Integrating Remote Sensing Data with WRF for Improved Simulations of Oasis Effects on Local Weather Processes over an Arid Region in Northwestern China

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ABSTRACT

Land use/cover types derived by satellite remote sensing data from the Earth Observing System Moderate Resolution Imaging Spectroradiometer (MODIS) were used to replace the U.S. Geological Survey (USGS) data in the Weather Research and Forecasting Model (WRF). Simulations in this study were further improved by modifying the initial fields of WRF with soil temperature and moisture observations, because these two variables are important to producing “cold–wet island” effects. A series of WRF simulations were performed to describe microclimate characteristics and the local thermal circulation generated by the inhomogeneous surface over the Jinta oasis, which is located in Gansu—a northwestern province of China. Comparison between simulations and observations showed that the WRF results produced with observed soil temperature and moisture initializations agreed well with near-surface measurements of air temperature, relative humidity, and wind direction. Moreover, low temperatures over the oasis were found to coexist with high temperatures over the bare land, further leading to developments of local atmospheric circulation. The simulated winds over the oasis showed airmass divergence over the surface layer, triggering local circulation in the upper level. The integration of the MODIS land use/cover data with WRF and the initialization of WRF’s soil temperature and moisture with in situ observations improved the simulations in air temperature, relative humidity, and heat fluxes. These improvements enabled the WRF to reproduce the observed “cold and wet island” effects of the oasis.

1. Introduction

Oases are unique intrazonal landscapes in arid and semiarid areas of the world (Zhang et al. 2003). In northwestern China, oases are originally formed from melting snow in the Tian and Qilian Mountains (Qi et al. 2007; Chu et al. 2005). Although oases represent only a very small portion (4%–5%) of the land surface in northwestern China, they are important to more than 95% of the local population for agriculture and other activities (Qi et al. 2007). These oases have become important in supporting a commodity grain base in northwestern China, and they hold increasing social and economic significance. Almost no natural rainfall occurs in the arid environment of the oases, so irrigation is the basic necessary condition for their existence and extension. In the last half century, rapid population growth and overexploitation of water, soil, and biological resources have led to drought, salinization, and desertification, and have consequently hindered the development of sustainable agriculture (Chu et al. 2005). Oasis distribution and shape have also changed in the last several decades. For example, Ma et al. (2005) identified that groundwater reservoirs with a sustainable water supply equivalent to $57.8 \times 10^7$ m$^3$ yr$^{-1}$ are needed to irrigate the Minqin oasis to keep it ecologically and agriculturally sound; however, the vegetation fraction has decreased from 44.8% to 15% between 1985 and 2010.

Atmospheric as well as human effects may be important for oasis maintenance. Between 1988 and 1993, the Heihe River Basin Field Experiment (HEIFE), a joint Sino–Japanese investigation of the atmosphere–land
surface interactions in the Heihe River basin in northwestern China, examined the atmospheric characteristics in oases and the surrounding Gobi (Wang and Mitsuta 1992). Other experiments such as the Field Experiment on Interaction between Land and Atmosphere in Arid Region of North-West China (NWC-Aliex; Qiang and Huang 2004) and Jinta Experiment (JTEX; Meng et al. 2009) were carried out in 2000 and 2005, respectively. These experiments were focused on the land surface processes of arid climate formation and the transport of water vapor over the arid region in northwest China. Several distinct features of the oasis–Gobi were discovered during these experiments: 1) The “oasis effect,” wherein the oasis is a wet, cold island capped by warm, dry air in the upper layer—a situation that could be caused by evaporative cooling due to heat advection from the surrounding Gobi (Oke 1987; Tsukamoto et al. 1992, 1995). 2) A temperature and humidity inversion layer developed over the Zhangye and Dunhuang oases (Kai et al. 1997) from the surface to 8-m height in the afternoon when the wind speed was strong. The temperature difference between 1 and 8 m was about 2°C. The specific humidity exhibited a steep vertical gradient over the oasis. 3) The local thermal circulation generated between the oasis and the Gobi was confirmed by numerical simulation (Chu et al. 2005; Liu et al. 2007). The circulation with lower layers flowing out of the oasis and upper layers flowing into the oasis was the crucial mechanism in reducing heat and moisture exchange between the oasis and the surrounding Gobi. At the same time, the development of circulation causes a stable inverse stratification over the cold island of the oasis. The oasis forms a stable, cool, and humid microclimate that is helpful for vegetation growth (Gao et al. 2004). 4) Oasis microclimate is affected by irrigation, vegetation fraction, and vegetation category (Qi et al. 2009; Wen and Jin 2011). Correlated studies show that irrigation not only helps to decrease the temperature of croplands (Bonfils and Lobell 2007; Lebassi et al. 2009), but can also increase precipitation over irrigated lands (Bourque and Hassan 2009; Prabhjyot and Hundal 2009).

Mesoscale modeling is an effective tool in analyzing and understanding the exchange of water and energy over oases, but the lack of observational data for accurate specification of these components in the initial conditions of the model is one of the difficult aspects in evaluation of such modeling. Molders (2001) indicated that the uncertainties of plant and soil parameters (e.g., albedo, evaporative conductivity, roughness length, soil volumetric heat capacity, emissivity, soil type, subgrid-scale heterogeneity, and inhomogeneity) could remarkably affect the simulations of mesoscale atmospheric processes (e.g., fluxes, variables of state, cloud, and precipitation formation). Trier et al. (2004) found that simulated thermodynamic stability and convection initiation were affected by initial soil moisture distribution. Case et al. (2008) showed that using high-resolution representations of surface properties such as vegetation, soil temperature and moisture, and sea surface temperature in the Weather Research and Forecasting Model (WRF) led to a better understanding of land surface–atmosphere interactions and an improvement of numerical weather and climate predictions. In addition, some studies indicated that initializations of weather and climate models with high-resolution land data could also result in a similar improvement (Chen et al. 2007; Holt et al. 2006).

In land surface process simulations from regional weather and climate models, model parameters such as surface emissivity, thermal capacity, roughness length, and soil water capacity are obtained from a lookup table based on a land use classification scheme (Chen and Dudhia 2001a,b). The feedback of these land surface forcings are then captured in the models. The distribution and variation of land use types play a key role in changes of atmospheric local circulation, precipitation, temperature, and humidity. Research on the impact of land use change on land surface processes includes the “urban heat island effect” and the effects caused by variable and changing crops. Case et al. (2008) found that using the high-resolution land surface initial conditions with the WRF led to an improvement in the timing and evolution of a sea-breeze circulation over northwestern Florida. Rosenfeld (1999) and Ramanathan et al. (2001) indicated that a change in the microphysical processes in clouds due to the existence of metropolitan areas preceded a reduction in local precipitation. Bornstein and Lin (2000) pointed out that the formation and steering of thunderstorms in the U.S. city of Atlanta had possible correlations with the urban heat island effect. Mahrt et al. (1994) observed that a relatively cool, moist inland breeze was generated by an irrigated area. Rabin et al. (1990) found that in Oklahoma after the wheat was harvested, the surface was warmer than it was in adjoining areas where vegetation was still growing. All the above research shows that changes of land use type and land surface parameters may also change land surface processes and affect the atmospheric lower boundary layer, further leading to a change in atmospheric circulation patterns, air temperature, and humidity.

Over last two decades, as the exploitation of water resources has increased in arid northwestern China, the spatial distribution of oases has also changed rapidly (Qi et al. 2007). However, the U.S. Geological Survey (USGS) land use data derived from the Advanced Very High Resolution Radiometer (AVHRR) are for the period of April 1992–March 1993 (Lo et al. 2007). There
are grassland and shrubland over most of the Jinta oasis in the USGS land use type data; however it is now actually irrigated cropland (Meng et al. 2009). The Moderate Resolution Imaging Spectroradiometer (MODIS) data give the most updated land use and land cover over this arid area. Shifts in land use affect the stability of the oasis effect, especially over inhomogeneous underlying surfaces, and also affect oasis development. Chu et al. (2005) performed an idealized simulation using the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5), where the oasis shape was prescribed as a square, and the oasis was surrounded by the Gobi. Their results indicate that the oasis effect was limited to the oasis area. However, satellite data can provide fine-resolution spatial distribution of oases that can be incorporated into numerical models. Kurkowski et al. (2003) showed that application of satellite-derived fractional vegetation coverage in the Eta model improved the temperature simulations at a height of 2 m. De Foy et al. (2006) integrated high-resolution land surface data from MODIS (e.g., land use types, albedo, and surface temperature) into the MM5 model and improved energy budget simulations in the Mexico City basin. Consequently, a wealth of satellite remote sensing data describing the earth’s surface (Townshend and Justice 2002) can be used in simulations of oasis effects on weather and climate to improve modeling results over the inhomogeneous land surfaces of oases.

In this study, the 1-km land use–cover type data derived by satellite remote sensing from the Earth Observing System (EOS) MODIS are used to replace the USGS data in the WRF to improve the simulation of the oasis effect in Jinta oasis. The purpose of this work is to simulate and understand the oasis effect and reveal some features of oasis water and energy cycles. It will also provide a new way to better understand the land surface processes needed for sustainable development in an arid region.

2. Brief description of the Jinta oasis and the model

a. Jinta oasis and observation data

Jinta oasis is an inverse triangle situated between 39°56’–40°17’N and 98°39’–99°08’E in the north–central Heihe River basin in northwestern China (Fig. 1). The average annual total precipitation is about 59.5 mm and the annual potential evapotranspiration is about 2538.6 mm (Meng et al. 2009). The total area is about 1652 km². Jinta oasis is a typical irrigated area in arid northwestern China. It has an undulating topography and varies in elevation by only 80 m.

Field experiments on the energy and water exchange and the atmospheric boundary over the inhomogeneous underlying surface of the oasis were carried out over the Jinta oasis from June to August 2008 by the Cold and Arid Regions Environmental and Engineering Research Institute of the Chinese Academy of Sciences. In the field, there were four automatic weather stations (AWSs) and one oasis meteorological tower station in the vegetated areas, and one Gobi meteorological tower station was located in the nonvegetated area. The four AWSs were at 2 m height, and the two tower stations were at four heights (1.8, 5.8, 13, and 18.9 m). In this study, we used meteorological elements such as air temperature, humidity, and wind direction at 2 m from the AWSs and 1.8 m from the tower sites; latent heat flux and sensible heat flux data were obtained from two portable automated mesonet stations at 3 m and ground heat flux data at 0.02 m from the tower sites. Soil temperature and moisture measurements were obtained from a thermistor thermometer and a water content reflectometer from the meteorological tower stations in five layers (0.05, 0.1, 0.2, 0.8, and 1.0 m) and the AWSs in two layers (0.05 and 0.2 m). These data were checked for reliability and used in model comparisons and in an analysis of the meteorological characteristics and water-energy budget over the oasis–Gobi.

b. Satellite data

MODIS gathers data in 36 spectral bands on board the Terra (EOS AM) and Aqua (EOS PM) satellites. Each delivers global coverage twice a day at 250-, 500-, and 1000-m resolutions, which enables them to provide
valuable support for weather and climate studies (see http://modis.gsfc.nasa.gov/). The MODIS is particularly useful because of its global coverage, radiometric resolution and dynamic range, and multiple thermal infrared bands designed for retrieval of land surface parameters and atmospheric properties. In this study, land use type data were obtained from EOS MODIS data and fractional vegetation coverage data were estimated by using MODIS level 1 B data according to Carlson and Ripley (1997). This paper focuses on the application of land surface parameters estimated from MODIS data in the mesoscale model.

c. Model and experiment

The WRF is a next-generation mesoscale forecast model and data-assimilation system that will advance both the understanding and prediction of mesoscale weather and accelerate the transfer of research advances into operations. It was developed collaboratively by NCAR and the National Centers for Environmental Prediction (NCEP; see http://www.mmm.ucar.edu/wrf/users/). The nonhydrostatic WRF version 3.1 modeling system, released in April 2009, is used in this study. A triple-nested grid system with the center located at 40.1°N, 98.8°E is used in this study (Fig. 2). The Jinta oasis is located at the center of domain 3. In the vertical dimension, 35 unevenly spaced full Eta levels were defined. Based on a series of tests, a set of physical options within WRF were selected. The planetary boundary layer processes were resolved with the Mellor–Yamada–Janjić scheme (Janjić 1990, 1996, 2002). The microphysics was described with the Lin scheme (Lin et al. 1983), and the cumulus clouds were simulated with the Kain–Fritsch convection scheme (Kain and Fritsch 1993; only for domains 1 and 2 and no convection scheme for domain 3). The Rapid Radiative Transfer Model (RRTM; Mlawer et al. 1997) and the Dudhia shortwave radiation scheme (Dudhia 1989) were used to calculate longwave and shortwave radiation and their transfer within the atmosphere. The Noah land surface model with four soil layers was used to resolve land surface processes within WRF (Chen and Dudhia 2001a). The simulation time began at 1800 UTC 18 July 2008 and ended at 1800 UTC 22 July 2008, for a total of 96 h. The 6-h, 1° × 1° NCEP Final Analysis (FNL) from the Global Forecast System (GFS) provided initial and lateral boundary conditions for WRF. The model configurations of the nested domains are listed in Table 1, and the land use classification and vegetation parameters are summarized in Table 2.

Three sets of simulations were performed to investigate oasis effects on local weather processes:

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**Table 1. Model configuration of nesting structure of three grids.**

<table>
<thead>
<tr>
<th>Grid ID</th>
<th>Center lat–lon</th>
<th>Domain dimension</th>
<th>Model resolution (km)</th>
<th>Time step(s)</th>
<th>Data resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40.1°N, 98.8°E</td>
<td>37 × 37</td>
<td>9</td>
<td>54</td>
<td>10 min</td>
</tr>
<tr>
<td>2</td>
<td>40.1°N, 98.8°E</td>
<td>40 × 40</td>
<td>3</td>
<td>18</td>
<td>2 min</td>
</tr>
<tr>
<td>3</td>
<td>40.1°N, 98.8°E</td>
<td>61 × 61</td>
<td>1</td>
<td>6</td>
<td>1 km</td>
</tr>
</tbody>
</table>

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**Table 2. Land use classification and vegetation parameters of the WRF.**

<table>
<thead>
<tr>
<th>Vegetation description</th>
<th>Albedo (%)</th>
<th>Moisture availability (%)</th>
<th>Emissivity (% at 9 μm)</th>
<th>Roughness length (cm)</th>
<th>Thermal inertia (calorie cm⁻² K⁻¹ s⁻¹/²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irrigated cropland</td>
<td>18.3</td>
<td>35</td>
<td>98.5</td>
<td>23</td>
<td>0.04</td>
</tr>
<tr>
<td>Cropland–grassland mosaic</td>
<td>18</td>
<td>25</td>
<td>98</td>
<td>14</td>
<td>0.04</td>
</tr>
<tr>
<td>Grassland</td>
<td>19</td>
<td>15</td>
<td>96</td>
<td>12</td>
<td>0.03</td>
</tr>
<tr>
<td>Shrubland</td>
<td>22</td>
<td>10</td>
<td>93</td>
<td>5</td>
<td>0.03</td>
</tr>
<tr>
<td>Water</td>
<td>8</td>
<td>100</td>
<td>98</td>
<td>0.01</td>
<td>0.06</td>
</tr>
<tr>
<td>Barren or sparsely vegetated</td>
<td>22</td>
<td>2</td>
<td>90</td>
<td>0.1</td>
<td>0.02</td>
</tr>
<tr>
<td>Mixed tundra</td>
<td>15</td>
<td>50</td>
<td>92</td>
<td>15</td>
<td>0.05</td>
</tr>
</tbody>
</table>

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Case 1: A control experiment was performed in which all parameters and land use categories were the default values in the WRF. The seven land use/vegetation categories (Table 2) were irrigated cropland, cropland/grassland mosaic, grassland, shrubland, water bodies, barren or sparsely vegetated land, and mixed tundra. These were derived from the USGS terrain data in the 1-km-resolution domain (Fig. 3a), and the initial soil temperatures and moistures were obtained from the FNL gridded analysis data.

Case 2: The WRF soil temperatures and moistures were initialized with observations in this case. Because of the irregular distribution of the soil temperature and moisture data, it is difficult to obtain such soil initial conditions for each model grid cell. Thus, the average soil temperature and moisture observations from the five oasis stations were adopted to all the grid cells for the model initial fields of the oasis areas. At the same time, we applied the soil moisture and temperature data from the aforementioned Gobi station to all the model grid cells with the desert land use type for the initial fields in the WRF (Figs. 5b, e). We interpolated the observed soil moisture and temperature data from depths of 5, 20, 80, and 100 m into those of 5, 25, and 70 cm that are the center points of the top three Noah soil layers. The observed 100-cm soil data were directly used for the bottom model layer (100–200 cm). The detailed information of the soil data is included in Table 3. The purpose of this experiment is to identify the effects of soil moisture and temperature initialization on the modeling results to reproduce the observed cold and wet island effects of the oasis.

Case 3: One additional WRF test was carried out, where the default land use/vegetation types were replaced with the MODIS land use classification (Fig. 3b), and the fractional vegetation coverage was also replaced with the MODIS data (Fig. 4b). The soil temperature and moisture observations were used to initialize the WRF as described in case 2. This WRF experiment is to quantify the contribution of the vegetation type and coverage changes to the cold and wet island effects.

### Table 3. Observed and interpolated soil moisture and temperature values in four Noah soil layers.

<table>
<thead>
<tr>
<th>Land use types</th>
<th>Noah soil layers</th>
<th>Observed soil moisture (cm$^3$ cm$^{-3}$)</th>
<th>Interpolated soil moisture used in case 3 (cm$^3$ cm$^{-3}$)</th>
<th>Observed soil temperature ($^\circ$C)</th>
<th>Interpolated soil temperature used in case 3 ($^\circ$C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oasis</td>
<td>0–10 cm</td>
<td>0.38(at 5 cm)</td>
<td>0.38(at 5 cm)</td>
<td>21.3(at 5 cm)</td>
<td>21.3(at 5 cm)</td>
</tr>
<tr>
<td></td>
<td>10–40 cm</td>
<td>0.48(at 20 cm)</td>
<td>0.47(at 25 cm)</td>
<td>23.3(at 20 cm)</td>
<td>23.1(at 25 cm)</td>
</tr>
<tr>
<td></td>
<td>40–100 cm</td>
<td>0.30(at 80 cm)</td>
<td>0.33(at 70 cm)</td>
<td>21.1(at 80 cm)</td>
<td>21.5(at 70 cm)</td>
</tr>
<tr>
<td></td>
<td>100–200 cm</td>
<td>0.26(at 100 cm)</td>
<td>0.26(at 150 cm)</td>
<td>20.2(at 100 cm)</td>
<td>20.2(at 150 cm)</td>
</tr>
<tr>
<td>Gobi</td>
<td>0–10 cm</td>
<td>0.07(at 5 cm)</td>
<td>0.07(at 5 cm)</td>
<td>27.5(at 5 cm)</td>
<td>27.5(at 5 cm)</td>
</tr>
<tr>
<td></td>
<td>10–40 cm</td>
<td>0.10(at 20 cm)</td>
<td>0.10(at 25 cm)</td>
<td>32.6(at 20 cm)</td>
<td>32.1(at 25 cm)</td>
</tr>
<tr>
<td></td>
<td>40–100 cm</td>
<td>0.04(at 80 cm)</td>
<td>0.05(at 70 cm)</td>
<td>25.5(at 80 cm)</td>
<td>26.7(70 cm)</td>
</tr>
<tr>
<td></td>
<td>100–200 cm</td>
<td>0.06(at 100 cm)</td>
<td>0.06(at 150 cm)</td>
<td>24.8(at 100 cm)</td>
<td>24.8(at 150 cm)</td>
</tr>
</tbody>
</table>

![Fig. 3. Land use–vegetation maps for the 1-km-resolution domain from (a) the default data (USGS) and (b) MODIS data.](image)
3. Model results

a. Land use–vegetation

Key land surface variables include soil temperature and moisture and vegetation classification. These significantly affect surface heat fluxes, radiation balance, and vertical circulation, which play an important role in the evolution of the planetary boundary layer of the atmosphere (Meng et al. 2009). Land use classification is an important step in assuring accurate retrieval of crop-specific parameters. In the study area, the land cover was primarily corn and cotton within relatively barren or sparsely vegetated land. Figure 3 shows the comparison of land use–vegetation maps between the default (USGS) and modified MODIS data for the 1-km-resolution domain. Most of the oasis is irrigated cropland, with grassland decreasing rapidly in the interior and outer edges of the Jinta oasis and degrading to desert (Fig. 3b). With population growth, more and more grassland is used to plant crops, which results in the reduction of shrubland and grassland. Figure 4 shows the comparison of the default (from the AVHRR) and MODIS vegetation fractions at

![Image of vegetation maps](image-url)
1-km resolution. It is seen that the fractional vegetation coverage is all below 20% in the default data (Fig. 4a), while it ranges from 40% to 75% over the oasis area in the MODIS data (Fig. 4b). General, the classifications from the MODIS data were shown to be more consistent with the local landscape maps of the Jinta oasis (Ma et al. 2003) than the default USGS classifications.

b. Soil temperature and moisture

A sufficient water supply is necessary for oasis existence and extension over arid and semiarid regions in northwestern China. The spatial distribution of soil water affects the size, location, and shape of oases. The soil moisture in the default initial field was interpolated from the NCEP–FNL gridded analysis data in case 1 (Fig. 5a), and is uniform over entire grids. When the soil temperature and moisture are replaced by observations in case 2 (Fig. 5b) and in case 3 (Fig. 5c), the initial value of soil moisture compared to the default model is increased when underlying surfaces are cropland and grassland, and decreased when the underlying surfaces are Gobi. With the MODIS data in case 3, differences appear between the oasis and the Gobi. This could reflect the soil moisture of actual underlying surfaces. The initial value of soil temperature from the three cases is displayed in Figs. 5d, e, and f, respectively. Compared with the default model (Fig. 5d), differences can be seen in the other cases. When soil temperature is input in the initial fields, the distribution of soil temperature over the oasis shows distinctly different patterns (Fig. 5e) than those of the default model. Similarly, once the land use–vegetation data are replaced in case 3, a significantly different pattern emerges (Fig. 5f), where the irrigated crop areas are colder than the surrounding area.
The time series comparison of the soil moisture and temperature fields at a depth of 10 cm is shown in Fig. 6. The average observed soil moisture value in the oasis at a depth of 10 cm declined from 0.38 to 0.3 cm$^3$ cm$^{-2}$ within 4 days (Fig. 6a). The average soil temperature and moisture observations were adopted as soil initial conditions in case 3, so the simulation agreed with observations during the 4 days; the observed soil moisture declined from 0.07 to 0.04 cm$^3$ cm$^{-2}$ in the Gobi site (Fig. 6b), demonstrating that the soil moisture was greater in vegetated areas than in nonvegetated areas. The average observed soil temperatures were also from 17$^\circ$C to 27$^\circ$C lower in the oasis (Fig. 6c) than in the Gobi site (Fig. 6d), where the peak value reached nearly 50$^\circ$C. The simulated values of soil temperatures in all three cases were higher than the average observed soil temperatures, but the simulations from case 3 are closest to the observations in both the oasis and Gobi sites.

c. Air temperature and humidity

A comparison of observed and simulated land surface air temperatures at the four AWSs and the two tower sites for cases 1 and 3 is shown in Fig. 7. The modified model results agree better with observations than do the default results; the peak value of the air temperature in case 1 is higher than observations. A possible reason may be a smaller area of vegetation coverage and drier soil over the oasis in the default model, resulting in weaker evaporation and thus a lower peak temperature when compared to cases 2 and 3. The mean observed temperature is 26.5$^\circ$C at the oasis tower site and 27.4$^\circ$C at the Gobi tower site, while the mean simulated temperature is 26.4$^\circ$C at the oasis site and 28.9$^\circ$C at the Gobi site in case 3. So the oasis is always a “cold island” compared with the surrounding Gobi. The peaks appear in the daytime between 1300 and 1500 LT, and the valleys occur at night between 0200 and 0400 LT. Error statistics were calculated for the entire simulation time and integrated with the six stations. The coefficients of correlation between the simulated and observed air temperatures at 2 m for the three cases are 0.909 [the 95% confidence interval (CI) values are 0.894–0.922], 0.911 (the 95% CI values are 0.896–0.924), and 0.934 (the 95% CI values are 0.923–0.944), respectively; the root-mean-square error (RMSE) of the three cases is 2.7, 2.2, and 2.0$^\circ$C, and the bias of the three cases is 1.6, 0.8, and 0.9$^\circ$C, respectively. The RMSE and bias are both reduced in cases 2 and 3. The diurnal variation of the simulated surface skin temperature is similar to that of air temperature, differing only in amplitude (figure omitted). Because soil moisture and thermal capacity are relatively higher in the oasis than in the Gobi, more energy is required to raise the temperature over the oasis during the daytime, while relatively less energy is required over the
Gobi. At night, evaporation in the oasis is still significant, so the air temperature is still lower than in the surrounding Gobi (Liu et al. 2007).

Figure 8 shows air temperatures over the Jinta oasis at 0900 UTC 21 July 2008 (1500 LT) for the three simulated cases. With the default NCEP–FNL gridded analysis data in case 1, the oasis is a “hot island” compared with the surrounding Gobi (Fig. 8a), and the air temperature is also hotter than in the Gobi at 850 hPa (Fig. 8d). In case 2, when the initial soil moisture increases from 0.05 to 0.38 over the oasis, and the initial soil temperature decreases from 28°C to 22°C over the same area, the simulated air temperatures at the 2-m height and the 850-hPa level show an obvious change, and the cold island effect of the oasis can be simulated by the model. Finally, the soil moisture and soil temperature are replaced in case 3, also showing the cold island effect of the oasis. Distinct vegetation patches appear as “cold patches” and exposed soil and nonvegetated lands in the inner oasis remain as hot areas (Fig. 8c), similar to the soil temperature map in Fig. 5f. The simulated 2-m air temperature is about 34.2°C over the oasis and 35.4°C over the Gobi. The cold area is formed at 850 hPa (Fig. 8f), and the cold air is diffused to the surrounding atmosphere by advection. But the secondary circulation driven by the thermal inhomogeneity in the inner oasis would probably affect the balance of the cold island effect.

Figure 9 shows the relative humidity at 2 m for the observations and simulations for the three simulated cases at simulation time. A U-shaped curve results from the diurnal variation of observations, the peak appearing at about 0500 LT and the valley appearing at 1500 LT. The coefficients of correlation between the simulated and observed relative humidity at 2 m for the three cases are 0.621 (the 95% CI are 0.568–0.669), 0.678 (the 95% CI are 0.566–0.667), and 0.637 (the 95% CI are 0.586–0.683), respectively; the RMSE of the three cases is 19.1%, 14.1%, and 14.1%, and the bias of the three cases is −14.8%, −7.5%, and −7.8%, respectively. It can be seen that the WRF simulations are improved with the integration of the MODIS data and the use of the observed soil moisture and temperature for the initial conditions. For case 2, the increase in relative humidity is due much to the stronger evaporation induced by the wetter soil. For case 3, the increased relative humidity is caused by stronger evaporation from the soil and higher transpiration from the enlarged vegetation coverage. The simulated relative humidity is less than observations, and the differences between the simulations and observations at the Gobi site are substantial. Possible reasons for these differences may be 1) actual evaporation over the oasis is greater than in the simulation because of occasional irrigation, but the simulated results depend on initial conditions, so the increase of soil moisture cannot be simulated; and 2) because of the proximity of the Gobi site to the oasis, water vapor from the oasis can be transferred to the surrounding Gobi by advection. In addition, before the simulation, precipitation occurred on 18 July 2008 that would have increased air humidity. However, the modified model in case 3 captures the major physical processes involved in land–atmosphere interactions better than the default model in case 1 over the oasis in this arid area.

Specific humidity at 2 m and 850 hPa from the three cases is displayed in Fig. 10. Compared with the default model (case 1), differences can be seen in cases 2 and 3,
which indicates that simulations including soil moisture obviously make the oasis a typical “wet island” compared with the Gobi (Fig. 10c). The output in case 3 (Fig. 10c) also shows that the distribution of the specific humidity is similar to that of the soil moisture map in Fig. 5c. When soil water and vegetation types are put into the model, higher specific humidity values appear above the vegetated areas, while the lower humidity values are at the edge of the oasis. In the oasis, the dominant vegetation is grass and the fractional vegetation coverage is only about 5%–15% in the default model (Fig. 4a), but in case 3 the vegetation type changes to cropland and the vegetation coverage is approximately 60%. Owing to the difference in vegetation type and vegetation coverage, the areas of the high humidity are different too; in the oasis with its abundant green vegetation, there is an area of higher humidity that may be caused by the greater local evaporation—a phenomenon that cannot be simulated by case 1 (Fig. 10d).

d. Circulation analyses

Figure 11 shows the near-surface wind direction at 10 m for the observations and simulations of case 3 at simulation time. Simulated wind directions agree well with observations in the first half of the simulation time because of a strong background wind, and in the latter half of the simulation time, when the background wind becomes weaker, the low-level divergence generated by evaporation over the oasis can be reflected by observations and simulations. The simulated wind speed does not agree well with observations (figure omitted), but wind directions were better represented in the modified case 3. Because of the uncertainty of randomized turbulence processes, it is difficult to simulate wind speed and direction accurately (Hanna and Yang 2001), but the tendency of wind direction can be simulated well in the modified model of cases 2 and 3.

As a result of the great difference in the surface thermal characteristics between the oasis and the surrounding Gobi, there is a strong horizontal gradient in the horizontal temperature field at the intersection of the inner boundary layer of the oasis and the Gobi. The wet and cold air masses are transferred to the surrounding Gobi through advection, and the updraft over the edge of the oasis could prevent the water vapor flowing away from the oasis, which would aid in its protection (Chu et al. 2005).

In this study, we selected the model results and observations for 1500 LT 21 July 2008 for analysis. At this selected time, the oasis effect on local atmospheric processes is significant, where the low-level divergence generated by evaporation over the oasis can be seen in both observations and simulations. The simulation of horizontal surface winds over the Jinta oasis is shown in Figs. 12 a–c for the three cases. The oasis effect reached a maximum in the afternoon at 1500 LT 21 July 2008. In case 1 (Fig. 12a), the horizontal winds show a random
pattern over the oasis. Compared with case 1, cases 2 and 3 can both simulate the phenomenon of a low-level divergence pattern over the oasis. With the observed soil moisture and temperature initializations (case 2; Fig. 12b) and the higher vegetation coverage (case 3; Fig. 12c), evaporation in the cropland is stronger than in the grassland and shrubland, the surface aerodynamic roughness length is changed, and wind speeds at the lower atmospheric layer are enhanced. Divergence in the lower atmosphere is strong over the oasis, where cold, wet air is transferred into the dry surrounding Gobi through advection, while hot, dry air over the Gobi moves into the oasis from the upper part of the atmosphere. As a result, the substitution can help simulate the features of the wind stress field in the inhomogeneous landscape over the oasis.

Because the horizontal velocity flow in the lower layer over the oasis is divergent, the wind velocity in the upper layer will be downward. The hot, dry air over the surrounding Gobi interacts with cold, wet air over the oasis, which could generate the local thermal circulation. From the vertical section along 40.15°N, the vertical velocity for the three cases can be seen in Figs. 12d–f. The downdraft winds appear between the surface and 500 m over the oasis in case 1 (Fig. 12d), with vertical wind speeds of $-0.2$ m s$^{-1}$. Above 500 m, the updraft wind speeds are mostly positive at 0.2 m s$^{-1}$. Obviously, the local thermal circulation cannot reach the higher level because of less vegetation, weaker evaporation, and lower soil moisture over the oasis in the default model. Figure 12e shows a negative vertical wind velocity between the near-surface and 4.5-km heights in case 2 (from $-0.1$ to $-0.2$ m s$^{-1}$). In case 3, not only can the phenomenon of low-layer divergence be simulated, but updrafts and downdrafts can also be found over the upper layer. The downdraft wind speeds are mostly negative at $-0.4$ m s$^{-1}$, and the updraft wind speeds could reach $0.6$ m s$^{-1}$. The turbulent mixing and secondary circulation are very strong in case 3 over the upper air of the oasis. The oasis–Gobi local thermal circulation is induced by the underlying horizontal thermal difference. So case 3 produces the integral image of the oasis–Gobi interaction as aforementioned. The horizontal wind, the divergence, and the vertical velocity in the modified simulation all indicate that the inhomogeneous underlying surface leads to larger turbulence; but on the other hand, it could cause instability in the low layer over the oasis (Gao et al. 2004). This suggests that connecting the small oases together would enhance the efficiency of irrigation and maintain the oasis.

e. Energy heat flux

Temperature over the oasis and Gobi surfaces is determined in such a way that it satisfies the requirement of surface heat balance. Figure 13 shows the comparison
between the observations and simulations of the three cases of net radiation and heat flux from two flux observation sites. Figures 13a,b show that the peak observed value for net radiation in the oasis is about 700 W m$^{-2}$ at 1200 LT, which is 50 W m$^{-2}$ less than in the Xiaotun oasis in the central Heihe River basin in August 1991 (Liu et al. 2007). Because the albedo in the Gobi (about 0.232) is higher than in the oasis (about 0.183), the peak value of net radiation in the Gobi is about 500 W m$^{-2}$, which is 100 W m$^{-2}$ less than in the Huain Gobi in the Heihe River basin (Liu et al. 2007). Kai et al. (1997) found that the latent heat flux is an order of magnitude smaller over the Gobi (67 W m$^{-2}$) than over the oasis (634 W m$^{-2}$) in the HEIFE region. In this study, the observed latent heat flux over the oasis is about 400 W m$^{-2}$, and about 30 W m$^{-2}$ over the Gobi (Figs. 13c,d). The observed peak value of sensible heat flux over the oasis is about 150 W m$^{-2}$ and is about 300 W m$^{-2}$ over the surrounding Gobi; both values are higher than those in Xiaotun oasis and Huain Gobi over the Zhangye oasis during the HEIFE experiment (Liu et al. 2007). Kai et al. (1997) found by analyzing the HEIFE data that the ground flux was almost the same as that in the oasis and the Gobi, but in this study, the difference in ground heat flux between the oasis and the Gobi is about 50 W m$^{-2}$; the peak value is slightly lower over the Gobi than over the oasis.

For case 2, when the soil moisture and temperature were initialized with observed values, the simulated peak latent heat flux is about 300 W m$^{-2}$ at the oasis tower site, which is 250 W m$^{-2}$ higher than in case 1 (Fig. 13c), and the peak sensible heat flux is about 200 W m$^{-2}$ (Fig. 13e), which is 200 W m$^{-2}$ less than in case 1. In case 3, when the grassland–shrubland (the default USGS data) is changed to irrigated cropland (the MODIS data) and vegetation coverage increases from about 10% to 60% over the oasis, the peak latent heat flux is about 550 W m$^{-2}$ at 1400 LT 21 July 2008, which is 250 W m$^{-2}$ higher than that in cases 1 and 2 (Fig. 13c). It is due mainly to vegetation transpiration. The diurnal variation of ground heat flux in the three cases is shown in Fig. 13g. The simulated peak ground heat flux in case 3 is about 100 W m$^{-2}$ at the oasis tower site, which is 100 W m$^{-2}$ less than that in cases 1 and 2, and the simulated minimum value is about −40 W m$^{-2}$, which is 50 W m$^{-2}$ higher than that in cases 1 and 2. When
compared to cases 1 and 2, case 3 has a 50% higher vegetation coverage, where the soil receives less radiative energy during the daytime and loses less longwave radiation during the nighttime because of the sheltering effects of the canopy.

The model bias and RMSE were calculated and summarized in Table 4 for the fluxes over our study period. The RMSEs for net radiation, latent heat flux, sensible heat flux, and ground heat flux in case 3 are 78.9, 100.5, 35.8, and 22.2 W m\(^{-2}\) over the oasis, respectively, and the biases in case 3 are 13.7, 40.7, 215.4, and 23.8 W m\(^{-2}\) over the same area. When compared with those in cases 1 and 2, the reductions in RMSEs and biases are still significant over the Gobi area in case 3 except for sensible heat flux. For example, the RMSE of the simulated net radiation decreases from 79.6 to 69.6 W m\(^{-2}\), and its bias decreases from 19.8 to 14.8 W m\(^{-2}\). The RMSE of the simulated ground heat flux decreases from 40.2 to 36 W m\(^{-2}\), and the bias decreases from −5 to 1.6 W m\(^{-2}\).

In general, the differential sensible heat fluxes over the oasis and the surrounding Gobi regions drive the oasis breeze circulation with the downdraft over the oasis and the updraft over the Gobi. Surface albedo and evaporation are the two essential and competing factors that determine the sensible heat flux gradient and in turn the local circulation. The errors for simulating the energy

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heat flux in case 1 are a result of unsuitable USGS vegetation classification and coarse grids of soil water data from NCEP–FNL gridded analysis data. Therefore, including soil observations in case 3 leads to improved simulations of latent, sensible, and ground heat fluxes.

4. Summary and discussion

The main goal of this study is to improve the simulation of oasis effects on microscale processes over the inhomogeneous surface in the Jinta oasis by applying satellite remote sensing data to the WRF model. The modified results show the distribution of elements such as soil temperature, soil moisture, air temperature, and relative humidity to be in accord with actual conditions, and the oasis appears as a “cold–wet island.” Land–atmosphere interactions over the Gobi–oasis and the vertical structure of the oasis effect are also simulated quite reasonably.

A key factor in simulating the characteristics of micrometeorology over an inhomogeneous underlying surface is using more accurate land surface parameters and initial conditions. The replacement of land use–vegetation types enhances the aerodynamic roughness over the oasis; soil temperature and moisture from observations change the soil temperature and moisture in the initial fields, which enhances the land–atmosphere interaction for the inhomogeneity over the oasis. The modified simulation results—including air temperature, relative humidity, and circulation—are superior to the default model results, and are also better than the results from changing only soil temperature and moisture. Furthermore, the modified simulations improve the modeling of energy heat fluxes, especially latent heat flux and sensible heat flux. These results prove that the WRF could be used to simulate energy and water vapor exchange over inhomogeneous underlying surfaces in arid and semiarid regions in northwestern China.

Theoretically, the downdraft of the oasis breeze circulation may stabilize the atmosphere and in turn reduce the vertical moisture transport, which helps to stabilize the oasis. But, in fact, the modified simulation results show intense local thermal circulation and turbulent mixing in the upper layer above the oasis. The divergence and vertical velocity in the modified simulation indicate that the inhomogeneous underlying surface leads to greater turbulence and instability in the lower layer and increases evaporation over the oasis.

The application of satellite retrievals can improve numerical simulations of regional micrometeorological characteristics and local circulation with high-resolution simulation over small-scale areas, and can help especially with the description of inhomogeneous underlying surfaces. These results all demonstrate the validity of the modified model. Therefore, the model provides a good tool for better understanding the inhomogeneous features and mechanisms leading to the regional oasis–Gobi macroclimate.

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