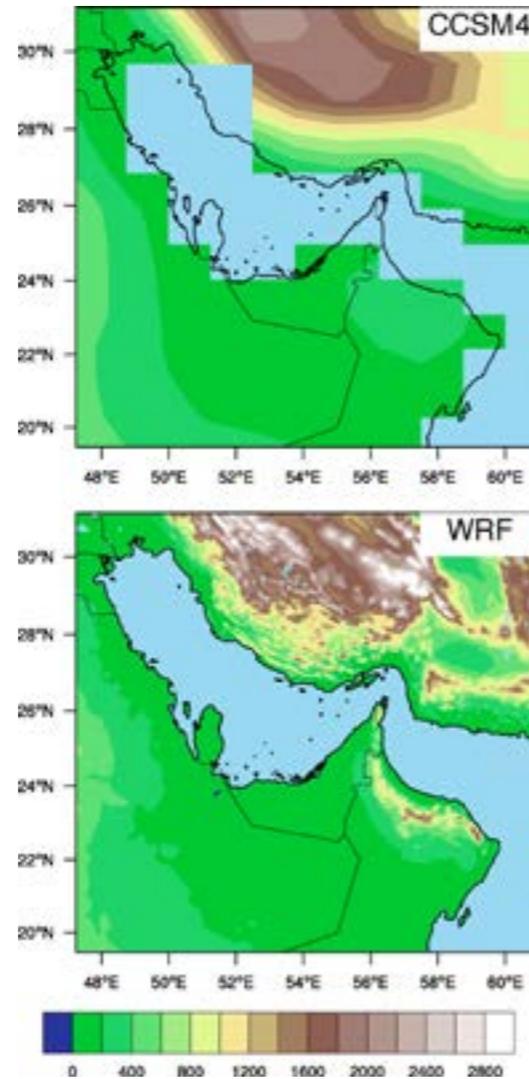


Figure 5. Terrain height (m, color scale at bottom) and land/sea mask for CCSM4 (top) and 4-km WRF (bottom). Actual coastlines and political boundaries shown in black

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; Bruyère 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:

$$\begin{aligned} CCSM &= \overline{CCSM} + CCSM' \\ ERAINT &= \overline{ERAINT} + ERAINT' \\ CCSM_R &= \overline{ERAINT} + CCSM' \end{aligned}$$

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).



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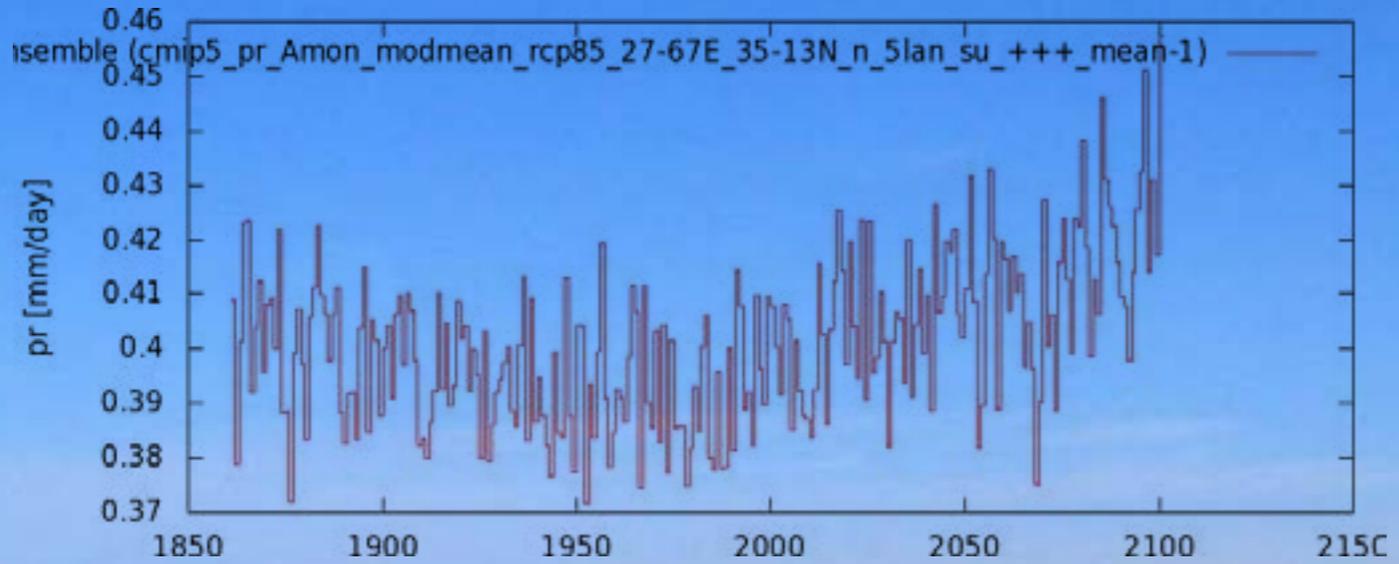


Figure 6. Mean precipitation anomaly from the full suite of GCMs from the IPCC AR5 experiment for the Arabian Peninsula region.

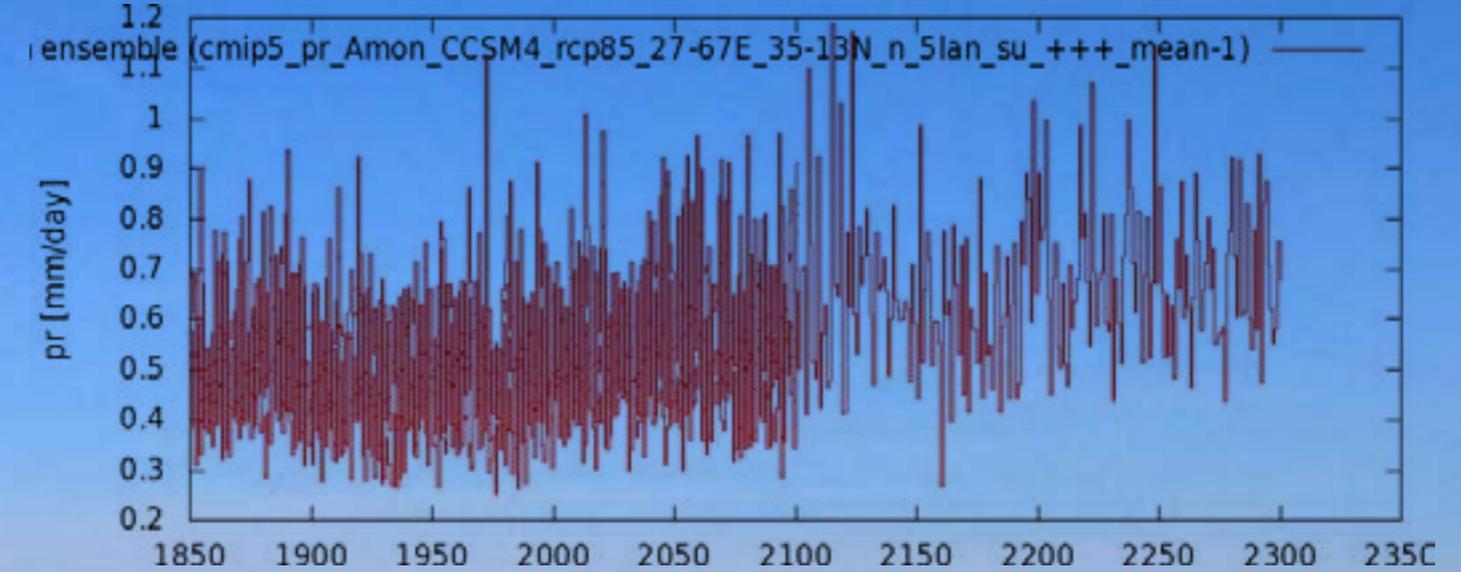


Figure 7. Projected change in the precipitation anomaly for the CCSM4 model, which includes multiple ensemble members. Some ensemble members included runs past 2100 and is why the graphs extends to 2300, with some ensemble members run out that far.

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 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 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.

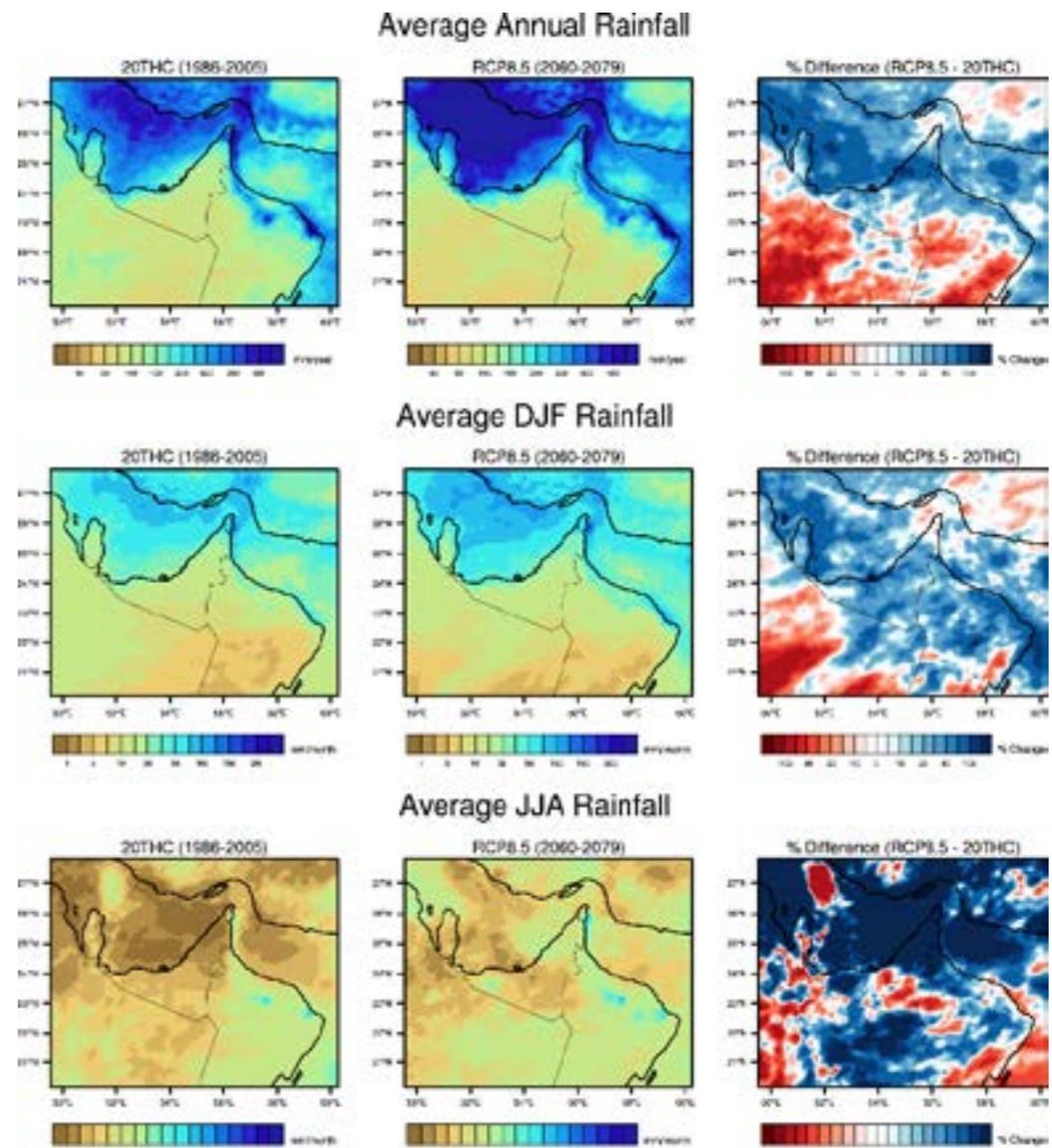


Figure 8. WRF rainfall estimates for the 20THC simulation (left column), RCP 8.5 simulation (center column), and the difference (percentage change of RCP 8.5 minus 20THC; right column), averaged annually (top row), winter (middle row), and summer (bottom row).



Wet Days Index

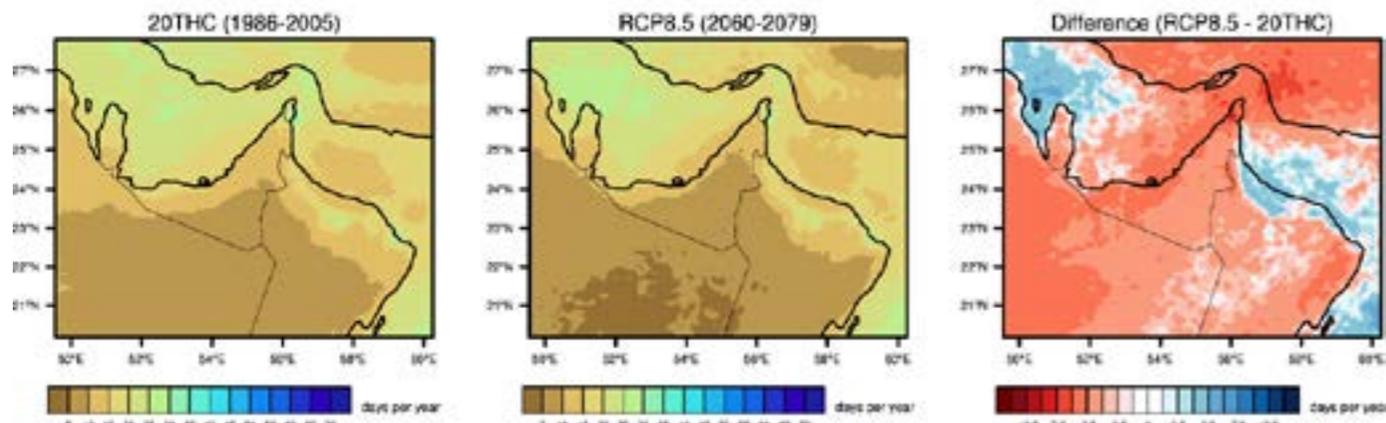


Figure 9. Wet Days Index values (the number of days with rainfall greater than 1 mm, summed over the 20-year time periods), for 20THC (left), RCP 8.5 (center), and the difference (RCP 8.5 minus 20THC; right).

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.

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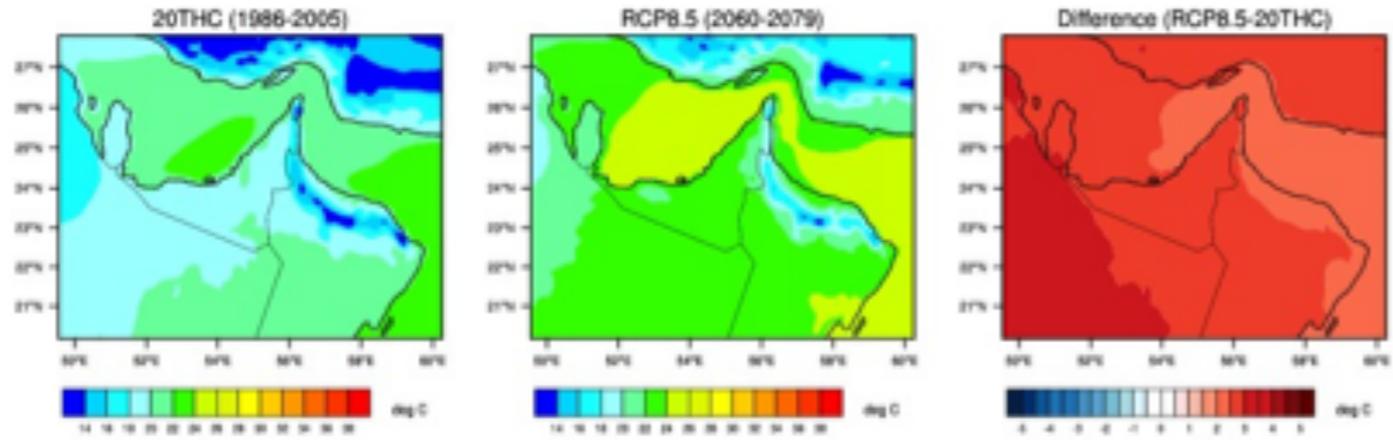
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Average DJF 2-m Air Temperature



Average JJA 2-m Air Temperature

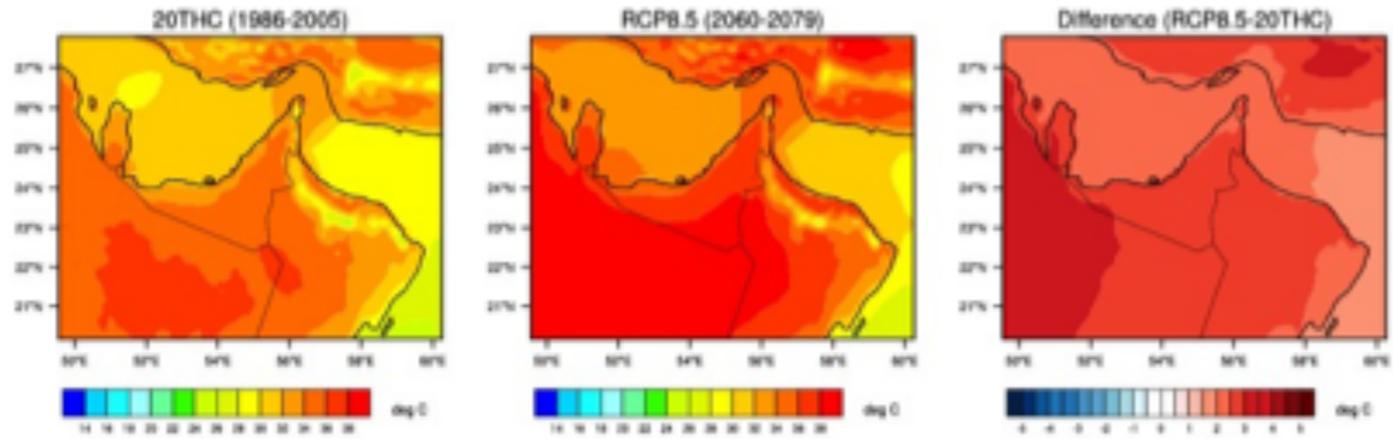
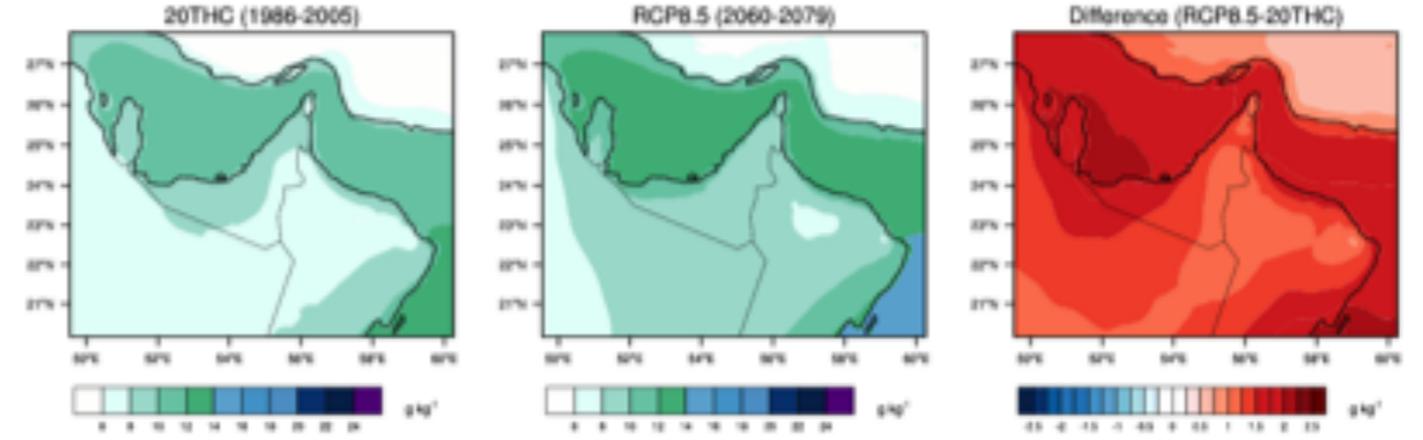


Figure 10a. Seasonal changes in 2-m air temperature (°C) and 10-m specific humidity (g/kg)



Average DJF 10-m Specific Humidity



Average JJA 10-m Specific Humidity

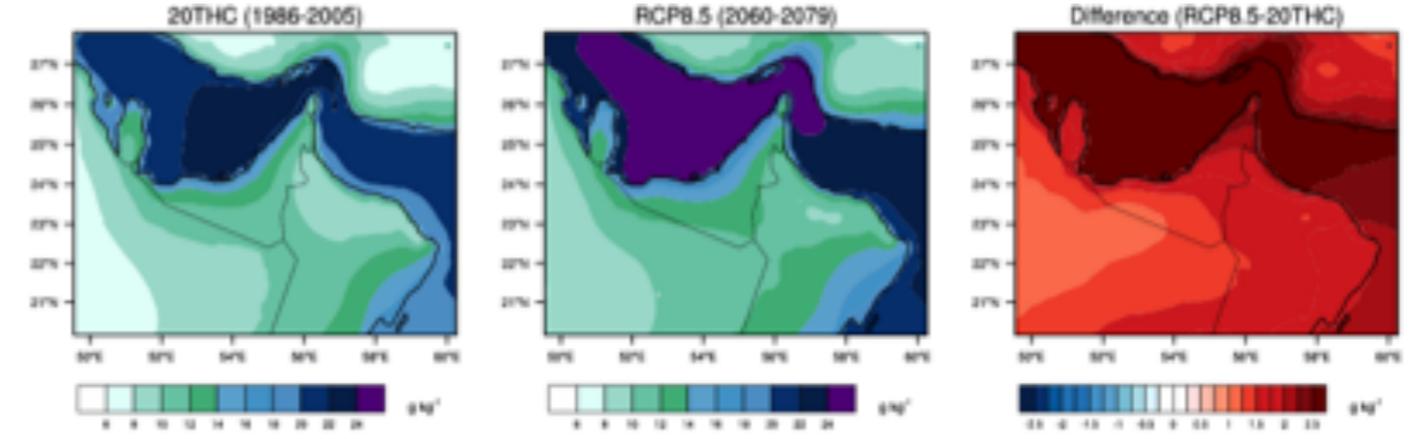


Figure 10b. Seasonal changes in 2-m air temperature (°C) and 10-m specific humidity (g/kg)

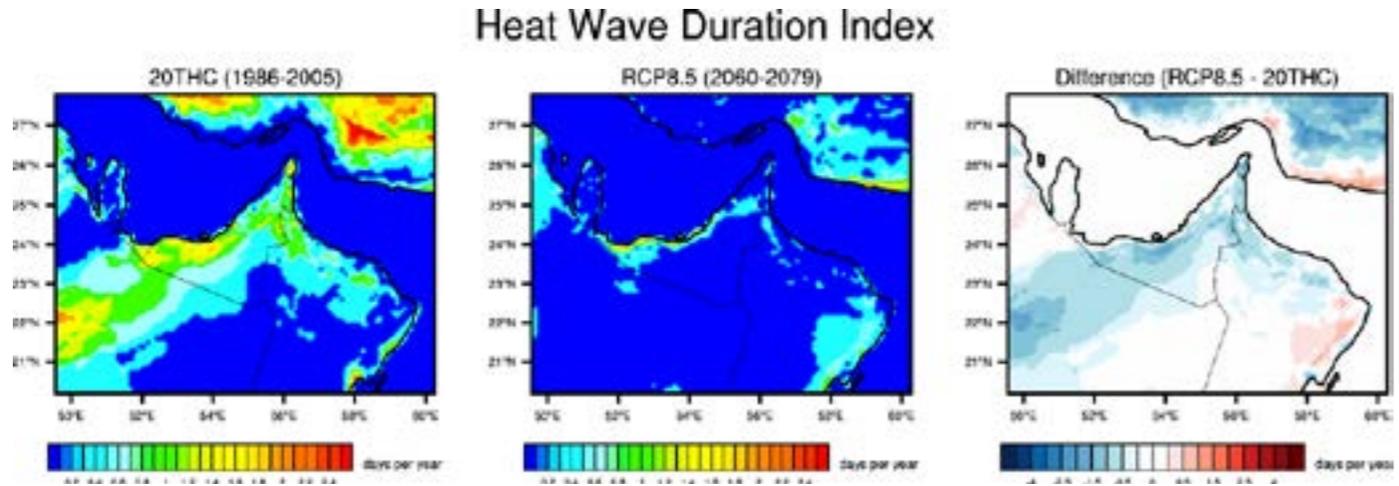


Figure 12. Heat Wave Duration Index values (the number of days, in intervals of 6 days, that the daily maximum temperature is greater than 5°C above a reference value), for 20THC (left), RCP 8.5 (center), and the difference (RCP 8.5 minus 20THC; right).

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.

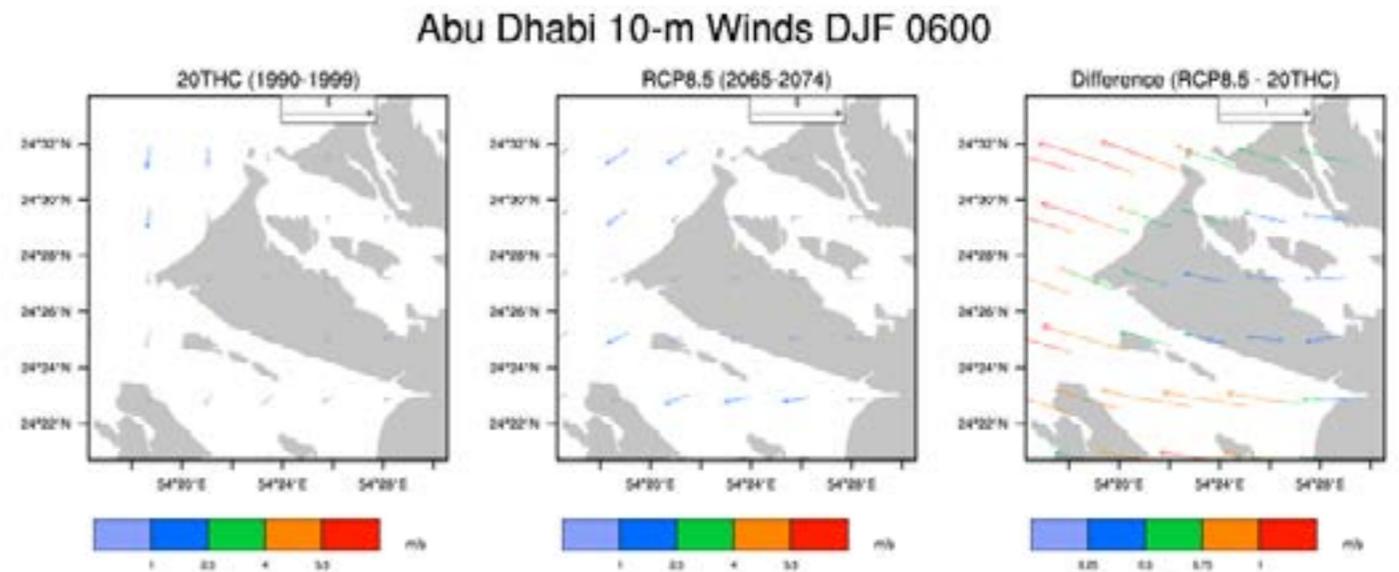


Figure 12a. Mean 10-m winds around Abu Dhabi Island for DJF, early morning local time (0600).

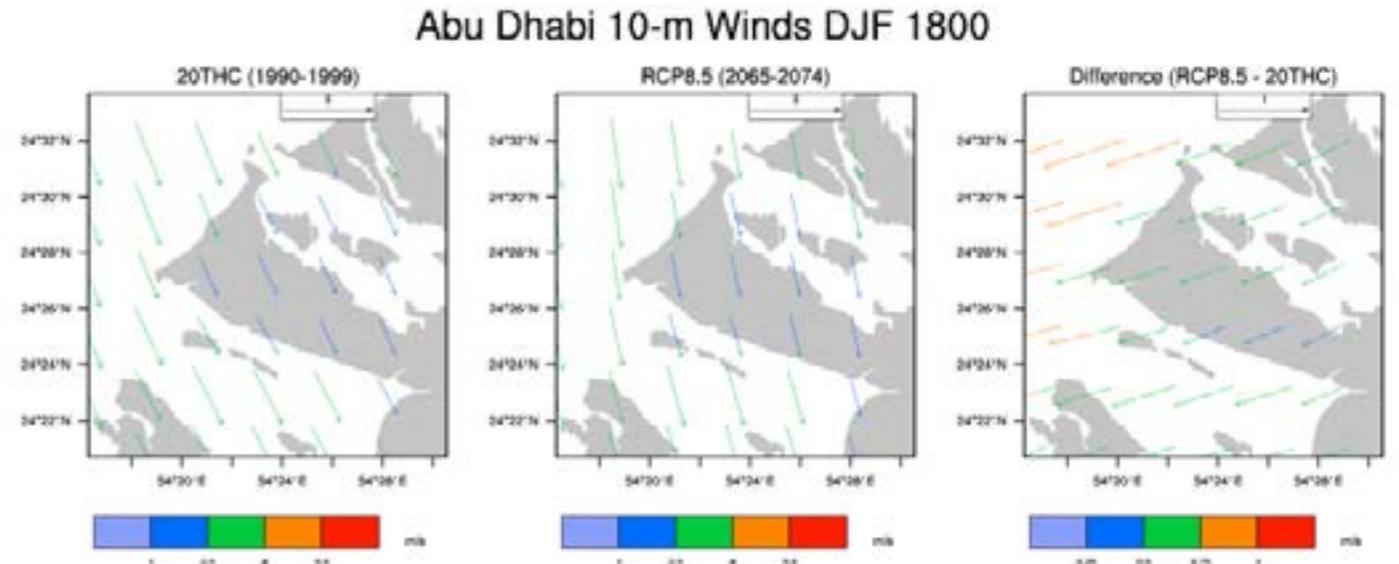


Figure 12b. Same as Figure 12a, except for the early evening (1800 local)



Figure 13a,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 morning, 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.

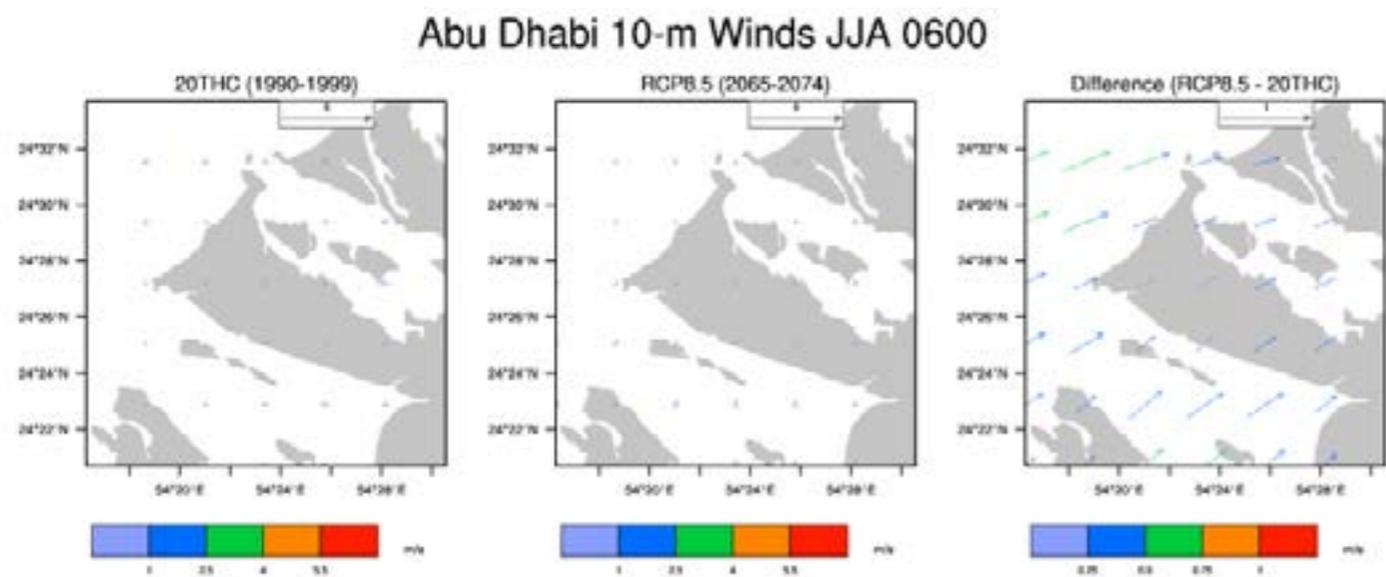


Figure 13a. Mean 10-meter winds near and around Abu Dhabi Island for JJA, early morning local time (0600).



Abu Dhabi 10-m Winds JJA 1800

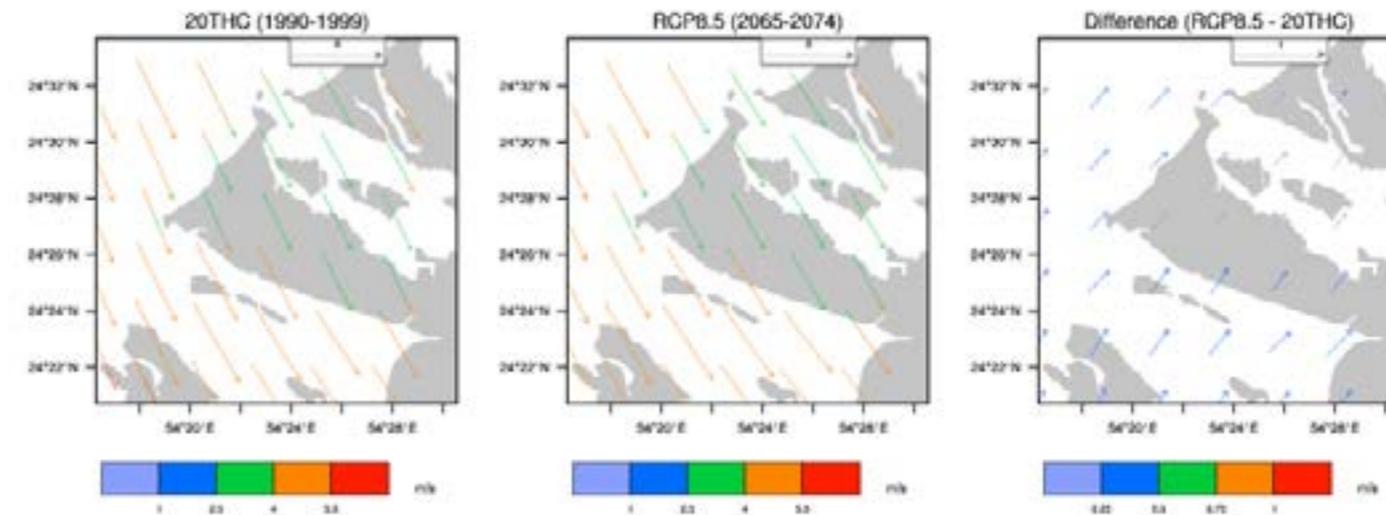
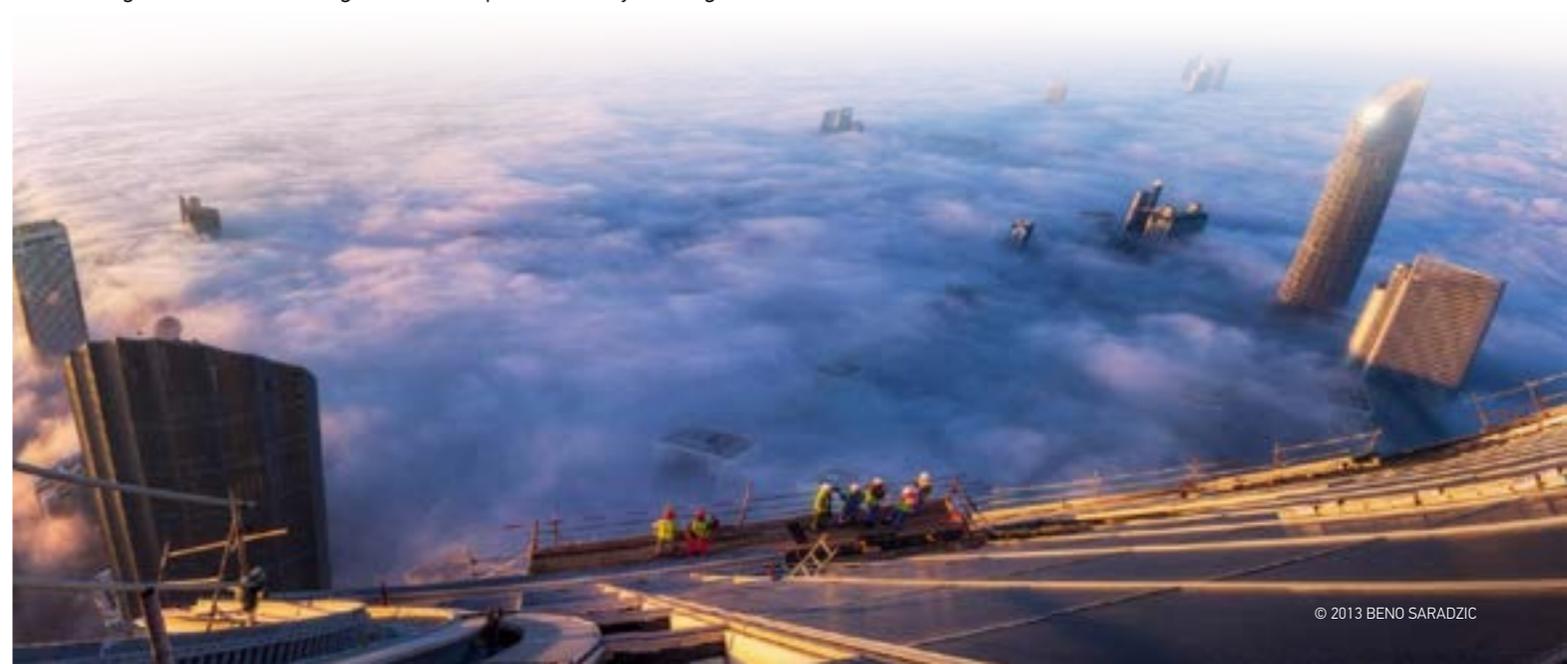


Figure 13b. Same as Figure 13a, except for the early evening (1800 local)





This Regional Atmospheric Modeling 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 of 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-Interim 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 analyses. 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.



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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 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 modeling 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 modeling 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 modeling. Given the importance of dust, it would be valuable to explore how changing climate might impact dust formation, transport and deposition in the region.



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 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 modeling 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 modeling

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-Interim 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



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About



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