Impact of Global Warming on Regional Climate over the Arabian Peninsula

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• **Focus:** Regional climate change, Climate feedbacks, Dust effect on climate and air quality - this is my group research effort

• **Motivation:** The pace of warming in the Middle East is higher than average over the Globe. The regional climate is more challenging to predict than global because of the nonlinear effect of circulation and desired high spatial resolution. New high-resolution predictive methods are required to produce a reliable regional climate forecast suitable for planning and adaptation purposes

• **Objective:** We evaluate the mechanisms of the regional climate sensitivity in the Middle East. For this we consider the observed regional impact of the 1991 Pinatubo aerosol forcing and quantify the impact of the regional dust aerosol forcing. I also introduce a coupled regional research tool we developed for this purpose
Regional Warming (with respect to pre-industrial 1850-1900) over the Arabian Peninsula (AP) is 30% faster than average over the Globe.

The AP and other desert regions are more sensitive to radiative forcing than the Globe.

21 Member CMIP5 Model Ensemble Prediction for the 21st Century
Spatial Distribution of Projected Warming in 2100

- The interior of the Arabian Peninsula warms faster than the coastal areas due to the effect of internal water bodies Red Sea, Arabian Gulf, and Mediterranean Sea.

Temperature Anomalies for 2069-2098 with respect to pre-industrial mean 1850-1900
The Middle East contributes 20-30% to global dust emissions

Dust affects Climate and Air Quality

- Dust storms originating in the Middle East strongly affect the regional radiation budget, cyclogenesis, atmospheric circulation, and air quality.

- Dust also severely affects the regional seas, the Red Sea and the Arabian Gulf.

- The mean dust shortwave radiative (SW) forcing over the southern Red Sea is the largest in the world, reaching 60 W/m².

- Dust provides nutrients for marine microorganisms.
Dust is raising

Pinatubo Cooled the Planet by 0.5 C

Dust absorbs SW Radiation & cools the Sea

Middle East Cooling was Much Higher than Global

Dust absorbs SW Radiation & cools the Sea

Global Volcano Plume and its Radiative Effect

Klingmuller et al., 2016

Robock, 2000

Aerosol Optical Depth is the largest in the Southern Red Sea in Summer

Solar radiative forcing is the largest in the World reaching 60 W m²
We Developed Coupled Ocean-Atmosphere Regional Modeling System to better understand

- Why the Middle East has high Regional climate sensitivity
- What is the regional effect of locally generated radiative forcing
- How internal seas could be affected by radiative forcing

**Pinatubo case:**
Mie + Sato optical depth and effective radius (Sato, 1993 & Stenchikov, 2006)

**Dust case:**
Mie, T-matrix and geometric optics + SEVIRI optical depth (Osipov, 2015, Brindley, 2015)

**Framework:**
A Coupled Ocean Atmosphere Wave Sediment Transport Modeling System (COAWST)

**Atmosphere:**
Weather Research and Forecasting Model (WRF)

**Ocean:**
Regional Ocean Modeling system (ROMS)

**Osipov and Stenchikov, JGR-Oceans 2017 & 2018**

WRF, 30 km

WRF, 10 km

ROMS, 2 km

WRF BCs

30 min

Atmosphere (WRF, RRTMG)

Ocean (ROMS)

WRF BCs
Healthy coral reef

The observed Red Sea surface temperature decreased more than 1°C

The simulated Red Sea Temperature Anomaly well replicates the observations

Genin et al., 1995
Atmospheric response to Volcanic Forcing

Total cooling = Perturbed run minus 1987-1991 DJF climatology

Dynamical response is well captured by model due to imposed “observed” large scale circulation

Severe 1991 & 1992 DJF cooling of -1 and up to -2.5 C

Dynamical cooling = Control run minus climatology

Radiative cooling = Perturbed minus Control run

Dynamical cooling is 2-3 times bigger than direct radiative cooling by volcanic aerosol.

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<tr>
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<td>SST anomaly peak</td>
<td>-1 C</td>
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<td>Main forcing</td>
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<td>Heat uptake time scales</td>
<td>0.5 years</td>
<td>15 year</td>
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<td>Overturning anomaly</td>
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<td>10% (Atlantic Ocean)</td>
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Volcanic Forcing Strengthens Red Sea Overturning by 50%

Weakly stratified water column and strong atmospheric cooling result in increased deep water formation and strengthening of the overturning circulation.

θ, winter (DJF) climatology

Overturning stream function response

θ, 1992 winter (DJF) anomaly wrt climatology

Deep water formation region

Red Sea overturning time scales are 10 and 40 years for the 1st and 2nd cells, respectively.
Dust radiative Impact on the Red Sea

- Heavy climatological dust loading over southern Red Sea during JJA
- Surface radiative SW cooling up to -60 Wm$^{-2}$ and LW warming up to 20 Wm$^{-2}$
- SST response reaches -0.5 K
- Annual heat and freshwater budgets reduction by 3.2 Wm$^{-2}$ and 0.086 m year$^{-1}$.
- Dust slows down the Red Sea overturning circulation by 5-10%
The Middle East regional climate sensitivity is significantly higher than average over the Globe.

Regional Warming depends on the emission scenario but, in the worst case, could exceed 5 K in the central Arabian Peninsula by 2100. The spatial distribution of predicted warming indicates the important role of regional seas.

Coupled WRF-ROMS regional ocean-atmosphere model is a proper tool to tackle the Middle East regional climate. It calculated exceptionally well the impact of Pinatubo and dust radiative forcing on the Middle East.

Dust-induced regional radiative forcing develops an important climatological impact on the surface air temperature, SST, and sea circulation and has to be incorporated in predictive models.

The changes in atmospheric circulation patterns associated with the phase of Arctic Oscillation, Indian Monsoon, Atlantic SST, position of ITCZ, and ENSO contribute to regional sensitivity of the Middle East climate and produce even stronger climate signature than direct radiative forcing.

Red Sea, Arabian Gulf, and the Mediterranean Sea are affected by global warming and have to be interactively included in a coupled regional systems for future climate assessments.
This study was conducted in the scope of the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region supported by the United Nations Economic and Social Commission for Western Asia (ESCWA)
Volcanic Radiative Forcing

Aerosol optical depth for 0.55 micron

Instantaneous Net Radiative Forcing at T0A
Dust Forcing Slows Down the Overturning

October-May, driven by thermohaline forcing (inside the Red Sea)

June-September, driven by local wind forcing and GAIW intrusion (outside of the Red Sea)
Red Sea circulation responds differently to dust and volcanic radiative forcings

Winter:
- Wind
- Southern Red Sea
- Northern Red Sea

Summer:
- Dust: radiative cooling
- Wind

Pinatubo: dynamics cooling
Conclusions: Pinatubo case

- For the first time, regional coupled modelling approach was successfully applied to study the severe post-Pinatubo winter cooling in the MENA region.
- Regional model captures well the dynamical response in the region (unlike global models).
- Observed cooling in the MENA region was dominated by the circulation changes forced by volcanic aerosol. Dynamical cooling is 2-3 times stronger than radiative.
- Strong post-Pinatubo Red Sea SST reduction up to -1 C was reproduced.
- Regional modeling approach provides a natural way to separate dynamical (through boundary conditions) and radiative (through prescribed aerosol optical properties) impacts and could be used along with the global modelling approach.

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<td>Advection through the strait</td>
<td>Not perturbed</td>
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Dust Observations at the Red Sea coast

KAUST Campus Aeronaet Site

DUST observations using hand-held sunphotometer

Micropulse Lidar

DUST Deposition Measurements
Natural variability in the Red Sea

- Red Sea and North Atlantic SST variability exhibits a strikingly strong correlation
- Anomalies oscillate in a 60-70 year period
- The last warming cycle initiated in 1980 is rather abrupt, partly due to volcanic eruptions

Area-weighted three-monthly Hadley SST anomaly since 1870 averaged over the Red Sea and North Atlantic (0N-70N, 100W-30E).
We use the same Modeling Technology to assess Airborne Wind Energy Resources and Conduct Hazard Management Studies

Airborne Wind Turbines Annual Generation (kWh) Per Capita

Simulation of Rabigh Fire

Oil Tanks Fire in Rabigh at Saudi Electric Company Power Plant on 9-11 April 2021
Mean Annual surface air temperature anomaly projection over the MENA region until 2050 in RCP4.5 and RCP8.5 emission scenarios. The projections are calculated at KAUST using global High-Resolution Atmospheric Model (HiRAM) with 25-km grid spacing.
Regional Dust Impact

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Boundary Conditions:
ERA-INTERIM

Experiments:
Perturbed (with DUST) – P
Control (without DUST) – C
Runs for the 1996-2016 period

In Short Wave Spectrum:
Mie, Spheroidal particles, T-matrix and geometric optics + SEVIRI optical depth (Osipov, 2015, Brindley, 2015)

In Long Wave Spectrum:
Mie, Spherical Particles

Size Distribution from the AERONET climatology

Spectral optical properties $\varepsilon(\lambda)$, $\omega(\lambda)$, $g(\lambda)$

Atmosphere (WRF, RRTMG)

Ocean (ROMS)
Regional Geoengineering to Increase Precipitation over the Red Sea Coastal Plain

- Red Sea is the major natural resource and the major climatological entity
- Breezes circulate 1 Tt of water vapor from the Sea to the land
- Science question: Could precipitation be triggered by
  1. Coastal Afforestation – 1 billion trees (1/10 of Saudi Green Initiative)
  2. Surface albedo change or PV panel deployment in the coastal plain

Red Sea Evaporates 1000 Gt Water per year
Process Oriented Regional Model WRF-Chem

- One-Way Boundary Conditions
- Two-Way Boundary Conditions
Thermal response and validation

Temperature and salinity weekly anomalies (P-C)

Climatological monthly TOA fluxes

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<th>CERES TOA SW flux RMSE/Bias, (Wm²)</th>
<th>CERES TOA LW flux RMSE/Bias, (Wm²)</th>
<th>OISST-AVHRR SST RMSE/Bias, (C)</th>
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<td>COAWST C</td>
<td>15.33/-14.65</td>
<td>4.55/0.37</td>
<td>0.78/-0.39</td>
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<tr>
<td>COAWST P</td>
<td>2.31/-0.30</td>
<td>4.79/-2.16</td>
<td>0.62/0.01</td>
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Root-mean-square error and bias comparison statistics for monthly climatological CERES TOA SW and LW fluxes and OISST-AVHRR SST in relation to COAWST P and C simulations. Statistics are computed in the observation-simulation sense.
Red Sea is a concentration basin with inverse estuarine circulation at the strait of Bab el Mandeb.

**Heat budget:**
-3.75 Wm⁻² (-11 ± 5 Wm⁻²)

**Freshwater budget:**
2.08 m year⁻¹ (2.06 ± 0.22 m year⁻¹)
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