Regional Geoengineering to Increase Rainfall over the Red Sea Arabian Coastal Plains by Utilizing Sea Breezes

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Abstract. The Red Sea (RS), which is squeezed between Africa and Arabian Peninsula, has a high evaporation rate, exceeding 2 m of water per year. The water vapor is transported from the shorelines by breezes as far as 200 km landward. Relative humidity in the vicinity of the RS exceeds 80% in summer. Nevertheless, precipitation is scarce in most of the Arabian RS coastal plain except its Southern part, where mountain ridges reach 3 km height. The coastal mountains in the central part of the RS (18N-24N) are 1 km high and therefore cannot trigger orographic precipitation in the same way as the southern part of the RS coastal plain.

In this work we assess how deliberate changes (geoengineering) in land-surface characteristics affect precipitation over the Arabian RS coast. For these purposes we use the Weather Research and Forecasting (WRF) regional model to test whether altering the surface albedo or converting bare lands to wide leaf forests over an extended coastal plain region could trigger precipitation from the vast amount of water vapor transported by see breezes to the land. The calculations are performed using a cloud-resolving model configuration with 3 km grid spacing for the Summer season of 2013, 2015, and 2016, with boundary conditions derived from ECMWF 9 km operational analysis.

Our simulations show that geoengineering of land surface characteristics perturbs the coastal circulation. This includes the heat, moisture, and momentum exchange between land surface and atmosphere, as well as the breezes, the structure of the planetary boundary layer, cloud coverage, and eventually the amount of precipitation. We found that extended afforestation and increase in surface albedo are not effective in triggering precipitation over the RS coastal plains. Conversely, decreasing surface albedo over the coastal plains intensifies breezes, enhances vertical mixing within the Planetary Boundary Layer, and triggers more coastal precipitation. Such a decrease of surface albedo could be achieved by distributing solar panels over the coastal area, which will not only provide clean energy but also increase fresh water supply. This form of regional land-surface geoengineering, along with advanced methods of collection and underground storage of fresh water, provides a feasible solution to the mitigation of the Water Crisis in the Desert Coastal Regions.
1 Introduction

Water is an essential element of life for all living beings: humans, animals, and plants. Water plays a central and critical role in all aspects of human activity. Management of water resources over the Arabian Peninsula (AP) and the entire Middle East (ME) is challenging. Population growth, industries, and agricultural expansion over the past century have led to an increase in demand for water supply (Almazroui et al., 2012). Al-Ghamdi (2019), a water expert from King Faisal University, predicts that with the current rate of extraction, groundwater will run out within 13 years. The Kingdom of Saudi Arabia (KSA) has one of the highest rates of water consumption per capita in the world (Al-Zahrani et al., 2011; Al-Zahrani and Elhag, 2003).

There are four main sources of water in KSA: groundwater, surface water (precipitation runoff), treated water, and desalinated sea water from the Red Sea (RS) and Arabian Gulf. Desalination is an extremely energy-intensive process. KSA desalinises about 1 Gt of water per year in 30 water desalination plants using 1.5 million barrels of oil per day, thus producing 25-30% of all desalinated water in the world. Water treatment facilities also provide 1 Gt of freshwater annually. These two water sources are far not enough to cover the annual freshwater demand of 280-300 ton per capita.

Natural freshwater sources (groundwater and surface water) are scarce in KSA, since precipitation is low. Permanent river flows or natural lakes are not present since more than 70 % of the area in KSA is covered by deserts. Groundwater is pumped out from deep aquifers almost one kilometer below the surface, and is more than 9000 years old. These fossil aquifers are not replenishing and will be exhausted soon, as precipitation only replenishes groundwater in shallow aquifers in the upper soil layers. KSA captures about 0.78 Gt of rain water annually in 260 artificial water reservoirs. This is about a quarter of available runoff. The total water supply from natural renewable resources in KSA is about 6 Gt and it is controlled by available precipitation (Al-Rashed and Sherif, 2000).

According to the Koppen classification, the major parts of AP are hot and dry (Köppen, 1936), with little to no precipitation (Al-Jerash, 1985; Al-Taher, 1994). Almazroui et al. (2012) analyzed 27 ground weather stations for the period 1978 - 2009 and found a significant negative trend of rainfall over the KSA (47.8 mm per decade). Also, they demonstrate a positive trend of air temperature with a rate of 0.6°C per decade. Winter is considered the "wet" season while the precipitation in summer is very low. The annual total rainfall decreases in most regions of the KSA. According to Hasanean and Almazroui (2015) and Almazroui et al. (2012) a positive precipitation trend was observed only in the Southwest of the Arabian Peninsula that is under the influence of the Intertropical Convergence Zone (ITCZ) in summer.

The idea of artificially increasing the precipitation over the Arabian Peninsula has attracted attention for many years. For example, the feasibility of cloud seeding for precipitation enhancement was studied in Saudi Arabia in 2007-2009 (Kucera et al., 2010). The United Arab Emirates (UAE) is currently funding research on a rain enhancement program that explores different technical options (Mazroui and Farrah, 2017). Afforestation is another proven way of improving environmental conditions, one that has been practiced for a long time globally. Both afforestation and cloud seeding methods affect a specific region, with little consequences in the surrounding areas. These approaches could be developed as climate adaptation measures, and we collectively refer to them as regional geoengineering. We use this term in contrast with "global" geoengineering approaches, which have been proposed to counteract the effects of global warming (Shepherd, 2009; Fox and Chapman, 2011). One of the
most feasible geoengineering measures, known as Solar Radiation Management (SRM), involves injecting aerosol precursors, e.g., \(SO_2\), in the lower stratosphere similar to volcanic eruptions (Crutzen, 2006; Fox and Chapman, 2011). Robock et al. (2008) showed that injection of 5 Mt of \(SO_2\) per year to the lower stratosphere could decrease the global temperature by more than 0.5°C. The main concern of global geoengineering approaches like SRM is that their adverse regional effects that could worsen the environmental conditions in some highly populated regions. For example, it is known that SRM, similar to volcanic eruptions, could dampen monsoon circulation and decrease rainfall in Sahel (Trenberth and Dai, 2007; Haywood et al., 2013; Dogar et al., 2017). These effects might cause far reaching humanitarian crises, a concern which limits the application of such planetary-scale geoengineering technologies.

Regional geoengineering is free from the above-described disadvantage. Regional decrease of surface air temperature could be achieved by afforestation (Shrestha and Lal, 2006), or by the modification of surface properties such as surface albedo. These local scale geoengineering methods have potential to alter regional rainfall (Liu et al., 2018).

Such regional approaches could work if they successfully enhance the natural precipitation processes. The only region in KSA with regular rainfall is the South West coast, where the orographic precipitation occurs as a result of interaction between see breeze flow and mountainous terrain, where land elevation exceeds 2 km. The close proximity of the northern edge of the ITCZ in summer also plays a role. The mean annual precipitation in this region reaches 250 mm (Ter Maat et al., 2006) with the maximum in March and April (50 mm) and the minimum in October (3 mm) (Almazroui et al., 2012).

Unfortunately, the mountain range along most of the Arabian RS coast is not as high as in the southern RS. Therefore, most of the inhabited coastal plains of the KSA are much dryer than its southern region. In this study, we consider deliberate land-use changes that could potentially affect breeze intensity and consequently trigger precipitation over the coastal plains. We aim to utilize the vast amount of moisture that is naturally circulating between the RS and the coastal plains to enhance coastal precipitation.

Land cover changes are the major forcings that, along with greenhouse gases and aerosols, drive regional and global climate variability (Cao et al., 2015; Vitousek et al., 1997; Feddema et al., 2005; Foley et al., 2005). Forests play a vital role in local climate regulation due to their interaction with the hydrological cycle. Forests have relatively low surface reflectivity (albedo) which leads to the absorption of more solar radiation than bare land. To maintain their thermal regime trees increase evaporation, which cools the surface layer and facilitates precipitation. The role of land-use changes in altering convective rainfall has been documented, e.g., in (Pielke, 2001; Pitman, 2003). Junkermann W. (2009) demonstrated that large scale modification of vegetation cover can cause changes in local convection and water vapor availability. Pielke Sr et al. (2007) analyzed how the regional landscape affects rainfall. Kunstmann and Jung (2007) used a Mesoscale Meteorological Model 5th generation (MM5) for West Africa to investigate the role of initial soil moisture on the total rainfall and on the recycling of precipitation. The influence of land use on precipitation and the latent and sensible heat fluxes was demonstrated in (Chen and Avissar, 1994a, b). Eltahir (1989); Eltahir and Bras (1996) studied precipitation recycling in Central Sudan. They showed that the high levels of evaporation from the Bahr Elghazal basin has a significant effect on the climates of neighboring dry regions.

The land-sea breeze circulation is a local-scale phenomenon that is linked to the mesoscale weather processes (Haurwitz, 1947; Zolina et al., 2017; Davis et al., 2019). In the coastal regions, the precipitation cycle tends to be affected by the land-sea
breeze as well as by the local coastal terrain (Zhu, 2017; Mapes BE, 2003; Qian, 2008). For example, a strong land-sea breeze from Mississippi leads to greater areal precipitation coverage in summer (Hill CM, 2010). Davis et al. (2019) analyzed in situ meteorological measurements to characterize the RS land-sea breeze circulation and its impact on regional climate. They claim that the RS land-sea breeze circulation system is one of the strongest in the world and has a deep influence on precipitation and surface temperature regime in all four seasons of the year. It is most intensive in summer and early fall. We also know that the RS loses about 2 m of water per year by evaporation. In total this brings about 0.9 Tt of water per year to the atmosphere, which is 7.6% of the mass of total atmospheric water vapor (Morcos, 1970; Nassir, 2012; Trenberth and Smith, 2005). In the RS coastal plains, sea breezes transport this water to land areas but little of this water forms precipitation (Khan et al., 2018; Davis et al., 2019). Instead, most of this water returns back through the reverse upper branch of breeze circulation and is advected south to the ITCZ. The water vapor abundance in the atmosphere and its naturally driven transport to the land by sea breezes intrigued us to test the feasibility of controlling this process, with the aim of increasing precipitation in the RS coastal areas.

Thus, in this study we evaluate the potentials of RS breeze management techniques in enhancing freshwater resources. We consider this approach to be regional-scale geoengineering. Unlike global geoengineering, it will only affect a restricted area where most of the possible side effects could be controlled. The science questions we explore in this study are as follows:

- How do changes of surface albedo, soil moisture, and afforestation in the Arabian RS coastal plains affect precipitation and surface air temperature?
- How sensitive the outcome of regional land surface geoengineering to the size and geographic positioning of a geoengineered region?

To answer the above questions we conducted a series of numerical experiments using the mesoscale regional model WRF to change the land-use type and surface albedo within a limited coastal area. We then analyzed the results and model sensitivity to input parameters. The paper is organized as follows: Section 2 describes the climatology of the region; Section 3 presents the data used in this work; Section 4 describes the model setup and regional climatology; Section 5 discusses the model evaluation and the results of the experiments; and finally, discussions and conclusions are presented in Section 6.

2 Red Sea Coastal Climatology

The western coast of the AP (or the eastern coast of the RS) is located in dry subtropics. It has a semi-arid climate with little rainfall, especially in its northern part (Rasul and Stewart, 2015; Khan et al., 2018). A mountain range that runs along the coastline directs the wind along the RS coast. For the entire summer (May to September) the prevailing winds are northwesterly over the entire RS region (Pedgley, 1974; Sofianos and Johns, 2002; Ralston et al., 2013). However, in the winter season (November to April) the so-called Red Sea Trough (RST), a low-pressure system centered in Sudan, combined with a seasonal collapse of the Somali Jet, create southeasterly winds in the southern part of the RS. The area where warm southern wind meets a relatively cold northern wind is called the Red Sea Convergence Zone (RSCZ). Heavy rainfalls and dust storms tend to
occur more frequently in this area (Tsvieli and Zangvil, 2005; El Kenawy et al., 2014; Awad and Almazroui, 2016). North of the RSCZ, the Mediterranean low-pressure system and its atmospheric cold front remain the main atmospheric controls. The annual mean precipitation over the RS coastal area is about 60 mm/year with the maximum in the south and the minimum in the north (Davis et al., 2019)

The RS is one of the warmest and saltiest basins on Earth. According to recent observations, the annual average Sea Surface Temperature (SST) of the RS is about 30°C (Chaidez et al., 2017).

Breeze circulation is driven by the high horizontal thermal contrast between land and sea, which creates a pressure gradient force directed from sea to land and pushes the moist sea air into a shallow layer over the land. Sea breeze circulation occurs when thermal forcing exceeds synoptic-scale forcing (Steyn and Faulkner, 1986; Khan et al., 2018). Local topography may block or channel this flow (Miller et al., 2003; Papanastasiou and Melas, 2009). When a warm and moist sea air mass meets opposing winds or coastal mountain ranges, it is forced to ascend (see Figure 1). If there is enough moisture in the air, clouds and precipitation can form (Evans and Westra, 2012). The inland extension of the breeze scales proportionally to the thermal contrast between sea and land. Khan et al. (2018) analyzed data from five RS coastal weather stations and found that the maximum inland breeze extent is in July, reaching about 200 km, and the minimum is in January at about 150 km. If the mean temperature and wind speed at the coastline are known, the breeze circulation length (inland extent) can be calculated using the following equation 1 (Pokhrel and Lee, 2011):

\[ BL = \frac{0.3429 \times 10^5 h}{T_m V} (T_{land} - T_{sea}) \]  

(1)

where, \( T_m \) is the mean surface air temperature (K) at coastline; \( V \) is mean wind speed (m/s) at the height of \( h = 10 \text{ m} \), \( T_{land} \) and \( T_{sea} \) are, respectively, surface air temperatures over land and sea, and \( BL \) is the breeze circulation length (km).

### 2.1 Land-use and surface albedo controls

The vegetation, type of soil, and other components of the terrestrial biosphere influence the climate by controlling the land-atmosphere interaction, i.e., the fluxes of latent and sensible heat, momentum, and chemical species between the atmosphere and underlying surface (Bright et al., 2015). Equation 2 presents the equilibrium surface energy budget,

\[ R_{SW\downarrow}(1 - \alpha_s) + R_{LW\downarrow} - R_{LW\uparrow} = R_G + H + LE \]  

(2)

where \( \alpha_s \) is surface albedo, \( R_{SW\downarrow} \) - downward shortwave radiation, \( R_{LW\downarrow} \) - downward longwave radiation, \( R_{LW\uparrow} \) - upward longwave radiation, \( R_G \) - ground heat flux, \( H \) - sensible heat fluxes, \( L \) - latent heat of evaporation, \( E \) - evaporation, and \( LE \) -
the total latent heat flux from the surface to the atmosphere that comes with water vapor. Strictly speaking, the total evaporated water results from evaporation from bare land and from vegetation by evapotranspiration. But here we do not separate these two processes and refer to them as evaporation, E.

Precipitation driven by mesoscale processes is rare because it requires multiple complex meteorological, thermodynamic, and circulation mechanisms to work in concert (De Vries et al., 2018; de Vries et al., 2013; Tanarhte et al., 2012). Modifying the mesoscale circulation is difficult and potentially dangerous, as it might affect vast areas. Instead, here we suggest deliberately changing the land-surface characteristics on a regional scale to alter the surface energy balance and trigger local precipitation. Within the scope of this work, we demonstrate how changes in land-use and/or the surface albedo \( \alpha_s \) can affect RS breeze circulation and consequently increase local precipitation. Because surface characteristics are altered in a limited area, these changes have little potential to affect the environment on a larger scale.

3 Observations

In order to evaluate model outputs, we compare model precipitation fields with the Modern Era Retrospective-Analysis for Research and Applications (MERRA2) reanalysis (Randles et al., 2017) and the Tropical Rainfall Measuring Mission (TRMM) (Liu et al., 2012).

3.1 MERRA2

The MERRA2 dataset provides 3D gridded meteorological data (reanalysis) on a latitude-longitude grid with a horizontal resolution of 0.625\( \degree \) X 0.50\( \degree \) and 72 sigma hybrid levels (Randles et al., 2017; Buchard et al., 2017). In this study, we use MERRA2 3-hour total precipitation fields to evaluate model output. MERRA2 data were obtained from https://gmao.gsfc.nasa.gov/reanalysis/MERRA2/.

3.2 TRMM

The Tropical Rainfall Measuring Mission (TRMM) is a joint space mission between the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Agency (JAXA) designed to monitor and study tropical rainfall. Operating until 2015, TRMM collected 17 years of valuable scientific data. The mission comprises 5 instruments: a 3-sensor rainfall suite (Precipitation Radar (PR), TRMM Microwave Imager (TMI), Visible and Infrared Scanner (VIRS)), and 2 related instruments (Lightning Imaging Sensor (LIS) and Clouds and the Earth’s Radiant Energy Sensor (CERES)). TRMM observations were processed by NASA and distributed to users on a uniform space and time grid with 25 km horizontal resolution and 3-Hours temporal resolution. TRMM data can be downloaded from http://disc.sci.gsfc.nasa.gov/precipitation/documentation/TRMM_README/TRMM_3B42_readm. In this study the Clouds and the Earth’s Radiant Energy Sensor (3B42RT) dataset is used. A detailed description of TRMM data can be found in Huffman et al. (2007).
4 Model Setup

The Weather Research and Forecasting (WRF) model is a mesoscale numerical weather prediction system, fully compressible and non-hydrostatic. It is used in a large number of applications for climate and land-atmosphere research. In this study, we use the WRF Advance Research Weather (ARW) dynamics solver (Skamarock et al., 2005) version 3.9.1. To describe land surface processes and estimate surface fluxes to the atmosphere, we employ the Noah land surface model (Tewari et al., 2004). The list of main physical parameterizations used in our experiments is presented in table 1.

Table 1. Model configuration and main physical parameterizations used in experiments.

<table>
<thead>
<tr>
<th>Atmospheric Process</th>
<th>WRF-Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longwave radiation</td>
<td>RRTMG (option 4) Scheme (Iacono et al., 2008)</td>
</tr>
<tr>
<td>Shortwave radiation</td>
<td>RRTMG (option 4) Scheme (Iacono et al., 2008)</td>
</tr>
<tr>
<td>Microphysics Scheme</td>
<td>Thompson Scheme (option 8) (Thompson et al., 2008)</td>
</tr>
<tr>
<td>Boundary-Layer</td>
<td>Mellor-Yamada-Janji Turbulent Kinetic Energy (TKE) Scheme (option 2) (Janjić, 1994)</td>
</tr>
<tr>
<td>Cumulus cloud</td>
<td>Turned off</td>
</tr>
<tr>
<td>Surface Layer</td>
<td>Monin-Obukhov (Janjić) Scheme (option 2) (Janjić, 1994)</td>
</tr>
<tr>
<td>Land Surface Model</td>
<td>Unified Noah land-surface model (option 2) Tewari et al. (2004)</td>
</tr>
</tbody>
</table>

We configured the WRF model with one domain (see Figure 2) which covers the RS and its coastal regions. The model domain has an area of 3,881,250 km² with 575 grid points along the latitude and 750 grid points along the longitude, and a horizontal resolution of 3x3 km². 50 hybrid levels, 25 of which are located in the planetary boundary layer, describe the vertical structure of the computational domain. We use the Lambert Conformal Conic (LCC) geographic projection (Brown, 1935; Snyder, 1978). For calculating the meteorological initial and boundary conditions, we use the European Centre for Medium-Range Weather Forecasts (ECMWF) operational analysis (F1280) with a spatial resolution of 9x9 km² and temporal resolution of 6 hours.

To ensure that the large-scale meteorological processes are correctly resolved in our simulations, we use spectral nudging of zonal and meridional wind components above the desert planetary boundary layer (z > 5 km) with a characteristic time of 10,000 s (Miguez-Macho et al., 2004). We nudge only the 10 largest modes in the free troposphere. This preserves large-scale meteorological forcing and allows the model to develop its own small-scale processes in the boundary layer.

In order to simulate regional or local meteorology accurately, land-use and other static fields should be of a high spatial resolution (Sertel et al., 2010; De Meij and Vinuesa, 2014; Baklanov et al., 2008). Therefore we compile land-use static parameters such as albedo, surface roughness, and vegetation cover using US Geological Survey (USGS) land cover data (USGS Gap Analysis Program, 2016) with effectively 1 km spatial resolution.
Figure 2. Simulation domain, geoengineering areas, and distributions of surface parameters: a) default surface albedo. The red contour line indicates the large geoengineered area used in experiments 2, 3, 4 and 5; b) land elevation (m), red contour lines depict selected northern and southern geoengineered areas used in Exp4,5_{north} and Exp4,5_{south}, respectively.

4.1 Experimental setup

In order to explore in detail the effects of land use and surface albedo together with sea breeze circulation on the amount of precipitation in the coastal region of the AP, we designed ten numerical experiments (see Table 2). The spatial domain we chose for the numerical experiments stretches along the RS east coast and covers both the RS and the coastal plains (see figure 2 - domain configuration). We chose the width of the geoengineered area, to be of the order of the breeze inland extent length...
The geoengineered area covers the parts of the coastal plain with low summer precipitation (less than 0.3 mm/day on average) in the north and the areas with relatively high summer precipitation in the south.

The control or reference experiment (Exp1) was calculated using the model settings from Table 1. In the second experiment (Exp2) we converted $150 \times 10^3$ km$^2$ of bare land in the selected area (Figure 2a) to wide leaf forest with a tree density of 50%, meaning 50% of each grid cell in the selected area was covered with wide leaf trees. The surface albedo, soil moisture, and leaf area index (LAI) were changed accordingly (see Table 2). In Exp2_smois we changed only soil moisture as in the wide leaf forest Exp2, keeping all other surface parameters identical to the control run. To assess the effect of surface albedo, three simulations Exp3, Exp4 and Exp5 were performed by modifying the albedo over the selected "Large area". We imposed a land surface albedo of 0.85 in Exp3, corresponding to the albedo of white sand; a surface albedo of 0.08, corresponding to the albedo of sea surface, in Exp4; and an albedo of 0.2 in Exp5, corresponding to the albedo of solar panels. It is known that the coastal terrain can affect breezes and precipitation. E.g., Qian et al. (2012) found that sea breeze intensity is sensitive to the height of the nearby plateau. To study the effects of topography, size, and geographic position of the geoengineered region on precipitation, we applied the same surface modifications as in Exp4 and Exp5 to smaller northern and southern areas (see 2b). The northern area, where the mountain range lies far from the coastline, has a terrain height of about 1 km. In the southern area, where the mountain range is closer to the coastline, the terrain height exceeds 2 km. We refer here to these experiments as Exp4_north, Exp5_north, Exp4_south and Exp5_south (see Table 2).

Table 2. Numerical experiments

<table>
<thead>
<tr>
<th>Experiment Name</th>
<th>Selected Area, $10^3$km$^2$</th>
<th>Surface Albedo, %</th>
<th>Topography</th>
<th>Land cover characteristics</th>
<th>Leaf area index, m$^2$m$^{-2}$</th>
<th>Green fraction, %</th>
<th>Soil moisture, m$^3$m$^{-3}$</th>
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</thead>
<tbody>
<tr>
<td>Exp1 (Reference Experiment)</td>
<td>0</td>
<td>Default</td>
<td>Default</td>
<td>Default (USGS dataset)</td>
<td>Default</td>
<td>Default</td>
<td>Default</td>
</tr>
<tr>
<td>Exp2</td>
<td>150</td>
<td>12</td>
<td>Default</td>
<td>Wide leaf forest</td>
<td>4</td>
<td>50</td>
<td>0.25</td>
</tr>
<tr>
<td>Exp2_smois</td>
<td>150</td>
<td>Default</td>
<td>Default</td>
<td>Default (USGS dataset)</td>
<td>Default</td>
<td>Default</td>
<td>Default</td>
</tr>
<tr>
<td>Exp3</td>
<td>150</td>
<td>85</td>
<td>Default</td>
<td>Default (USGS dataset)</td>
<td>Default</td>
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<td>Default</td>
</tr>
<tr>
<td>Exp4</td>
<td>150</td>
<td>8</td>
<td>Default</td>
<td>Default (USGS dataset)</td>
<td>Default</td>
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<td>Default</td>
</tr>
<tr>
<td>Exp5</td>
<td>150</td>
<td>20</td>
<td>Default</td>
<td>Default (USGS dataset)</td>
<td>Default</td>
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<td>Default</td>
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<tr>
<td>Exp4_north</td>
<td>67.5</td>
<td>8</td>
<td>Default</td>
<td>Default (USGS dataset)</td>
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<td>Exp4_south</td>
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<tr>
<td>Exp5_north</td>
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<tr>
<td>Exp5_south</td>
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<td>20</td>
<td>Default</td>
<td>Default (USGS dataset)</td>
<td>Default</td>
<td>Default</td>
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</tr>
</tbody>
</table>

According to observations, summer in the AP is the driest season (Climate.com, 2018). There is almost no precipitation in the north-western coastal area of the AP. Also, the inland extent and number of occurrences of sea breezes in summer are at their maximum (Khan et al., 2018; Davis et al., 2019). We, therefore, chose the summer season of 2013 (July-September) for...
our simulations. We report the results from this entire period, except the one-week spin-up time at the simulations’ beginning. To test how the inter-annual variability affects the results, we also conducted simulations for the summer seasons of 2015 and 2016.

5 Results

5.1 Model Evaluation

We tested the modeled precipitation against reanalysis and available observations. Since ECMWF operational analysis was employed to calculate initial and boundary condition, we preferred not to use this data set for the verification of precipitation fields, and instead chose the independent TRMM observations and MERRA2 reanalysis output. To conduct statistical analysis we interpolated all of the fields on to the same unified grid using a conservative interpolation routine (Bonelle et al., 2018). Since the subject of our research is precipitation, we have presented here a temporal and spatial statistical evaluation of the model primarily for precipitation fields. The model’s temporal bias (BIAS), root mean square error (RMSE), and Pearson correlation coefficient (R) for daily precipitation fields with respect to TRMM observations are shown in Figure 3 a,b,c. The model fields closely resemble the observations, with slightly dry biases in the area with a low precipitation rate(<0.3 mm/day), mostly on the eastern coast of the RS. The maximum dry (2-4 mm/day) and wet (8-10 mm/day) biases are seen over Africa, in the region with heavy precipitation related to Inter-Tropical Convergence Zone, with an average precipitation rate of 12-15 mm/day. In the southern part of the RS coastal plain, where convective activity over the local topography causes heavy rainfalls (Abdullah and Al-Mazroui, 1998), the model results exhibit a dry bias (1 mm/day). Figure 3 d,e,f shows a temporal correlation coefficient, RMSE, and the bias of daily precipitation from WRF with respect to MERRA2. The results are very similar to those of the WRF versus TRMM comparison.

We also evaluated the spatial patterns of the 3 months accumulated precipitation in WRF by comparing the simulated fields with the TRMM observations and the MERRA2 reanalysis. Figure 4 compares accumulated precipitation in different grid cells, both as simulated by the model and as observed by TRMM. It demonstrates a generally good agreement between simulated precipitation (WRF - red; MERRA2 - blue) and that observed by TRMM. Light cumulative (for 3 months) precipitations (up to 200mm) in WRF and MERRA2 are well correlated with TRMM. However, WRF overestimates heavy precipitation. Figure 5 confirms that the model captures the spatial distribution of accumulated precipitation over land well, but it shows disagreement with observations over the RS. The simulated average amount of precipitation over the domain is 138 mm which is closer to TRMM (130 mm) than MERRA2 (154 mm). The statistical characteristics of accumulated precipitation fields (Table 3) show that WRF can reproduce the precipitation patterns and that the model results are in a better agreement with TRMM than MERRA2.
Figure 3. Statistical evaluation of WRF daily precipitation rates using observations: a) the correlation coefficient of WRF vs. TRMM, b) the root mean square error of WRF vs. TRMM, c) the temporal bias of WRF vs. TRMM, d) the correlation coefficient of WRF vs. MERRA2, e) the root mean square error of WRF vs. MERRA2, f) the temporal bias of WRF vs. MERRA2
Figure 4. Scatter diagram of WRF (red) and MERRA2 (blue) accumulated precipitation for July-September 2013 versus TRMM observations. Solid lines are regression curves. Shaded area shows the 95% confidence interval for the regression estimate.

Table 3. Pearson correlation coefficient ($R$), root mean square error ($RMSE$) and temporal bias (BIAS) calculated for the 3 months accumulated precipitation fields from WRF, MERRA2, TRMM

<table>
<thead>
<tr>
<th></th>
<th>$R$</th>
<th>RMSE</th>
<th>BIAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>MERRA2 vs. WRF</td>
<td>0.881</td>
<td>170.2</td>
<td>16.1</td>
</tr>
<tr>
<td>TRMM vs. WRF</td>
<td>0.891</td>
<td>156.5</td>
<td>-8.7</td>
</tr>
<tr>
<td>TRMM vs. MERRA2</td>
<td>0.837</td>
<td>216.4</td>
<td>-24.7</td>
</tr>
</tbody>
</table>
Figure 5. Spatial distribution of accumulated precipitation (mm) from WRF simulations and MERRA2 and their comparison with gridded observation: a) TRMM, b) MERRA2, c) WRF, d) the difference between TRMM and WRF, e) the difference between MERRA2 and WRF, f) the difference between TRMM and MERRA2
5.2 Geoengineering scenarios

In this section, we analyze the geoengineering experiments’ results by comparing the output from sensitivity runs with the control \( Exp1 \) (see Table 2). In the first series of experiments (\( Exp2 \) and \( Exp2_{\text{snois}} \)) therefore we considered afforestation and change of soil moisture when latent heat flux is the primary forcing. In the second series of experiments (\( Exp3, Exp4, Exp5 \), and experiments with the application of geoengineering in the northern and southern subareas), we utilize the surface albedo as a geoengineering tool. In this case, the change in solar heating is the primary forcing.

5.2.1 Evaporation control

In \( Exp2 \) we converted \( 150 \times 10^3 \) km\(^2 \) of bare land into a broad-leaf forest (Table 2). Trees evaporate large amounts of water consuming only a small portion of it (about 5%) for their metabolism (Sinha, 2004). Since trees only evaporate if there is enough water available to sustain them, we assume that the soil moisture level of the upper soil layer is kept at 25%. The broad-leaf trees stop evaporating water and die if soil moisture falls significantly below this level. A water balance was calculated to define the water gain against the watering consumption in this modification scenario. The left column in Figure 6 shows the cumulative precipitation, evaporation, and their differences for the reference and perturbed experiments (see Table 2), integrated over the large and small geoengineering regions. The right column shows their added values in comparison with \( Exp1 \). In \( Exp2 \) evaporation significantly increases but precipitation (\( P \)) decreases. As a result, the soil water balance (\( P - E \)) is negative. To maintain the forest, it would require 37.6 Gt of water for the period of simulations (85 days), almost two-fold annual water consumption in Saudi Arabia.

This is counter-intuitive, since accumulated evaporation from the large afforested area is 39.5 Gt, which provides moisture to the atmosphere. The forested area has lower albedo than bare land (Swann et al., 2012) and therefore absorbs more solar radiation. Nevertheless, latent heat cooling prevails and surface temperature decreases. This leads to a weakening of breeze circulation and the shutting down of the moisture flux from the RS, which appears to be more important for formation of coastal precipitation than the added evaporation.

Figure 7 shows the wind vector, water vapor, air temperature, and relative humidity in \( Exp1 \), and their change in \( Exp2 \) with respect to the control run. The fields are averaged along the RS coast in the vertical cross-section that is perpendicular to the coastline. The time averaging was performed during the daytime from 0600 UTC to 1800 UTC when the sea breeze is active (Khan et al., 2018).

In \( Exp1 \) sea breeze in-land propagation is approximately 150-200 km (Figure 7, left column). This inland propagation is consistent with observations (Khan et al., 2018; Davis et al., 2019). The vertical extent of breeze circulation, as shown in Figure 7, reaches 3 km, almost 10 times higher than in mid-latitude breezes, because of strong surface heating and ascending coastal terrain. Figure 7 (right column) shows the increasing of the water vapor mixing ratio in \( Exp2 \) by up to 1 g/kg and relative humidity by 5% on the slopes of near-shore mountains. However, temperature over land decreases by 1 K, and breeze circulation significantly weakens. This damping of the breeze leads to a decrease in precipitation in the coastal plain.
Figure 6. Accumulated (for summer 2013) precipitation $P$, evaporation $E$, and $P - E$ integrated over the large (green), northern (red), and southern (blue) geoengineering areas in (Gt) in Exp1, Exp2, and Exp2_smois: a) $P$, c) $E$, e) $P - E$. Change of accumulated precipitation $\Delta P$, evaporation $\Delta E$, and $\Delta (P - E)$ integrated over large (green), northern (red), and southern (blue) geoengineering areas in (Gt) in Exp2 and Exp2_smois with respect to Exp1: b) $\Delta P$, d) $\Delta E$, f) $\Delta (P - E)$.
The spatial effect of afforestation on the amount of accumulated precipitation is shown in Figure 8a, which depicts the difference in accumulated precipitation in Exp2 and Exp1. The greenish color indicates an increase in precipitation, and the brownish color a decrease. The strongest decrease of accumulated precipitation exceeds 150 mm in the southern part of the selected region (south of 22.2°N, see Figure 8a), where breezes interact with the steep terrain, triggering precipitation. When breezes weaken, this process ceases. In the northern part of the coastal plain the decrease of cumulative precipitation reaches 40-50 mm (Figure 8a). We observe a slight increase of precipitation in the southwest of the Arabian Peninsula, as well as in the southern Yemen (not shown).

In summary, the afforestation experiment’s primary driving mechanism is the increase of evaporation that leads to surface cooling. The entire effect is complicated by the fact that the afforested area also changes the surface albedo. To better demonstrate this mechanism, we designed a more straightforward experiment Exp2_smois where soil moisture alone is changed to 25% in the geoengineered area, and land use and surface albedo remain the same as in the control run. Watering of bare soil was previously attempted to dampen dust generation (Fitz and Bumiller, 2000). The results from Exp2_smois are very similar to that from Exp2. However, the evaporation over the bare land is smaller than over the forested area. It requires 25.3 Gt of water for soil watering per season to maintain the soil moisture at a 25% level (see Figures 6 and 8). Intensified latent heat flux cools the surface by about 1 K, damps breeze circulation, and decreases precipitation over the geoengineered area.
Figure 8. Anomaly of accumulated precipitation (mm) in Exp2, Exp3, Exp4 and Exp5 for the period from 7 July to 31 September of 2013 with respect to Exp1: a) Exp2 – Exp1, b) Exp3 – Exp1, c) Exp4 – Exp1, d) Exp5 – Exp1
Figure 9. Accumulated (for summer of 2013) precipitation $P$, evaporation $E$, and $P - E$ integrated over the large (green), northern (red), and southern (blue) geoengineering areas in (Gt) in $Exp_1$, $Exp_3$, $Exp_4$, $Exp_5$, $Exp_{4\text{north}}$, $Exp_{4\text{south}}$, $Exp_{5\text{north}}$, and $Exp_{5\text{south}}$: a) $P$, c) $E$, e) $P - E$. Change of accumulated precipitation $\Delta P$, evaporation $\Delta E$, and $\Delta(P - E)$ integrated over large (green), northern (red), and southern (blue) geoengineering areas in (Gt) in $Exp_3$, $Exp_4$, $Exp_5$, $Exp_{4\text{north}}$, $Exp_{4\text{south}}$, $Exp_{5\text{north}}$, and $Exp_{5\text{south}}$ with respect to $Exp_1$: b) $\Delta P$, d) $\Delta E$, f) $\Delta(P - E)$.
5.2.2 Surface Albedo Control

Surface albedo is another parameter which controls the energy balance of the surface, it is linked to the type of vegetation and land cover properties, but can also be changed independently. Modification of albedo has been proposed to control temperature in different environments. For example, painting the roofs of buildings white has been suggested as a way to decrease solar heating in urban areas (Ismail et al., 2011). Selection of crops with higher albedo has also been proposed to decrease temperature in rural regions (Pongratz et al., 2012). In this context, we changed the albedo of the land surface to explore its effect on surface temperature, breeze circulation, and precipitation in the Arabian coastal plains.

Figure 10. Vertical cross-section of time mean meteorological characteristics averaged along the coastal line a) Water vapor mixing ratio (g/kg) and wind vectors (m/s) for Exp3, b) Same as a) but for Exp3–Exp1, c) air temperature (C) and wind vectors (m/s) for Exp3, d) Same as c) but for Exp3–Exp1, e) Relative humidity (%) and wind vectors (m/s) for Exp3, f) Same as e) but for Exp3–Exp1.

In Exp3 we increased surface albedo to 85%, aiming to reduce absorption of solar radiation, cool the surface and increase large scale stratiform precipitation similar to Exp2 and Exp2_smosis. The effect on precipitation appears to be negative, as breeze circulation breaks due to land cooling by 5-7 °C (see Figure 8, 9). Figure 10 demonstrates that sea breeze circulation is reversed. The time-averaged maximum 2m land temperature in Exp3 is decreased to 301 K, giving a negative land-sea temperature contrast of -1.9 K (Table 4). Therefore the flow direction reverses and heads from land to sea. The vertical extent of high water vapor mixing ratio decreases in comparison with Exp1 (Figure 10b). Maximum water vapor mixing ratio over land is now located within a shallow layer of 400-500 m. The amount of precipitation and evaporation in Exp3 both decrease to almost zero (see Figure 9). Thus, afforestation, watering of land surface, and increase of surface albedo cause weakening of the sea breeze circulation and has an adverse effect on precipitation.
Figure 11. Vertical cross-section of time mean meteorological characteristics averaged along the coastal line a) Water vapor mixing ratio (g/kg) and wind vectors (m/s) for Exp4, b) Same as a) but for Exp4-Exp1, c) air temperature (°C) and wind vectors (m/s) for Exp4, d) Same as c) but for Exp4-Exp1, e) Relative humidity (%) and wind vectors (m/s) for Exp4, f) Same as e) but for Exp4-Exp1.

In Exp4, we decreased surface albedo of the entire region to 0.08 (albedo of ocean at nadir). Contrary to Exp2, Exp2_smois, and Exp3, this warms the land, increases land-sea temperature contrast, and intensifies sea breezes due to increase land-sea temperature contrast. Warming over land triggers shallow convection and intensifies vertical mixing, thus altering the land-atmosphere fluxes of momentum, moisture, and heat, which feeds back into breeze circulation and cloud formation, and affects the local precipitation (see Figure 11). The strengthening of near-surface vertical wind due to stronger onshore flow also excites Kelvin-Helmholtz instability and hence turbulence in the boundary layer (Drobinski et al., 2006).

The most notable feature in Exp4 is the more intensive vertical mixing of water vapor in comparison with Exp1 (see Figure 11). High water vapor mixing ratio in Exp4 extends up to 5 km, while in the control run it was confined within the lower 3 km layer (Figure 7c). In Exp4 we see an approximately 20% increase in the relative humidity at a height of 4.5 km in comparison with the reference experiment. Exp4 demonstrates the increase in accumulated precipitation up to 250 mm in comparison with the control run (see Figure 8c). Thus, decreasing the surface albedo to 8% leads to a fourfold increase in both precipitation and evaporation compared with the reference experiment (see Figure 9). 3.4 Gt accumulated water Δ(P − E) is added for three months of simulations.

In Exp4 we chose a low limit for albedo. We therefore conduct the more realistic Exp5, where surface albedo was changed to 20%, mimicking the albedo of solar panels in the coastal plain area (Figure 2). This surface modification leads to an increase in rainfall over the highlighted area (see 9a). As expected, the added precipitation (1.5 Gt) is less than in Exp4 but still
significant. Installing solar panels increases precipitation and simultaneously provides an extra source of renewable energy that can be used for water desalination or other industrial purposes. The drawback is the increase of the near surface air temperatures.

### Table 4. Numerical estimation of land-sea breeze length (BL)

<table>
<thead>
<tr>
<th>Experiments</th>
<th>( T_{2m} )</th>
<th>( V_{10m} )</th>
<th>( T_{\text{land}} )</th>
<th>( T_{\text{sea}} )</th>
<th>( \Delta T )</th>
<th>BL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp1</td>
<td>305.23</td>
<td>4.58</td>
<td>307.13</td>
<td>304.13</td>
<td>3.00</td>
<td>147.18</td>
</tr>
<tr>
<td>Exp2</td>
<td>304.09</td>
<td>1.54</td>
<td>304.48</td>
<td>303.86</td>
<td>0.62</td>
<td>91.10</td>
</tr>
<tr>
<td>Exp3</td>
<td>303.90</td>
<td>2.09</td>
<td>301.57</td>
<td>303.44</td>
<td>-1.87</td>
<td>None</td>
</tr>
<tr>
<td>Exp4</td>
<td>305.51</td>
<td>3.44</td>
<td>308.33</td>
<td>304.25</td>
<td>4.07</td>
<td>265.81</td>
</tr>
<tr>
<td>Exp5</td>
<td>305.41</td>
<td>3.18</td>
<td>307.92</td>
<td>304.22</td>
<td>3.70</td>
<td>261.42</td>
</tr>
</tbody>
</table>

#### 5.2.3 Sensitivity to size, geographic location, and background topography of the geoengineering region

To investigate the influence of the background topography and location of the geoengineering area on breeze circulation and, consequently, on the amount of added precipitation, we conducted four additional experiments (\( \text{Exp}4_{\text{north}}, \text{Exp}4_{\text{south}}, \text{Exp}5_{\text{north}}, \text{Exp}5_{\text{south}} \)). In experiments \( \text{Exp}4_{\text{north}} \) and \( \text{Exp}4_{\text{south}} \) we applied the same surface modification as in \( \text{Exp}4 \), separately in the northern sub-area where mountain range height is about 1 km, or in the southern sub-area (see Figure 2a), where the land elevation is twice as high. Similarly, in experiments \( \text{Exp}5_{\text{north}} \) and \( \text{Exp}5_{\text{south}} \), we applied the same surface albedo modification as in \( \text{Exp}5 \), but in only one of the sub-areas. Figures 12 and 13 show the changes in accumulated precipitation and surface air temperature with respect to the control run in all sub-area experiments. All experiments demonstrate a positive increase in precipitation and surface temperature. The southern sub-area generates much more added water \( \Delta (P - E) \) than the northern one. The total added accumulated water in \( \text{Exp}4_{\text{south}} \) is 1.6 Gt and in \( \text{Exp}5_{\text{south}} \) is 0.7 Gt. The geoengineered area warms up to 2 K in \( \text{Exp}4_{\text{north}}, \text{Exp}4_{\text{south}}, \) and up to 1 K in \( \text{Exp}5_{\text{north}}, \text{Exp}5_{\text{south}} \).

In figure 9 we compare the area integrated cumulative precipitation (see Figure 2a) in all albedo experiments. It demonstrates that the albedo modifications in \( \text{Exp}5 \) and \( \text{Exp}4_{\text{south}} \) generate 1.5-1.6 Gt of added water. This is twice the annual amount of rainwater currently collected and stored in Saudi Arabia. In all albedo experiments, the northern region is much less productive in terms of added precipitation than the southern region. This is because the breeze intensity and the terrain effect are weaker in the northern region than in the southern region. This suggests that installing solar panels in the southern geoengineering area could be a better option than geoengineering the northern area or the entire large area.

#### 5.2.4 Interannual variability

To test the robustness of our results we repeated the albedo experiments (\( \text{Exp}4 \) and \( \text{Exp}5 \)) for summers of 2015 and 2016 (see Figure 14 and 15). We found that the year 2013 chosen for the analysis, had fewer wet days, defined as days with averaged
Figure 12. Change in accumulated precipitation (mm) a) $Exp_{north} - Exp_1$, b) $Exp_{south} - Exp_1$, and surface air temperature (K) c) $Exp_{north} - Exp_1$, d) $Exp_{south} - Exp_1$. 

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Figure 13. Change in accumulated precipitation (mm) a) $Exp5_{north}$-$Exp1$, b) $Exp5_{south}$-$Exp1$, and surface air temperature (K) c) $Exp5_{north}$-$Exp1$, d) $Exp5_{south}$-$Exp1$. 
Figure 14. a) Accumulated (for summers of 2013, 2015, 2016) precipitation $P$ (Gt) over large (green), northern (red), and southern (blue) geoengineering areas in Exp1, Exp4, and Exp5. b) Anomaly of accumulated (for summers of 2013, 2015, 2016) precipitation $\Delta P$ (Gt) over large (green), northern (red), and southern (blue) geoengineering areas in Exp4, and Exp5 with respect to Exp1.
daily precipitation higher than 0.2 mm, and less precipitation than in 2015 and 2016. Thus, we have probably underestimated the added water effect based on the analysis for 2013 by about 10%. But all conclusions from our 2013-year analysis remain intact.

![Bar chart showing number of wet days for different experiments and years](image)

**Figure 15.** Number of wet days \( \left( \frac{1}{N} \sum_{i=1}^{N} P_i > 0.2 \text{mm} \right) \) in Exp1, Exp4, and Exp5 for years 2013, 2015, and 2016.
6 Conclusions

Water scarcity linked to climate changes and global warming poses a threat to regions with dry, hot climates. The majority of countries in the Middle East, including Saudi Arabia, are in the middle of a water crisis (Hameed et al., 2019). Groundwater resources in these countries are rapidly depleting (Rodell et al., 2018). The most commonly used water desalination methods are highly unsustainable since they consume a lot of fossil fuel energy (Ahmed et al., 2019). The sporadic rains over the Arabian RS coast, which can release up to 100 Mt of water within a matter of few hours, (Deng et al., 2015) could serve as sources of freshwater. There have been previous systematic efforts to collect and reuse rainwater in Saudi Arabia. For example, a freshwater reservoir was built in 2009 by constructing a gravity dam on the coast of the RS in Rabigh, 150 km north of Jeddah (see Figure 16). Although several such reservoirs are operating in this region, they are replenishing very irregularly. All of them are of the open type, and therefore lose significant amounts of water to evaporation.

In this study, we evaluate the effects of regional-scale modifications of land-surface characteristics on breezes, and coastal precipitation, aiming at developing a regular and reliable source of fresh water that could be collected, effectively stored, and reused. We performed a series of numerical experiments using cloud-resolving WRF model altering the surface properties over the $150 \times 10^3$ km$^2$ coastal area by converting bare land into the wide-leaf forest, altering soil moisture, and varying surface albedo.

We find that afforestation, soil watering, and increasing of surface albedo cool the region, but decrease precipitation in the breeze affected areas. This is because land-cooling damps sea breeze circulation and decreases water vapor flux from sea to land. Conversely, a decrease of surface albedo warms the coastal regions by about 1 K, strengthens the sea breezes, and increases precipitation. The precipitation response is sensitive to the geopositioning and size of the geoengineered area. The more robust increase in rainfall and added water is found in the southern part of the geoengineered area (south of $22^\circ$), where mountains are higher, and sea breezes are stronger. Imposing an 8% ocean albedo gives the most substantial effect on added water (3.3 Gt in Exp4). Still, a more realistic albedo modification of 20% that mimics the albedo-effect of the installation of large-scale solar panel plants also gives a sizable increase of about 10 kt of added water per km$^2$ during the dry summer season (1.5 Gt in Exp5 and 0.7 Gt in Exp5$_{south}$). The surface albedo geoengineering works best in the southern area in Exp4$_{south}$ and Exp5$_{south}$. The enhanced moisture flow and the stronger vertical instability in the boundary layer due to more vigorous surface heating combine to increase precipitation over the mountain slopes, where the orographic lift adds in triggering rainfall. We find that the number of wet days in Exp4 and Exp5 almost doubles in comparison with Exp1 (see Figure 15).

Figure 16. Freshwater reservoir in Rabigh, Saudi Arabia. The capacity of the water reservoir is 0.22 Gt.
Thus, our experiments show that changes in land surface characteristics modulate local breeze intensity and precipitation in the RS coastal plains and mountain slopes. The reduction of land albedo appears to be the most effective surface modification, producing the most substantial precipitation increase. Modification of the surface albedo most effectively could be archived by distributing solar panels or concentrated solar power devices over the near-coast mountains’ slopes. Installing solar panels only in the southern region can provide 0.6 Gt of freshwater per summer season. Assuming that annual per capita freshwater consumption in Saudi Arabia is 282 t (Ouda, 2013), this amount of water could cover the seasonal consumption of 10 million people. If one unit of a solar panel has an effective area of $2 \text{ m}^2$ generating 30 kWh of electricity per month, then only the southern geoengineering region with the area of $69 \times 10^3 \text{ km}^2$ can produce about 1.4 TW of clean energy free from greenhouse emission (Castellano, 2010). While our experiments are idealized, they point to the feasibility of freshwater recovery from sea breezes by regional land surface geoengineering. Further research, including field experiments, should be conducted to assess the efficacy of the proposed measures. Because our methods utilize sea breeze circulation, a local process that drives evaporated moisture from the RS to the land, adverse climatic effects to surrounding regions are low. Local-scale sea breeze management (along with cloud seeding) could be an attractive and viable adaptation measure to increasing water scarcity in the arid Arabian Peninsula, particularly given ongoing climate change.

**Code and data availability**

1. The MERRA2 reanalysis is available at https://gmao.gsfc.nasa.gov/reanalysis/MERRA2/
2. The ECMWF-OA is ECMWF Operational Analysis data are restricted data, which were retrieved from http://apps.ecmwf.int/archivecatalogue/?type=4v&class=od&stream=oper&expver=1 with a membership
3. The TRMM daily accumulated precipitation is available at http://disc.sci.gsfc.nasa.gov/precipitation/documentation/TRMM_README/TRMM_3B42_readm
4. Copy of the input datasets and details of the WRF model configuration can be downloaded from the KAUST repository https://repository.kaust.edu.sa/bitstream/item/604673 or by e-mail request to suleiman.mostamandi@kaust.edu.sa.

**Author contributions.** S. Mostamandi wrote the manuscript and took part in planning and performing the calculations. S. Osipov constructed meteorological initial and boundary condition based on European Center of Medium-range Weather Forecasts (ECMWF) Operational Analysis. G. Stenchikov planned the calculations, led the discussion, and reviewed and improved the manuscript. E. Predybaylo, O. Zolina, S. Gulev, S. Parajuli participated in the discussion, helped to formulate the research program, and reviewed the manuscript.

**Competing interests.** The authors declare that they have no conflict of interest.
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