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Modeling the Summertime Climate of Southwest Asia: The Role of Land Surface Processes in Shaping the Climate of Semiarid Regions

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ABSTRACT

Presented is a study on the role of land surface processes in determining the summertime climate over the semiarid region of southwest Asia. In this region, a warm surface air temperature bias of 3.5°C is simulated in the summer by using the standard configuration of Regional Climate Model version 3 (RegCM3). Biases are also simulated in surface albedo (underestimation), shortwave incident radiation (overestimation), and vapor pressure (underestimation). Based on satellite measurements documented in NASA’s surface radiation budget (SRB) dataset, a correction in surface albedo by 4% is introduced in RegCM3 to match the observed SRB data. Increasing albedo values results in a nearly 1°C cooling over the region. In addition, by incorporating RegCM3’s dust module and including subgrid variability for surface wind, shortwave incident radiation bias originally of about 45 W m⁻² is reduced by 30 W m⁻². As a result, the reduction of shortwave incident radiation cools the surface by 0.6°C. Finally, including a representation for the irrigation and marshlands of Mesopotamia produces surface relative humidity values closer to observations, thus eliminating a nearly 5-mb vapor pressure dry bias over some of the region. Consequently, the representation of irrigation and marshlands results in cooling of nearly 1°C in areas downwind of the actual land-cover change. Along with identified biases in observational datasets, these combined processes explain the 3.5°C warm bias in RegCM3 simulations. Therefore, it is found that accurate representations of surface albedo, dust emissions, and irrigation are important in correctly modeling summertime climates of semiarid regions.

1. Introduction

Blanketed by the Arabian Desert in the south and lined by the mountainous coastlines of Turkey and Iran in the north, the area known as southwest Asia can be described mostly as a semiarid or arid climatic region (see Fig. 1). The combination of a short, distinct, rainy winter season with a long, hot, dry summer leads to a large strain on freshwater resources, providing strong motivation to study the climate of the area (Rogers and Lydon 1994). Some prior work has been completed in compiling observations as well as modeling this regional climate. For example, Walters (1988) provides a thorough description of circulation patterns over southwest Asia, whereas Al Kulaib (1984) describes some of the major climatic features of the country of Kuwait and the surrounding area. Moreover, prior studies using regional climate models (RCMs) have simulated the climate of this area or those in proximity such as Central Asia (Small et al. 1999). For example, more recently, Evans et al. (2004) used the Regional Climate Model version 2 (RegCM2) to study rainfall simulation over the Middle East, whereas Marcella and Eltahir (2008) improved RegCM3’s performance of rainfall prediction over the Arabian Peninsula. However, to date, very little recent work has been completed in specifically modeling surface summertime temperatures over this region. For example, although some research has been performed using general circulation models or looking at general circulation patterns, most regional modeling has focused either on the eastern Mediterranean, other regions, or precipitation processes (Reddaway and Bigg 1996; Saaroni and Ziv 2000; Zaitchik et al. 2007; Nazemosadat and Cordery 2000; Evans 2010). Thus, here we focus on accurately modeling surface air temperatures as well as other surface processes over portions of southwest Asia: namely, Saudi Arabia, Iraq, and Kuwait.

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More specifically, this work identifies the surface features over southwest Asia or, in general, over many semiarid regions around the world that dictate the surface climate over dry periods. Particularly, this study will focus on the effects of two common surface processes in semiarid climates: dust emissions and irrigation. Both of these land processes are influenced by human behavior and can have profound effects on regional climates (Miller and Tegen 1998; Kueppers et al. 2006). During the 1970s, the irrigation and marshlands of Iraq were both completely intact, and hence this period is used to discern the effects of these land processes on the surrounding region’s climate. Moreover, model biases for other land characteristics, such as surface albedo, are addressed and therefore provide insight into the sensitivity of regional models to certain land parameters. Consequently, to allow for the future assessment of climate variability over southwest Asia, this paper presents a modified regional climate model that more accurately simulates the summertime climate over semiarid regions. Ultimately, this work strives to achieve a better understanding, as well as prediction, of the processes that determine the summertime climate of semiarid regions.

2. Model description and observational datasets
   a. Regional Climate Model version 3

   In this study, RegCM3 is used to simulate the summertime climate over the semiarid region of southwest Asia. Several studies have been completed using RegCM3, as referenced in Giorgi et al. (1998). Originally developed at the National Center for Atmospheric Research (NCAR) and now maintained at the International Center for Theoretical Physics (ICTP), RegCM3 is a three-dimensional, hydrostatic, compressible, primitive equation, σ vertical coordinate RCM. RegCM3 maintains much of the dynamical core of fifth-generation Pennsylvania State University–NCAR Mesoscale Model (MM5; Grell et al. 1994). The model now employs the NCAR Community Climate Model version (CCM3) radiative transfer package (Kiehl et al. 1996). In addition, land surface physics are modeled by the Biosphere–Atmosphere Transfer Scheme (BATS1e) of Dickinson et al. (1993), whereas boundary layer physics are modeled by the Holtslag et al. (1990) nonlocal planetary boundary layer scheme (Giorgi et al. 1993a). RegCM3 also employs Zeng’s bulk aerodynamic ocean flux parameterization, where sea surface temperatures (SSTs) are prescribed (Zeng et al. 1998). In addition, three different convection schemes (Kuo, Grell, and Emanuel) are available for nonresolvable rainfall processes (Giorgi et al. 1993a). After some experimentation with other convection schemes, the Kuo scheme best simulated the magnitude as well as spatial distribution of winter rainfall and thus was chosen for our experiments. That is, where both the Grell and Emanuel schemes greatly overestimate rainfall over the entire Arabian Peninsula, the Kuo scheme did best in simulating annual rainfall and spatial distribution of rainfall throughout most of southwest Asia. In addition, RegCM3 includes a large-scale, resolvable, nonconvective moisture scheme, the subgrid explicit moisture scheme (SUBEX; Pal et al. 2000). Additionally, RegCM3 features a fully coupled aerosol chemistry model including a radiatively active dust module for semidesert and desert grid cells (Zakey et al. 2006). The authors refer readers to Pal et al. (2007)
for the most current developments and description of RegCM3.

b. CRU TS 2.1 high-resolution temperature dataset

The Climate Research Unit (CRU) fine-resolution gridded dataset TS 2.1 consists of a monthly time series of various climate variables covering the period 1900 to 2002. Such variables include surface air temperature, precipitation, and vapor pressure, which are all interpolated from surface observations onto a global 0.5° × 0.5° resolution grid (Mitchell and Jones 2005). The goal of the CRU database is to provide the best estimate of the spatial pattern of climate variables at any moment of time (New et al. 1999). The weight placed on each station’s value for a given grid box is a function of the station’s distance from the grid box assuming an exponential correlation decay distance. Therefore, the measurement does not need to come from within the grid box to contribute to the grid box’s value. If there is insufficient data for a grid cell, the 1960–90 average value is used to compute the value. The exact construction and description of the interpolation scheme used for each variable can be found in Mitchell and Jones (2005). Station data come from a wide variety of sources [from World Meteorological Organization (WMO) stations to government agencies]; however, exact station information (i.e., location and record) is not available to the public domain. Over our boxed region, between four and nine stations are used for the CRU monthly values. Moreover, it is important to note that the CRU dataset is sensitive to the details of the observational network in a certain region. Therefore, CRU values over mountainous or uninhabited regions, where station coverage is scarce, may be somewhat inaccurate. Nevertheless, many studies (e.g., Yiao and Caya 2006; Syed et al. 2006) have used the CRU dataset for climate analysis and model validation.

The CRU data available for the years of 1969–79 are used in this study. However, because of the lack of observations in this region, some smoothing may occur in CRU estimates for temperature. For approximate locations of the mean climatology stations, the authors refer the reader to New et al. (1999).

c. NASA Langley Research Center surface radiation budget

To assess the performance of RegCM3 in simulating incoming surface solar radiation, the National Aeronautics and Space Administration (NASA) Langley Research Center surface radiation budget (NASA-SRB) is compared to RegCM3 values of shortwave incident radiation (SWI). NASA-SRB data are based on International Satellite Cloud Climatology Project (ISCCP) products as well as meteorological data from the Global Modeling and Assimilation Office (GMAO) reanalysis datasets. Using radiative transfer algorithms, the NASA-SRB dataset provides both surface shortwave and longwave radiation on a monthly averaged, global grid (Darnell et al. 1996; Gupta et al. 1999). In this study, dry period [June–August (JJA)] values of surface shortwave incident radiation from July 1983 through August 1991 are compared to model output. Although observational datasets used for comparison do not overlap with model output, this study is interested in constructing an accurate climatology more than reproducing actual time series observations. Therefore, exact overlapping of model and observations is unnecessary. Finally, it is important to note that data from the NASA-SRB during this time were available at 2.5° × 2.5° resolution.

To ensure the accuracy of SRB values for shortwave radiation and albedo over our region, we analyze station data from the Baseline Surface Radiation Network (BSRN). With a station in Saudi Arabia (Solar Village: 29.4°N, 46.4°E), the BSRN data provide 4 yr (1999–2002) of in situ measurements for incoming and reflected shortwave radiation and thus surface albedo. As shown in Table 1, we find that current SRB data compare very well to the Solar Village data. That is, SWI values are within 5% of the BSRN values (307 W m⁻² versus 322 W m⁻²). Likewise, SRB shortwave reflected radiation (SWU) is within 3 W m⁻² of BSRN. As a result, SRB estimates an albedo value of 0.319, whereas BSRN’s value is 0.314. Moreover, SRB values for SWI and albedo during this time period (1999–2002; 307 W m⁻², 0.31) are very similar to those SRB values in the time period used in this study (1969–80; 318 W m⁻², 0.30). We expect this result because summer radiation and albedo over desert regions should exhibit low variability. Therefore, we conclude that the SRB estimates are satisfactory for this analysis.

3. Experimental design

a. Experimental setup

Simulations using RegCM3 were completed spanning the period from 1969 to 1979. The domain, centered at

<table>
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<th>SWI</th>
<th>SWU</th>
<th>Calculated α</th>
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<tbody>
<tr>
<td>μ</td>
<td>83</td>
<td>83</td>
<td>307</td>
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<tr>
<td>σ</td>
<td>18</td>
<td>18</td>
<td>18</td>
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<tr>
<td>b</td>
<td>6</td>
<td>6</td>
<td>0.314</td>
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<td>μ</td>
<td>83</td>
<td>83</td>
<td>307</td>
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<td>σ</td>
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<td>18</td>
<td>18</td>
</tr>
<tr>
<td>b</td>
<td>6</td>
<td>6</td>
<td>0.01</td>
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31°N, 44.5°E at 30-km resolution, has 88 points in the zonal and 74 points in the meridional direction using a Lambert conformal projection. It is important to note that the IRR and FULL simulations use the subgrid BATS1e scheme of Giorgi et al. (2003), which allows for surface physics to be calculated at finer resolutions (here at 5-km grid spacing) based on finer topography and land-use cover. The domain covers most of the southwest Asia from the Mediterranean and Caspian Seas in the north to the Red Sea in the southwest and Oman in the southeast. Figure 1a represents the model domain as well as topography and land use in CONT. As examples of two different scales, areal averages are calculated over Kuwait (28.4°–30.2°N, 46.5°–48.5°E) and a boxed region (23.5°–33.5°N, 40°–50°E) (see Fig. 1). Initial and boundary conditions (LBCs) were enforced by applying the exponential relaxation of Davies and Turner (1977). To account for the local effects of LBCs on model results, output from a strip with a width of 3° along each boundary is not displayed. As mentioned earlier, SSTs are prescribed to RegCM3 from the Hadley Center Met Office Global Ice and Sea Surface Temperatures (GISST) dataset, which has a temporal coverage from 1871 to 2003. The SST datasets have a 1° × 1° monthly resolution and are based on in situ and satellite observations.

**b. Albedo simulation description**

Comparing RegCM3's prescribed (via land-cover type) surface albedo to values from the NASA-SRB dataset reveals an underestimation in land surface reflectivity. More specifically, RegCM3's surface albedo over the Arabian and Syrian Deserts (areal average over our boxed region) is estimated at 0.27, whereas SRB values are closer to 0.31. The underestimated values are most likely due to BATS1e's prescribed desert albedo values, which were measured over the deserts of North America, where soils are significantly darker (Dickinson et al. 1993). As a result, we increase the surface albedo (for both longwave and shortwave energy) in all of RegCM3's semidesert and desert grid cells by 4% to match that of SRB. This modification is accomplished by increasing the soil color reflectance for semidesert and desert grid cells. From here, RegCM3 is allowed to calculate the actual surface albedo based on sun angle, soil moisture, etc., for bare soil albedo. Moreover, this change is also accomplished by increasing the vegetation albedo (for both shortwave and longwave radiation); however, over semidesert and desert regions, these values contribute less than the bare soil albedo. BATS1e then calculates a total gridcell surface albedo based on these values, soil moisture, and solar angles. The simulation with this change is referenced as ALB throughout this study. It is important to note that these albedo changes are also contained in all other simulations except CONT.

**c. Dust simulation description**

A simulation of RegCM3 including the dust module of Zakey et al. (2006) is performed including a scheme for subgrid wind variability (Marcella and Eltahir 2010). In the dust scheme, emissions are strongly dependent on wind speeds, surface characteristics, and soil particle sizes. Following the work of Marticorena and Bergametti (1995) and Alfaro and Gomes (2001), the emission calculation is based on empirical parameterizations for both soil aggregate saltation and sandblasting processes. Dust emissions within the module follow these basic steps: 1) based on a three-mode lognormal distribution determined by the soil textural class, the soil aggregate size and distribution for each model grid cell are specified; 2) a minimum threshold friction velocity based on empirical parameterizations of Marticorena and Bergametti (1995) is calculated; 3) the horizontal saltating soil aggregate mass flux is calculated; and finally 4) the calculation of the vertically transportable dust particle mass flux generated by the saltating aggregates is performed. Essentially, a portion of the horizontal saltation flux is partitioned to a kinetic energy flux, and the vertical flux of the soil aggregates is determined via binding energies and this kinetic energy. From here, transport bins for different dust particle sizes are used for advection and deposition (both wet and dry) of dust particulates following the chemical tracer model in RegCM3.

Assuming surface wind speeds follow a Gaussian distribution that can be described with a mean value (gridcell resolved) and a standard deviation, the dust module is improved upon by adding the variability of wind speeds within the grid cell. Given that research has shown that strong surface solar heating can result in dry convection that mixes dust up from the surface layer to the atmosphere, it is assumed that wind speed variability, or the standard deviation within a grid cell, is driven by these dry convective eddies: the dry convective velocity scale (Miller et al. 1992; Lunt and Valdes 2002; Cakmur et al. 2004). From here, the dust module then performs all calculations involving wind speeds for a given distribution of wind values with their corresponding probabilities. The total dust emissions are then integrated over all wind speed bin values with their corresponding probability. Over this region, results have shown that RegCM3’s dust model is sensitive to the inclusion of wind variability with a nearly 35% increase in emissions, which leads to simulated aerosol optical depth values significantly closer to
observations (Marcella and Eltahir 2010). This simulation including the dust scheme with wind variability is referenced as WIND throughout this study.

d. Irrigation and marshlands simulation description

To reflect the substantial irrigation and marshlands of the Mesopotamian valley, land cover is altered in another simulation labeled IRR. The spatial as well as the areal coverage is determined from two different datasets. First, the Food and Agriculture Organization (FAO) of the United Nations and the University of Frankfurt’s joint collaboration Global Map of Irrigation Areas (Siebert et al. 2005). This dataset provides irrigation intensity at 10-km resolution as well as magnitudes of total area equipped for irrigation, as reported by country. For Iraq, this dataset approximates 35,000 km² of land equipped for irrigation with high intensity values between the Tigris and Euphrates. Additionally, the International Water Management Institute (IWMI) Global Irrigated Area Map (GIAM) at 10-km resolution is used for spatial distribution of irrigated land in the region. The IWMI constructs its GIAM based on Advanced Very High Resolution Radiometer (AVHRR) data, Système Probatoire d’Observation de la Terre (SPOT) satellite vegetation, ground truth, and a variety of other observations (Thenkabail et al. 2006).

To reflect the information from both datasets, RegCM3 land cover is altered to include irrigated cropland and marshlands between the Tigris and Euphrates Rivers (see Fig. 1b). As a result, surface properties such as soil texture, roughness length, soil moisture, and albedo are significantly changed. To simulate the effects of irrigation, RegCM forces soil moisture values in the root zone to field capacity at every time step of the year. However, this representation requires unrealistic amounts of water to be supplied to the system. In fact, the Tigris and Euphrates combined annual flow, approximately 80 km³, could not supply this amount of water (over 100 km³). Therefore, we alter the irrigation scheme to saturate the root zone only in the first week of June, July, and August, a form of irrigation scheduling. This modification mimics actual irrigation practices more closely and reduces water requirements to nearly 40 km³ yr⁻¹.

e. FULL simulation description

Finally, a simulation including the albedo changes, dust emissions, and irrigationmarshlands land cover is performed. This simulation represents the most realistic representation of both land surface cover and processes in the region. It will be referred to as FULL throughout the study (see Table 2 for a complete summary of the simulations performed).

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Description of processes included</th>
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<tr>
<td>CONT</td>
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<tr>
<td>ALB</td>
<td>Dust module α increased by 4%</td>
</tr>
<tr>
<td>WIND</td>
<td>Modified subgrid BATS1e land cover to include irrigation and marshlands with α increase</td>
</tr>
<tr>
<td>IRR</td>
<td>Includes albedo increase, dust, and irrigation/marshlands</td>
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4. Results and discussion

When comparing CONT to CRU and SRB measurements, several biases at the surface are found over the summertime period. Most striking is the excessive warm bias for summertime (JJA) 2-m surface temperatures. Nevertheless, from the cool, mountainous regions of Turkey and Iran in the north to the warm, desert regions of Iraq and Saudi Arabia in the south, RegCM3 generally does well in capturing the spatial distribution of average temperature over the region (see Figs. 2a,b). However, comparing Figs. 2a,b, CONT clearly overpredicts surface air temperatures by over 4°C in many parts of Iraq, Iran, and Saudi Arabia. For example, Kuwait’s average daily JJA temperature is 3.5°C warmer than CRU’s estimated value of 35°C (see Fig. 3a). Further biases were found in surface albedo (underestimation by 4%), shortwave radiation (overestimation by 40 W m⁻²), and vapor pressure (by nearly 5 mb). These biases will be discussed further in sections to follow. RegCM3 total column water vapor is compared to ERA-40 data; however, the fields simulated by the model and ECMWF reanalysis data do not differ significantly. Therefore, it is not believed that an underestimation of atmospheric water vapor is contributing too much of these biases.

a. Effects of surface albedo increase

As discussed earlier, a 4% increase in surface albedo is implemented across all semidesert and desert grid cells in RegCM3 by modifying vegetation and bare soil albedo values. This modification results in surface albedo values that are closer to SRB estimates of 0.30–0.35 across the desert portion of the domain. The increased albedo results in a reduction of about 15 W m⁻² of shortwave radiation absorbed at the surface. However, model values of shortwave radiation absorbed are still nearly 30 W m⁻² larger than SRB values. The larger values are attributable to the large overestimation of
shortwave incident radiation reaching the surface and will be discussed later. As a result of the reduced shortwave absorption, cooling on the order of 1°C occurs across the entire Arabian Peninsula and the large warm tongue across the Mesopotamian valley is reduced (see Figs. 2c, 4a). Consequently, biases (comparing to CRU estimates) for surface air temperature are reduced to 1.8°C over the boxed region (see Fig. 3b). Likewise, as shown in Table 3, increasing the surface albedo decreases both the maximum and minimum surface air temperatures by about 1°C ($T_{\text{max}}$ and $T_{\text{min}}$, respectively) over the boxed region. As a result, biases with CRU are reduced to between 1.5°C and 2°C for both $T_{\text{max}}$ and $T_{\text{min}}$. It is important to note that, as expected, increasing the surface albedo does not dramatically affect other model biases or meteorology.

Fig. 2. Average 2-m JJA temperature (°C) in (a) CRU observations, (b) CONT, (c) ALB, (d) WIND, (e) IRR, and (f) FULL. Also shown under each panel are the values for the country of Kuwait and the boxed region.
b. Effects of including dust emissions

In addition to a large warm bias, a significant overestimation in shortwave radiation reaching the surface is observed. As shown in Fig. 5a, SRB estimates of shortwave incident radiation are around 315 W m$^{-2}$; however, CONT and ALB values are closer to 360 W m$^{-2}$ (see Figs. 5b,c). In addition, although the spatial distribution of SWI within RegCM3 is fairly homogeneous, SRB features a maximum over the Syria and lower values over the Arabian Gulf. Although temporal coverage is different between SRB and RegCM3, it is believed that incoming shortwave radiation is fairly consistent over this desert climate in summertime months.

Moreover, it is well known that, as dust particulates are suspended into the atmosphere, incoming shortwave radiation is either scattered or absorbed depending on the particulate size (Tegen and Lacis 1996; Miller and Tegen 1998). This attenuation of shortwave incident radiation is plainly seen when including the simulation with dust emissions. Here, some of the dust sources of southern Iraq receive incoming shortwave radiation...
nearly 30 W m\(^{-2}\) less than the surrounding region (Fig. 5d). In fact, as expected, dust emissions cause a dramatic reduction in SWI throughout the entire Arabian Peninsula. Over the country of Kuwait, SWI values (334 W m\(^{-2}\)) are now within 19 W m\(^{-2}\) of observations. Moreover, in regions of intense dust loading along the Arabian Gulf coast, large reductions in average SWI (on the order of 30–40 W m\(^{-2}\)) spread southeasterly following the northwesterly “shamal” winds common in this region’s summer climate (see Fig. 6a). Therefore, including mineral aerosols in RegCM3 simulations significantly improves the model’s ability to reproduce average SWI. Likewise, the spatial distribution of SWI now more closely follows that of SRB, with maximum values over Jordan and western Saudi Arabia and minimum values down the Arabian Gulf (cf. Figs. 5a,d). Regardless, RegCM3 still overestimates SWI by approximately 20 W m\(^{-2}\) throughout the domain. Because cloud cover over this region in the summertime is nearly zero and modeled total column water vapor matches reanalysis data, it is believed that the radiative physics package within RegCM may not properly absorb radiation aloft as alluded to in Zhang and Lin (1998) and Winter and Eltahir (2010). Further work is necessary in addressing this bias. Additionally, the work of Marcella and Eltahir (2010) concluded that dust loading over this region is underestimated by RegCM3. Increased mineral aerosols would also reduce the shortwave bias at the surface via further scattering and absorption aloft.

As expected, including dust emissions significantly impacts surface temperatures across the domain and helps reduce surface biases (Fig. 3c). More specifically,
with a substantial attenuation of shortwave incident radiation, average JJA temperatures over Kuwait drop from 37.5°C to 37.0°C and over the boxed region, equally by half a degree (Figs. 2d, 4b). This reduction occurs throughout most of the Arabian Gulf, demonstrating the importance of including dust emissions in simulating the mean summertime climate over the region. Moreover, Table 4 displays maximum and minimum temperatures over Kuwait for each RegCM3 simulation. Similar to average temperature values, including dust emissions decreases $T_{\text{max}}$ and $T_{\text{min}}$ values by about 0.5°C. This reduction helps bring the diurnal temperature range to within 0.3°C of CRU’s value (see Table 4). Nonetheless, with average temperatures still 1°–2°C warmer than CRU over the region, the occurrence of dust and albedo differences alone cannot fully account for the bias.

FIG. 5. Average daily JJA SWI (W m$^{-2}$) for (a) SRB observations, (b) CONT, (c) ALB, (d) WIND, (e) IRR, and (f) FULL. Also shown below each panel are the values for the country of Kuwait and the boxed region. Note that all values are for 1969–79, except SRB, which has a temporal coverage of 1983–92.
c. Effects of Mesopotamian irrigation and marshlands

Known as the cradle of civilization, the Mesopotamian valley of Iraq has been irrigated for thousands of years from the flow of the Tigris and Euphrates Rivers. As mentioned earlier, the spatial coverage of Iraqi irrigation and the Mesopotamian marshlands is quite extensive. For example, in their peak coverage (in the 1970s) the marshlands covered nearly 17,000 km², roughly the size of the country of Kuwait or the state of New Jersey; Iraqi irrigation was nearly double this size. Therefore, it seems likely that these land processes and ecosystems may have profound effects on the regional climate.

With the marshlands and irrigation of Mesopotamia included in RegCM3 simulations, significant reductions in surface temperature and increases in surface humidity occur. For example, in areas covered with irrigation, average daily JJA temperatures decrease by more than 4°C (see Fig. 4c). This cooling results in RegCM3 temperatures in the Mesopotamian valley nearly matching CRU observations (Fig. 3d). Excessive cooling over the southern Iraq–Iran border is most likely due to the representation of marshlands in RegCM3. Unlike irrigation, this land is kept constantly saturated, most likely resulting in unrealistic overcooling. However, cooling is not limited to just those regions covered with irrigated crops or marshlands. Farther downwind, along the Arabian Gulf coast, cooling of over a half degree also occurs in average summertime 2-m temperatures (Fig. 4e). For example, average daily summertime temperatures over Kuwait cool from 37.5°C in ALB to 36.9°C in the IRR simulation (see Figs. 2c,e). However, over the boxed region, the effects of irrigation/marshlands occur only with $T_{\text{max}}$ not $T_{\text{min}}$ values, with 0.8°C cooling for $T_{\text{max}}$ but only $-0.1^\circ$C change in $T_{\text{min}}$ (see Table 3). This change actually eliminates the diurnal temperature range bias completely.

Because of an increase in surface water available, evaporation leads to an increase in the latent heat flux, a reduction in the sensible heat flux, and thus surface cooling in this area. With this added evaporation, vapor pressure values also become significantly larger, helping reduce the dry bias observed in RegCM3. For example, Fig. 7 shows the surface vapor pressure for CRU observations as well as all RegCM3 simulations. Clearly seen in the observations is a moist tongue stretching from the southern Iraq–Iran border, farther north through the Mesopotamian valley. In some regions, average surface vapor pressure values are close to 20 mb. However, this signature is lacking in RegCM3’s ALB simulation (Fig. 7b). That is, throughout central and southern Iraq, a large dry bias is found with vapor pressure values closer to 10 mb. More specifically, by Iraq and Iran’s coastal regions, where the marshlands exist, a nearly 10-mb underestimation in vapor pressure is present (Fig. 8a) in ALB. As expected, this dry signature is also found in the CONT experiment (not shown). Because predominant wind patterns during this time of the year are from the northwest and RegCM3 accurately simulates these wind directions, it is not the absence of an onshore wind flow in...
the model that is causing a dry bias. Nevertheless, including irrigation and the marshlands, as expected, increases the vapor pressure in this area. For example, surface values over Kuwait increase to nearly 12 mb (Fig. 7c). As a result, the bias over Kuwait is reduced to 2 mb and nearly zero over central Iraq because of a nearly 50% increase in vapor pressure over this region (see Figs. 8b,d). Finally, it is important to note that including irrigation and marshlands in the summer months does not significantly impact other model dynamics. For example, no additional rainfall is observed over the region and increased cloudiness is rather minimal (less than 5%). The lack of change is most likely attributable to strong subsidence over the region caused by the Indian monsoon during the summer months. However, the increased evaporation and hence water vapor (which absorbs shortwave radiation) in the lower levels of the atmosphere result in a small reduction in shortwave incident radiation over the Mesopotamian valley (on the order of 5 W m⁻²). This signature can be seen when looking at shortwave radiation reaching the surface (Fig. 5e).

d. Combining ALB, WIND, and IRR

By combining the processes of increased surface albedo, dust emissions, and irrigation/marshlands, a more accurate representation of the land surface of southwest Asia is completed. Thus, a simulation of RegCM3 with all these processes included, FULL, is performed. This simulation has the regional surface air temperature at now 33.8°C and more closely resembles the spatial distribution of CRU’s temperature in the region (see Fig. 2f). For example, a once 3.5°C warm bias over Kuwait has been reduced to 1.2°C (see Fig. 3e). Nevertheless, the boxed region is now within 0.8°C of observations. More specifically, areas in CONT that had excessive warms biases such as most of central and coastal Saudi Arabia, the Mesopotamian valley, and western Iran are now regions within a degree of observations (see Fig. 3e). By combining all of these processes, the most profound temperature reductions occur over the Mesopotamian valley: some areas of central Iraq cool by over 6°C. In fact, some regions farther south from the Mesopotamian valley experience nearly 2.5°C cooler temperatures.
because of albedo increases, dust emissions, and irrigation (see Fig. 4d). In addition, these effects are further seen in maximum and minimum temperatures. For example, over both the boxed region and Kuwait, both warm $T_{\text{max}}$ and $T_{\text{min}}$ biases are reduced by about 2°C. As a result, the diurnal temperature range is now within 0.5°C for both the boxed region and Kuwait (see Tables 3, 4).

In addition to strides made in surface air temperatures, the excessive overestimation of shortwave incident radiation is also addressed with the modifications made to RegCM3. Mostly attributable to including dust emissions with subgrid wind variability, the amount of incoming shortwave radiation is reduced between 20 and 40 W m$^{-2}$ over southwest Asia (Fig. 6b). As a result, a bias of once nearly 45 W m$^{-2}$ over Kuwait has been reduced to 17 W m$^{-2}$ (Fig. 5f). Additionally, RegCM3 now performs better in simulating the spatial distribution of incoming shortwave radiation with maxima over Jordan, western Iraq, and Syria and minima down the Arabian Gulf coast. However, over the boxed region, and in general across the domain, RegCM3 still has a significant

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**Fig. 8.** Difference of average daily surface vapor pressure (mb) for (a) ALB–CRU, (b) IRR–CRU, (c) FULL–CRU, (d) IRR–ALB, and (e) FULL–ALB. Also shown below each panel are the values for the country of Kuwait and the boxed region.
overestimation (by approximately 20 W m$^{-2}$). Although, compared to ground observations, SRB root-mean-square errors are ±24 W m$^{-2}$, further work is necessary in addressing this bias in RegCM3.

Also noticeable in the FULL simulation is a strong reduction in the dry bias that RegCM3 once simulated. As shown in Fig. 8a, the difference between vapor pressure values in CRU and ALB ranged from 0 to 10 mb in the boxed region. With all three processes included, this dry bias is nearly completely corrected for as new differences range from −3 to 3 mb across Kuwait and the boxed domain (see Figs. 7d, 8c). These changes amount to approximately a 20% increase in vapor pressure over the region (Fig. 8e). The new wet biases in some of the marshlands and irrigation are most likely due to the constant saturation provided in the model. Further work may need to be completed in reducing this wet bias.

Finally, work was completed in examining the changes in dust emissions between FULL and WIND because of the inclusion of irrigation and marshlands. Only a small reduction in dust loading was observed in the dust emission sites near the Iran–Iraq border. The lower dust loading is most likely due to the increased soil moisture over this region, which decreases saltation and ultimately dust suspension. Nevertheless, the increase in lower-level moisture over the region does not impact dust emissions throughout the rest of the domain.

5. Summary and conclusions

Improvements are made to a regional climate model (RegCM3) over southwest Asia, which help correct a warm bias in simulated 2-m temperatures. To begin with, comparing model surface albedo to NASA-SRB satellite measurements reveals a large underestimation in RegCM3’s surface albedo. As a result, the model absorbs approximately 40 W m$^{-2}$ of shortwave radiation more than SRB, leading to excessive warming at the surface. Adjusting RegCM3’s surface albedo to match those of observations helps reduce the amount of shortwave radiation absorbed at the surface by nearly 15 W m$^{-2}$, therefore resulting in cooling on the order of 1°C across the entire Arabian desert.

In addition to the surface albedo bias, RegCM3’s simulated shortwave incident radiation is significantly larger than SRB estimates (by nearly 45 W m$^{-2}$). As a result, a simulation of RegCM3, including the dust module of RegCM3 with subgrid wind variability, is performed over southwest Asia. Results indicate that dust emissions do have a significant impact on the surface climate over the region. That is, mineral aerosols reduce shortwave radiation reaching the surface by about 15 W m$^{-2}$ across the region. Consequently, dust emissions cool the surface by 0.5–1°C. Interestingly, although the reduction in surface shortwave radiation absorbed caused by dust is comparable to the amount of shortwave radiation absorbed reduced by the albedo increase, cooling from dust is about 0.25–0.5°C less than that of the albedo changes. It is important to note that dust absorbs shortwave radiation as well as traps upwelling longwave radiation, depending on particle size (Tegen and Lacis 1996); as a result, dust causes some heating aloft, in the dust layer (Miller and Tegen 1998). These processes are noticeable in RegCM3 and most likely help mute the cooling signal at the surface. Still, an underestimation in RegCM3 aerosol optical depth indicates that dust loading over this region is not adequately modeled (Marcella and Eltahir 2010). With more suspended desert dust, shortwave radiation at the surface would be further reduced. Some of this bias could be explained by how RegCM3 represents dust at the boundaries. That is, currently no emissions occur at the boundaries, and there is no representation of dust from...
outside the domain. The importance of including realistic boundary conditions for dust is currently being examined. Preliminary results indicate that, over southwest Asia, including dust concentration values at the boundaries has a significant impact on dust across the domain.

Surface features not initially represented in RegCM3, the irrigated croplands and marshlands of the Mesopotamian valley, are also included by using two-satellite and state-provided datasets (FAO and IWMI). To offer a more realistic and feasible representation of irrigation scheduling, the irrigation scheme of RegCM3 is modified to only supply water during the first week of June, July, and August. By including irrigation scheduling, the amount of water supplied to the system (approximately 40 km$^3$) can realistically be supported by the combined annual flow of the Tigris and Euphrates Rivers, which was approximately 85 km$^3$ yr$^{-1}$ during the 1970s (Murakami 1995). When including these surface features, average daily summertime temperatures in the Mesopotamian valley cool by over 5$^\circ$C and areas downwind of the region also experience significant cooling. Likewise, increased surface evaporation from the marshlands and irrigation reduces a dry bias of nearly 10 mb once present over the region.

However, it is also important to note that, over the domain, a cool, wet bias occurs in some regions: namely, over the Zagros Mountains of Iran and the mountainous Alborz region (the southern portion of the Caspian Sea over Iran). Over both regions, a cool, wet bias occurs in CONT (see Figs. 3e, 8a), but little changes in temperature and moisture occur with changes in albedo, irrigation, and dust (see Figs. 4d, 8e). These contrasting results
are most likely caused by topographical and land-cover differences between the valley region of Iraq and Saudi Arabia and the mountainous regions of Iran. More specifically, little differences occur because the Iranian mountainous region is neither semidesert nor desert; thus, albedo values are not affected and not much dust advects over the area. Moreover, the cool, wet bias is most likely caused by excessive cloudiness and rainfall along the mountainous coastline of the Caspian Sea, which RegCM does not properly simulate. Nevertheless, neither this region nor this modeling feature is the focus of this study. However, future work with RegCM3 should address these problems.

Finally, a bias in actual CRU observations for surface air temperatures may exist over the desert regions of western Iraq and northern Saudi Arabia. Because of harsh, hot conditions this region experiences during the summertime months, few observations occur across the uninhabited desert area. As a result, most measurements are taken in the cooler, populated valley of central Iraq. A comparison of CRU observations to ERA-40 reanalysis data illustrates this phenomenon. It is found that ERA-40 values are nearly one degree warmer than CRU observations throughout this region (see Fig. 9a). Likewise, we compare CRU and ERA-40 estimates to the World Meteorological Organization (WMO) observations over Kuwait City Airport, a desert region (29.1°N, 47.6°E; from 1960 to 1990; Fig. 10a). Results indicate that CRU and WMO averaged JJA 2-m temperatures correlate very well (correlation coefficient of 0.95); this result is somewhat expected because the WMO station most likely contributes to CRU’s gridcell value. However, the WMO and ERA-40 2-m temperatures are consistently warmer than CRU, by about 0.5° and 1.3°C, respectively (see Fig. 10b). It is important to note that ERA-40’s spatial resolution is quite coarse (2.5° for ERA-40 versus 0.5° for CRU and point observations at Kuwait Airport). Nevertheless, CRU’s cool bias is consistent when spatially comparing CRU measurements to ERA-40 estimates again shown in Fig. 9a. Therefore, it is believed that, over these desert regions, CRU may contain a cool bias in estimating surface air temperature.

When accounting for this bias in observations, RegCM3’s surface air temperatures are within a half degree of CRU observations (see Fig. 9b). Any residual warm bias, like that observed over western Iraq, is most likely attributable to a conservative increase in surface albedo made within the model. That is, the increase to surface albedo was performed based on box aerial averages in RegCM3 compared to SRB values. Therefore, the spatial distribution of these values was neglected and only the magnitude was considered over the entire boxed area. As a result, some locations in western Iraq still have simulated surface albedo values lower than SRB, which may explain the residual warm bias over the region.

In short, by combining all these processes, a once 3°–6°C warm bias over southwest Asia has been corrected and albedo, shortwave energy, and surface humidity biases have been greatly improved (Fig. 9b). Given a model that can more accurately simulate the current climate over this region, climate sensitivity studies can now be performed. For example, work should be completed in examining the effects of dust emissions and irrigation on the interannual variability and extremes of temperatures and humidity across the region. Similarly, future studies in discerning the effects of human impact (e.g., irrigation) on the regional climate can be achieved. In any case, most importantly, this study uncovers the critical role that certain land surface processes common in semiarid regions have in determining the summertime climate of these regions.

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