MODIS-Derived Boundary Conditions for a Mesoscale Climate Model: Application to Irrigated Agriculture in the Euphrates Basin

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ABSTRACT

In arid and semi-arid parts of the world, evaporation from irrigated fields may significantly influence humidity, near-surface winds, and precipitation. Using Moderate Resolution Imaging Spectroradiometer (MODIS) Terra imagery from summer and autumn 2000 the authors attempt to improve the realism of a regional climate model (the fifth-generation Pennsylvania State University–NCAR Mesoscale Model) with respect to irrigated agriculture. MODIS data were used to estimate spatially distributed vegetation fraction and to identify areas of irrigated land use. Additionally, a novel surface flux routine designed to simulate traditional flood irrigation was implemented. Together these modifications significantly improved model predictions of water flux and the surface energy balance when judged against independent weather station data and known crop requirements. Model estimates of watershed-level water consumption were more than doubled relative to simulations that did not incorporate MODIS data, and there were small but systematic differences in predicted temperature and humidity near the surface. The modified version of the mesoscale model also predicts the existence of heat-driven circulations around large irrigated features, and these circulations are similar in structure and magnitude to those predicted by linear theory. Based on these results, it was found that accurate representation of irrigated agriculture is a prerequisite to any study of the impact of land-use change on climate or on water resources.

1. Introduction

The dual pressures of local water consumption and global climate change threaten water shortages in many of the world’s populated arid and semi-arid regions. The net impact of these changes on available water is not always obvious, and it is expected that regions will respond differently both to the global forcing and, perhaps, to local forcings associated with changing patterns of evaporation (Leung et al. 2004; Ruosteenoja et al. 2003). Notwithstanding recent increases in the consumption of freshwater for industrial and domestic purposes, agriculture continues to be the greatest anthropogenic consumer of freshwater throughout most of the world (Gleick 2003; Jackson et al. 2001). Accurate quantification of this human-appropriated “green water” (Postel et al. 1996) often depends on distributed models of hydrology and climate, as conventional measurements are not possible on the regional or global scale. Moreover, in the context of global climate change, models are the only tool available for formulating informed predictions on regional water availability and the significance of land-atmosphere hydrologic feedbacks in the near future (Jones and Reid 2001; Payne et al. 2004; Stone et al. 2001).

The fact that local climate and land surface characteristics determine latent heat flux at the surface is hardly a matter of debate. Boundary layer atmospheric conditions have a controlling influence on the rate of potential evapotranspiration (PET) from the surface (Penman 1948). Surface conditions, including soil moisture, surface roughness, and vegetation type and coverage, largely determine the fraction of PET that is recognized as actual evapotranspiration (AET; Brutsaert 1982). Thus, the importance of quality data on near-surface climate and on the hydrologic/vegetation status of the surface is obvious even in the one-dimensional case. Moving beyond a single dimension, we recognize that PET at one point may depend on AET at other points nearby; for example, a “fetch effect” may develop downwind of an actively evaporating
surface, mitigating PET due to a reduction in the vapor pressure deficit or atmospheric temperature. Conversely, a dry and/or hot surface may increase evaporative demand downwind via advective enhancement. In areas of diverse land use or other contrasts in boundary layer hydrometeorology, then, quantification of water consumption may require distributed information on the drivers of PET and AET, particularly when constant monitoring of near-surface climate is not available. A climate model of sufficient resolution, fed with proper lower boundary conditions and equipped with sophisticated schemes for the planetary boundary layer (PBL), can provide predictions of spatially and temporally distributed PET where monitoring networks are insufficient or nonexistent. A coupled land surface model (LSM), properly parameterized according to surface conditions, can be used to define the evaporative fraction and to determine AET.

In addition to direct consumption of freshwater, anthropogenic landscape changes can influence water resources indirectly through local and regional feedbacks on weather events and climate (Chagnon 1968; Diem and Brown 2003; Perlin and Alpert 2001; Pielke et al. 1999; Pielke et al. 1991). When irrigated agriculture is introduced to a dry area, feedbacks may result from increases in local evaporation, reduced albedo within the irrigated field, or the influence of surface cooling on mesoscale circulations and the stability of the lower atmosphere (Anthes 1984; Perlin and Alpert 2001). Using a simple global-scale model, Yeh et al. (1984) showed that the increase in evaporation associated with large-scale irrigation significantly moistens the lower atmosphere and leads to enhanced precipitation. The magnitude of the precipitation increase depends on background atmospheric conditions, however, and irrigation-induced cooling of the boundary layer may, in certain contexts, cause descending motion that inhibits precipitation in neighboring zones.

Such dynamical concerns are even more important for smaller, more realistic scales of irrigation. Segal et al. (1989) found that horizontal gradients in the sensible heat flux between cool irrigated fields and their hot, dry surroundings produce horizontal temperature gradients in the lower atmosphere that can drive a sea-breeze-like mesoscale circulation. For irrigation in eastern Colorado this irrigation-induced circulation was nearly overwhelmed by synoptic and terrain-forced flow (Segal et al. 1989), but in the context of weak synoptic forcing the heat-driven circulation can impact boundary layer stability and the potential for moist convection (Chen and Avissar 1994). In a preexisting conditionally unstable environment, discontinuities in sensible heating at the surface may determine the location of first convection of a storm event, thus influencing local precipitation patterns (Chang and Wetzel 1991). Alternatively, cooling associated with the evaporating surface can be advected to a region with convective potential, impacting the thermodynamic structure of the PBL and enhancing deep precipitating convection as much as one day downstream of the irrigated region (Beljaars et al. 1996). In other contexts, however, the introduction of irrigation can act to inhibit precipitation, either by modifying an existing mesoscale circulation that relied on local sensible heating (Lohar and Pal 1995) or by stabilizing a moist, low-level jet and preventing rainfall release (Paegle et al. 1996). Reduced albedo associated with irrigation can also influence precipitation patterns via an increase in net radiation and moist static energy at the surface (Perlin and Alpert 2001). The net impact of changes in land use on mesoscale circulations, atmospheric stability, and precipitation will depend upon landscape characteristics, the dominant precipitation mechanism, and the spatial scale of irrigation (Pielke et al. 1991).

In humid regions the impact of local land use on precipitation may be little more than a curiosity, since the climatological effect on humidity and precipitation is minor relative to background. In semiarid and arid zones, however, even small changes in hydrologically relevant parameters can affect the viability of water-limited ecosystems and marginal dryland agriculture. Extensive irrigation projects have the potential to effect such a change, and the influence of such feedbacks on watershed-scale hydrology and environment should be considered.

The Euphrates River basin spans a dramatic precipitation gradient, extending from humid highlands in the north (precipitation >1200 mm yr⁻¹) to the arid plain of Mesopotamia, where average annual rainfall is about 100 mm. The minimum precipitation required for dryland (nonirrigated) agriculture has been set by various authors at 200–250 mm (Beaumont 1996; Geerken and Ilaiwi 2004). In portions of the Euphrates Basin that are marginal for dryland production the difference of one or two rain events can mean the difference between crop success and crop failure. A similar sensitivity is observed in rangelands in the marginal zone, where chronic overgrazing and interannual variability in precipitation put large areas at risk of degradation (Evans and Geerken 2004). Irrigated agriculture is another significant land use in the marginal zone; irrigation is required for summer crops (June–September), which come to maturity at the height of the Mediterranean dry season, and is utilized in a supplementary fashion for winter crops (November–May) where the infrastructure allows. Approximately 1.5 million hectare
(ha) were under full irrigation in the Euphrates Basin of Syria and Iraq in 2002 (up from 650 000 ha in 1985), and Turkey is currently in the process of completing its massive Southeastern Anatolia Project [Guneydogu Anadolu Projesi (GAP)], which is planned to include 1.7 million ha of irrigation in the upper Euphrates Basin (Gruen 2000). The dominant summer crop is cotton and the preferred method of application is flood irrigation, with water diverted from the major drainages, drawn from shallow unconfined aquifers, or extracted from deeper, confined aquifers. Estimates from the upper Euphrates watershed (Turkey) indicate that the irrigated cotton regime consumes approximately 10 000 m$^3$ of water per hectare over a summer cropping season (Beaumont 1996). The sheer volume of water being introduced to the lower atmosphere—water that would otherwise remain below ground or flow in rivers to the Persian Gulf—suggests that irrigated agriculture might have an impact on weather events and climate in this region.

It would be valuable both to understand the influence of agricultural developments on climate in the Euphrates Basin and to develop an adequate modeling system to monitor and predict these impacts on a scale relevant to management. Regional climate models (RCMs) are valuable tools in the study of anthropogenic effects. Unlike global climate models (GCMs), RCMs are applied over a limited area and draw lateral boundary conditions from a regional or global dataset. This makes it possible to apply RCMs at relatively high resolution in order to resolve surface features ignored or only crudely represented by global models. When the RCM has interactive nesting capabilities it is possible to focus at very high resolution (even subkilometer) in a subset of the modeled domain while maintaining the spatial coverage needed to capture the mesoscale context. Such an approach is ideally suited to the study of irrigated agriculture in an arid region, as the local feature of interest operates on a scale much smaller than the drivers of aridity.

A sophisticated RCM, however, is necessary but not sufficient for the realistic simulation of land surface feedbacks. The quality and resolution of input data are of critical importance, and, in the case of agricultural land covers, events related to planting, irrigation, and harvest should be accounted for with some degree of realism. In this study we apply the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM5) (Grell et al. 1994) coupled to the Noah LSM to a portion of the Euphrates Basin. In previous work we have found that MM5 provides reasonable multiyear simulations of climate in this region at 25-km resolution. When applied to finescale irrigation studies, however, MM5 failed to give reasonable estimates of surface state conditions and hydrometeorological fluxes beyond the first few days of the simulation.

In this study we attempt to improve the modeled surface conditions by utilizing data from MODIS-Terra to derive the vegetation fraction dataset and to identify areas of irrigated land use. An irrigation regime based on Euphrates Basin practices is also introduced to the Noah LSM. Descriptions of the RCM (MM5-Noah), satellite imagery, and ground station data are provided in section 2. Details pertaining to the model setup and simulation experiments are given in section 3. Significant results are presented in section 4, and discussion and conclusions are offered in section 5.

2. Model and data

a. MM5-Noah

The PSU–NCAR mesoscale modeling system MM5 is described by Dudhia (1993) and Grell et al. (1994). MM5 is a limited-area nonhydrostatic model that uses a terrain-following vertical coordinate system. It has two-way nesting capabilities and flexible physics options. In this study MM5 was implemented with the Reisner mixed-phase explicit moisture scheme (Reisner et al. 1998), the Medium-Range Forecast (MRF) planetary boundary layer scheme (Hong and Pan 1996), the Rapid Radiative Transfer Model (RRTM) radiation scheme (Mlawer et al. 1997), and, for the outer domains, the Grell cumulus scheme (Grell et al. 1994).

MM5 is operationally linked with the Noah LSM. Noah is a direct descendent of the Oregon State University (OSU) LSM (Mahrt and Ek 1984; Mahrt and Pan 1984; Pan and Mahrt 1987), a sophisticated land surface model that has been extensively validated in both coupled and uncoupled studies (Chen and Mitchell 1999; Chen and Dudhia 2001). The Noah LSM simulates soil moisture, soil temperature, skin temperature, snowpack depth and water equivalent, canopy water content, and the energy flux and water flux terms of the surface energy balance and surface water balance. In its MM5-coupled form Noah has a diurnally dependent Penman potential evaporation (Mahrt and Ek 1984), a four-layer soil model (Mahrt and Pan 1984), a primitive canopy model (Pan and Mahrt 1987), modestly complex canopy resistance (Jacquemin and Noilhan 1990), and a surface runoff scheme (Schaeke et al. 1996).

One limitation that we encountered in our application of MM5-Noah on climatological time scales is the absence of an irrigation scheme within the surface flux module. Grid cells classified as irrigated crops or pasture are initialized at 100% soil moisture, but no addi-
ditional water is introduced during the simulation. This may be appropriate for 2–3-day weather simulations, but for studies of climate some modification is required. A universal irrigation regime would be difficult to emulate as irrigation practices can differ markedly between regions. Here we simulated the flood irrigation practices common in the region for a summer crop by bringing irrigated grid cells to saturation for 30 min at 0900 local time once every seven days. The irrigation season began on 30 May and concluded on 14 September, in accordance with average cropping patterns in the area (al-Khaier 2003). The length of the saturation period was selected based on local practice as well as trial and error in order to obtain a realistic periodic dry-down throughout the soil column (Fig. 1). Some accumulation of water was observed in the bottom soil layer over the length of the growing season, but this is not unrealistic for flood irrigation as it is traditionally practiced (e.g., Sharma and Tyagi 2004).

b. MODIS processing

The Moderate Resolution Imaging Spectrometer (MODIS) aboard Earth Observing System (EOS) Terra provides daily images of surface reflectance at 500-m resolution for the entire globe. MODIS product A09 offers 8-day clear-sky composite images of surface reflectance and has been validated extensively for scientific application. The A09 V004 product was used in this study to calculate Normalized Difference Vegetation Index (NDVI) for each 8-day composite period over the full length of the MM5 simulation. NDVI was converted to vegetation fraction (VF) through a linear relationship, following the methodology used to create the global Advanced Very High Resolution Radiometer (AVHRR)-based VF dataset that is currently operational for MM5. In the linear method VF is defined as

\[
VF = \frac{(NDVI - NDVI_0)(NDVI_{Max} - NDVI_0)}{(NDVI_{Max} - NDVI_0) - (NDVI - NDVI_0)}
\]

(Gutman and Ignatov 1998),

where NDVI is the index for each pixel, NDVI_0 is the scene minimum terrestrial NDVI, representing bare soil in this region, and NDVI_{Max} is the maximum vegetation index in the scene. In winter and spring images the NDVI_{Max} was often found in deciduous forests, while summer NDVI_{Max} was generally found in irrigated cotton fields. The resulting 8-day VF datasets were aggregated to 3 km to match the high-resolution model domain and incorporated into the MM5 TERRAIN input file in place of the default VF dataset. Noah converts 8-day inputs to daily VF values using a linear interpolation between adjacent input dates. Additionally, all pixels with vegetation fraction greater than 0.3 in the 1–9 September image (late in the dry season) were tagged as potentially irrigated and inves-
tigated using high-resolution Landsat enhanced thematic mapper (ETM+) imagery and digital photos taken on a June 2000 visit to the area. Areas that were confirmed as irrigated were classified as such and used to overwrite the operational U.S. Geological Survey (USGS) 30-s land-use classification for the high-resolution domain.

c. Weather data

Daily weather station data from Southern Anatolia (Turkey) were obtained from the Turkish State Meteorologic Department. For this analysis data from stations at Sanliurfa (37.13°N, 38.77°E) and Ceylanpinar (36.85°N, 40.03°E) were used, representing locations in the northern and central portions of the high-resolution domain. Stations were operated in accordance with Food and Agricultural Organization of the United Nations (FAO) guidelines and provided daily mean values for precipitation, 2-m temperature, 2-m wind speed and wind direction, surface pressure, net radiation, vapor pressure, pan evaporation, and day length. Daily reference crop evaporation was calculated using the FAO–Penman equation (Allen et al. 1998). Additional hourly data were available from a meteorologic station in the Harran Plain, Turkey (36.88°N, 38.92°E), which provided climatological information on diurnal patterns of temperature and humidity but which was not active during the period of modeling.

d. Linear heating model

To understand local heat-driven circulations predicted by MM5 we turned to a 3D linearized dynamic model of the type described by Lin and Smith (1986), Reisner and Smolarkiewicz (1994), and others. The model takes into account a constant background wind, static stability, Coriolis parameter, and Rayleigh friction, and predicts fields of pressure, wind, buoyancy, and vorticity produced by an oscillating heating source of specified horizontal shape and vertical structure under given atmospheric and geographic conditions (required parameters are listed in Table 1). A review of the governing equations for the linear model is beyond the scope of this application we were particularly interested in times to Lin and Smith (1986) or may contact the author. In this application we were particularly interested in times of “negative heating” when the source—set to the approximate shape of irrigated features in the study area—is cool relative to the surrounding surface.

3. MM5 setup and experiments

MM5 has been applied successfully at grid-cell resolutions ranging from greater than 100 km to less than 1 km and is used for both weather forecasts and climate research (Dudhia and Bresch 2002; Zhong and Fast 2003). Here we apply the model at 27 km in an outer, low-resolution (LR) domain that includes southwest Asia and portions of its surrounding water bodies (Fig. 2). This domain was initialized for a simulation beginning in November 1998 with initial and boundary conditions obtained from the National Centers for Environmental Prediction (NCEP)–NCAR reanalysis. After 18 months of model simulation (1 May 2000), we initialized a moderate-resolution (MR) domain as a one-way nest. The MR domain has a resolution of 9 km and covers the greater Fertile Crescent along with important neighboring topography. The MR domain encompasses the irrigated features of interest and a downwind area equivalent to more than one day of advection from these features, according to the mean wind. The MR domain was run in an interactive nest with a high-resolution (HR) domain at 3-km resolution that covers 84 600 km² and includes several major agricultural production centers of Turkey and Syria. The three-domain system was spun up for one month (May) and then run for the length of a typical summer cropping season plus six weeks into the fall, 1 June 2000–1 November 2000. A one-month spinup period was deemed to be sufficient, as soil moisture in nonirrigated lands dried to near minimum values (0.08–0.14 m³ m⁻³, depending on soil type) by the end of May. This is appropriate for early summer in the study region. All domains were run with 23 vertical levels. The vertical coordinate in MM5 (σ coordinate) is terrain following and is spaced more tightly near the ground surface. The Grell scheme for convective precipitation (Grell et al. 1994) was used for the LR and MR domains, but no parameterized convection scheme was applied for the HR domain.

In this study two nested model runs were performed. A control run that uses the MM5 default vegetation fraction data derived from AVHRR imagery and the USGS land-use dataset (referred to as MM5–CON),

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastward wind</td>
<td>U</td>
<td>3 m s⁻¹</td>
</tr>
<tr>
<td>Northward wind</td>
<td>V</td>
<td>1 m s⁻¹</td>
</tr>
<tr>
<td>Frequency</td>
<td>f</td>
<td>0.0000727 s⁻¹</td>
</tr>
<tr>
<td>Static stability</td>
<td>N</td>
<td>0.0005</td>
</tr>
<tr>
<td>Coriolis parameter</td>
<td>F</td>
<td>0.0001 s⁻¹</td>
</tr>
<tr>
<td>Damping coefficient</td>
<td>a</td>
<td>0.00015 s⁻¹</td>
</tr>
<tr>
<td>Cooling source x dimension</td>
<td>Lₓ</td>
<td>30 km</td>
</tr>
<tr>
<td>Cooling source y dimension</td>
<td>Lᵧ</td>
<td>48 km</td>
</tr>
<tr>
<td>Cooling source height</td>
<td>H</td>
<td>1300 m</td>
</tr>
</tbody>
</table>
and a MODIS run that uses MODIS-derived vegetation fraction and definition of irrigated areas (MM5-MOD).

4. Results

a. Vegetation fraction and irrigation regime

Vegetation fraction derived from MODIS had greater spatial structure and variability than the operational AVHRR dataset (Fig. 3). Domain-averaged seasonal variability, however, was greater for AVHRR-VF (Fig. 4). This was not surprising, since AVHRR-VF is driven by the seasonal cycle of natural vegetation and dryland agriculture: dense vegetation associated with irrigated fields is smoothed out at the 10-min (18.5 km) spatial resolution and 5-yr climatology offered by the AVHRR dataset (Gutman and Ignatov 1998), and irrigation developments established since the mid-1990s are missed entirely. In this region natural shrubs and grasses consistently senesce in May and June, causing a significant drop-off in spatially averaged vegetation in-

Fig. 2. (a) MM5 domains for all simulations. Domain resolutions are 27 (D01), 9 (D02), and 3 km (D03). Nesting was one-way between D01 and D02 and two-way between D02 and D03. (b) MODIS-derived 16-day vegetation index for D03 recorded 28 Aug–12 Sep 2000, with high vegetation index shown as dark. Features discussed in the text are a, the Harran Plain, b, the Euphrates River floodplain, c, the Ras-al-Ain irrigation development, and d, the Khabur River. The dotted line is the boundary of the Khabur watershed.

Fig. 3. Maps of vegetation fraction (plotted as % vegetation) according to (a) operational AVHRR input and (b) MODIS-based calculation. The example given is for the second week of Aug.
The MODIS-VF, in contrast, captures the phenological signal of both natural vegetation and crops for the year that is being modeled. This reduces the phase synchronicity of the vegetation cycle even though the seasonally averaged NDVI for the HR domain was similar for both methodologies (0.16 AVHRR, 0.18 MODIS).

The MODIS-based classification identified 5922 km² as irrigated cropland, representing just under 7% of the total domain area. This compares with only 774 km² of irrigated lands according to the USGS classification, or 0.1% of the domain. Some of the reclassified areas were isolated irrigation developments in the steppe, but the majority was found in and around the floodplains of the Euphrates, Balikh, and Khabur Rivers and in the massive irrigation projects of the Harran Plain (Turkey) and Ras-al-Ain (Syria). The MODIS-based area coverage is more reasonable when compared with independent satellite analyses (e.g., Ozdogan 2004) and state-reported figures (discussed in section 4c below).

The imposed irrigation scheme included 13 irrigation events in which 45–60 mm of water were added to all areas defined as irrigated. The depth of water added depended on soil texture and local evaporation rate, as faster draining soils and areas of high evaporative demand required a greater depth of water to return the top layer of soil to saturation and to keep the layer saturated for the length of the 30-min irrigation event. Over the season a total of 600–740 mm was applied as irrigation water. This figure is low relative to the 1000-mm rule-of-thumb estimate for irrigated crops in the region, but it seems reasonable considering that a 3-km pixel inevitably includes some nonirrigated areas mixed in with the fields. As demonstrated in Fig. 2, dry-down between irrigation events was fairly severe. The percent of irrigation water consumed in evapotranspiration ranged from 60% in early June to nearly 100% in late July, and values ranged from 65% to 80% in August and September. This compares well with typical ET efficiencies for irrigation in semiarid zones, where return waters average 20.6% of the applied volume (Beaumont 1996).

### b. Surface fluxes and atmospheric feedbacks

The domainwide energy balance was preserved in both the MM5-CON and MM5-MOD simulations (Table 2). Modeled values for incoming shortwave radiation (SW\textsubscript{down}) are reasonable for 35°–38° latitude with little cloudiness, and low values for domainwide latent heat flux are expected for summer in this predominantly dry region. The difference in upwelling longwave (LW\textsubscript{up}) radiation (lower in MM5-MOD) is primarily a product of the larger irrigated area in MM5-MOD, as irrigated areas have lower daytime surface temperatures than the dry areas they replace, provided that the crop is well watered. Reduction in daytime surface temperature is responsible for an increase in the net radiation (R\textsubscript{net}) at the surface (R\textsubscript{net} = SW\textsubscript{down} + LW\textsubscript{down} – SW\textsubscript{reflected} – LW\textsubscript{up}) in MM5-MOD relative to MM5-CON. On average, net surface radiation was 2.5 W m\textsuperscript{-2} greater in the MM5-MOD simulation. Reduced albedo associated with irrigated crops had no detectable impact on the energy balance; the albedo of irrigated areas was lower than that of the dry areas they

![Figure 4. Temporal variability in VF for irrigated land use, grasslands, and the entire HR domain (All) for operational AVHRR input and the MODIS-derived dataset.](image)

<table>
<thead>
<tr>
<th>Surface energy balance</th>
<th>MM5-CON</th>
<th>MM5-MOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW\textsubscript{down} (W m\textsuperscript{-2})</td>
<td>294.1</td>
<td>293.2</td>
</tr>
<tr>
<td>SW reflected (W m\textsuperscript{-2})</td>
<td>58.2</td>
<td>58.2</td>
</tr>
<tr>
<td>LW\textsubscript{down} (W m\textsuperscript{-2})</td>
<td>351.6</td>
<td>352.1</td>
</tr>
<tr>
<td>LW up (W m\textsuperscript{-2})</td>
<td>476.3</td>
<td>470.8</td>
</tr>
<tr>
<td>Net radiation (W m\textsuperscript{-2})</td>
<td>111.1</td>
<td>113.5</td>
</tr>
<tr>
<td>LH flux (W m\textsuperscript{-2})</td>
<td>3.6</td>
<td>11.2</td>
</tr>
<tr>
<td>SH flux (W m\textsuperscript{-2})</td>
<td>105.9</td>
<td>100.7</td>
</tr>
<tr>
<td>GH flux (W m\textsuperscript{-2})</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>EB (W m\textsuperscript{-2})</td>
<td>0.6</td>
<td>0.4</td>
</tr>
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replaced (0.18 versus 0.19–0.22), but averaged over the domain this change amounted to only a 0.2% decrease in albedo and virtually no change in SW reflected.

Integration of MODIS data also had an impact on the partitioning of available energy at the surface. Averaged over the whole domain, latent heat flux was 7.6 W m$^{-2}$ greater in MM5-MOD than in MM5-CON. This difference was greatest in the irrigated lands and was associated with a 5.2 W m$^{-2}$ decrease in average domainwide sensible heat flux. Ground heat flux was similar for MM5-MOD and MM5-CON averaged over the length of the simulation (Table 2), but MM5-MOD did exhibit a slightly damped diurnal range in the ground heat flux as a result of thermal inertia associated with irrigated lands (not shown). This effect was small relative to differences in the latent and sensible heat fluxes.

The influence of MODIS data on surface temperature, near-surface wind, and humidity was small but detectable throughout the simulation. Daytime temperatures were cooler over irrigated land in both simulations, so MM5-MOD had lower mean surface temperature throughout the growing season (27.5°C versus 27.9°C). Later in the season (September and October) predicted temperatures of the two simulations converged. It is difficult to assess the relative realism of the two simulations with regard to surface meteorology, both because station data are very limited in the study region and because the 3-km spatially averaged temperature returned by the model is not perfectly comparable to point measurements even where they are available. Nonetheless, it appears that monthly averaged values for 2-m temperature and 2-m relative humidity predicted by MM5-MOD are marginally more similar to available station values than those predicted by MM5-CON, particularly in midsummer, when evaporative cooling is greatest (Table 3). Both MM5 simulations appear to exaggerate seasonal variability in predicted fields, exhibiting a warm bias in summer and a cold bias in fall relative to station data; the warm bias is less severe for MM5-MOD than for MM5-CON, but the cold bias is greater. MM5-MOD is considerably closer to station-reported values for relative humidity through the summer months but overestimates humidity in the fall. Both simulations capture seasonal tendencies in wind speed (the absolute values of wind speed are not comparable, as MM5 values are for 10 m above the surface). Unfortunately we did not have access to subdaily station data for the summer of 2000, but comparison with 2001 and 2002 values for 2-m temperature and relative humidity from a station located in the heavily irrigated Harran Plain suggests that MM5 approximately captures the magnitude of the diurnal temperature range but exhibits the same seasonal biases as it did for the mean temperature field. Discrepancies with station data are a point of concern and suggest that the model exaggerates evaporation due to irrigation in the early fall (a subject of current investigation). Nonetheless, the apparent improvements that MM5-MOD offers in estimates of mean temperature and relative humidity during the months of greatest irrigation impact are encouraging, and we focus our analyses on the summer months.

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**Table 3.** Values of temperature and relative humidity predicted at 2-m height, and wind speed predicted at 10 m for MM5-CON and MM5-MOD, with 2-m meteorological station data given for comparison. Daily station data come from Ceylanpinar, Turkey, located in the middle of D03, while hourly station data are averaged from 2 yr of data at Koruklu, Turkey, also located in D03. Note that wind speed data are not directly comparable because of the difference in height between model predictions and station data.

<table>
<thead>
<tr>
<th></th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily $T_{\text{mean}}$ (°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MM5-CON</td>
<td>29.17</td>
<td>35.97</td>
<td>32.34</td>
<td>25.42</td>
<td>17.33</td>
<td>28.12</td>
</tr>
<tr>
<td>MM5-MOD</td>
<td>27.74</td>
<td>33.29</td>
<td>29.39</td>
<td>22.99</td>
<td>16.21</td>
<td>25.99</td>
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<tr>
<td>Station*</td>
<td>28.44</td>
<td>30.40</td>
<td>29.01</td>
<td>25.04</td>
<td>18.20</td>
<td>25.85</td>
</tr>
<tr>
<td>Daily $T_{\text{max}} - T_{\text{min}}$ (°C)</td>
<td></td>
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<tr>
<td>Daily $\text{RH}_{\text{mean}}$ (%)</td>
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* Diurnal values averaged from 2001 and 2002 data.
By far the greatest impact of including MODIS data was on evaporation in irrigated zones. Figure 5 shows daily average latent heat flux for an irrigated area near Sanliurfa, located in the northwest of the HR domain. Average daily latent heat flux was only 4.29 W m$^{-2}$ over the length of the MM5-CON simulation compared to 123.47 W m$^{-2}$ in the MM5-MOD simulation. The MM5-MOD value compares favorably with FAO-estimated mean latent heat flux calculated at the Sanliurfa weather station (114.95 W m$^{-2}$) and also represents a reasonable fraction of the latent heat flux in pan evaporation measured at the same station (231.38 W m$^{-2}$). It is possible that latent heat flux from flood-irrigated cotton might slightly exceed the FAO estimate for a standard crop. Indeed, field estimates for ET from traditionally irrigated cotton crops near Sanliurfa range from 6000 to 10 140 m$^3$ ha$^{-1}$ yr$^{-1}$ (Beaumont 1996), where the FAO PET over the 2000 growing season was only 6120 m$^3$ ha$^{-1}$ yr$^{-1}$ at the Sanliurfa meteorological station. For the MM5-MOD simulation average cumulative ET from irrigated areas was 5767 m$^3$ ha$^{-1}$ between 1 June and 30 October. We expect that the low ET value in the MM5-MOD simulation relative to field studies is the result of limited grid resolution (3 km) and low mean VF (0.47), both of which indicate that cells defined as irrigated actually represent a mix of cover types. In this regard VF is an important input when MM5 is coupled with Noah, as the LSM uses VF as an estimate of percent cover within each grid cell. Evapotranspiration in MM5-MOD was somewhat greater than it was for irrigated areas in the MM5-CON simulation (4800 m$^3$ ha$^{-1}$), and both were dramatically higher than MM5 estimates for seasonal evaporation in the absence of a modified irrigation surface flux scheme.

The dissipation of surface energy as latent heat has an impact on sensible heat flux and variables of state relevant to local meteorology. Lands classified as irrigated in MM5-MOD had an average sensible heat flux of 21.2 W m$^{-2}$ over the length of the simulation. The same area averaged 98.1 W m$^{-2}$ in sensible heat flux in the default run. This discrepancy was largely responsible for the greater overall sensible heat flux in MM5-CON (Table 2; Figs. 6a,b) and, from the perspective of land–atmosphere feedbacks, would be expected to cause a deeper daytime PBL and greater turbulent mixing within it. This expectation was fulfilled, as the afternoon height of the PBL was substantially higher for MM5-CON than it was for MM5-MOD over extended areas of irrigation (Figs. 6c,d). Reduced sensible heat flux also had an impact on the predicted stability of the PBL, as the MM5-CON PBL is classified in “free convection” throughout the domain well into evening, while the PBL over irrigated areas in MM5-MOD sta-
bilizes to a condition of “damped turbulence” in late afternoon. This pattern in predicted stability was most pronounced on clear days in July and August, when radiation inputs were greatest. It is important to note that discontinuities in albedo, thermal inertia, and surface roughness associated with irrigated areas may also influence the depth and structure of the PBL. Given the relatively modest impact that integration of MODIS data had on these parameters, however, and the dramatic impact that it had on latent heat flux, evaporative cooling and the associated reduction in sensible heat flux appears to be the dominant driver of the observed differences between MM5-MOD and MM5-CON.

Large irrigated areas made a substantial contribution to low-level water vapor. The Harran Plain, Ras-al-Ain development, and Euphrates River floodplain consistently produced plumes of water vapor in the afternoon that remained coherent into early evening up to a height of 800 mb; Fig. 7 shows the example of the Harran Plain. The water content of the plumes was small on a mass basis, rarely exceeding 1 g kg\(^{-1}\) of dry air, but under afternoon conditions this contribution produced a 30% to 40% increase in specific humidity up to 900 mb. The plume dissipates by late evening due to strong horizontal mixing within the Euphrates Basin, and the rapid dispersion of terrestrially introduced water vapor suggests that a precipitation feedback based on moistening of the PBL is unlikely in this region under sum-
mertime conditions. We did not observe any additional precipitation in MM5-MOD relative to MM5-CON locally or in downwind regions within the HR or MR domains.

The MM5-MOD simulation also predicts a diurnal mesoscale wind pattern associated with large irrigated areas. Differences in the 10-m wind field between MM5-CON and MM5-MOD were negligible at night and over drylands during the day, but around the irrigation features of the Harran Plain, Ras-al-Ain, and the Euphrates floodplain a “sea breeze”-type wind perturbation developed in the afternoon, with the locally driven wind perturbation directed from the cool irrigated feature toward the surrounding dry areas in MM5-MOD relative to MM5-CON (Fig. 8), though strong prevailing westerlies prevent any actual reversal of wind direction—the mean background wind was over 3 m s\(^{-1}\) while the local perturbation never exceeded 2 m s\(^{-1}\). This diurnal wind pattern is associated with a pressure gradient between irrigated and non-irrigated lands that is a consequence of greater sensible heat flux—and turbulent mixing—outside of the irrigated area. Interestingly, the center of high pressure migrates over the afternoon as cooled near-surface air is advected with the mean flow. The “sea breeze” advects along with the high pressure center (Fig. 8c; 1500

**Fig. 7.** Difference in the specific humidity field for MM5-MOD–MM5-CON, time-of-day average for the month of Aug at (a) 0900 (9 am), (b) 1200 (12 pm), (c) 1500 (3 pm), and 1800 (6 pm) local time. The cross section runs from southwest to northeast, following the mean background wind, along the dotted line indicated in Fig. 6a. Contour interval is 1 g kg\(^{-1}\). Vectors indicate the wind field along the cross section averaged for the two simulations. The black bar indicates irrigated extent of the Harran Plain.
local time), as does the downward anomaly in vertical motion (not shown), before breaking up as the pressure anomaly dissipates in early evening (Fig. 8d; 1800 local time). The perturbation is strongest in the direction against the mean background wind, suggesting that irrigation-induced cooling acted to slow the mean wind as well. We do not have weather station data to evaluate the realism of this wind field, but irrigated features of similar spatial scale have been observed to drive mesoscale circulations in other studies (e.g., Anthes 1984; Chen and Avissar 1994; Roy et al. 2003).

c. **Comparison with the linear heating model**

In simulations with the linear model, the reduced sensible heat caused by evaporation from the Harran Plain (Fig. 6) is represented as an imposed cooling over the irrigated rectangle, maximum at the surface and decreasing exponentially aloft. The scale height of the cooling was taken to be 1300 m, with a surface forcing of 250 W m$^{-2}$ (Fig. 6), and cooling was assumed to oscillate with a period of 24 h (Table 1). The orientation (west-southwesterly) and strength of the background
wind were taken from the MM5-MOD afternoon mean. Size of the cooling source, strength of surface forcing, and orientation of the rectangle relative to the background wind are all representative of the Harran Plain. A very small value for the static stability was chosen to capture the fact that the daytime boundary layer is deep and well mixed during the day. A large damping coefficient is used to mimic the turbulent dissipation in the convective boundary layer. While a number of simplifying assumptions are required in our linear dynamic formulation, the most fundamental assumption is that the time-averaged anomaly from the climate runs can be modeled by a deterministic set of equations that do not include the fluctuations of the mean field.

The linear model prediction is shown in Fig. 9. The model captures the basic magnitudes of wind and pressure perturbation and the spatial relationship between them, when compared with the MM5-MOD simulation. There is a positive pressure anomaly of nearly 30 Pa over the irrigated lands and a ring of outflowing winds on the order of 1–2 m s⁻¹. Some significant difference between MM5 and linear theory can be seen, however, mostly related to the poor representation of surface friction in the linear model and the horizontally uniform vertical profile of background wind, stability, and, within the source area, heating. Additionally, the predicted wind field downwind of the cooling source area is affected by a “wake” of residual velocity perpendicular to the flow that is an artifact of the linearized equations, and that is not considered when interpreting the result.

In spite of these limitations, the considerable agreement between a simple linear model and MM5-MOD with respect to local heat-driven circulations allows us to interpret the dynamics of the phenomenon. The relationship between wind and pressure in the linear model can be diagnosed using the following linearized momentum equation in the direction of the mean flow:

\[ u_i' + U u_x' - f v' = -p_i'/\rho_0 - au'. \]  

(1)

The order of magnitude of the four velocity-dependent terms in (1) can be written in terms of the
parameters in Table 1: that is, $\sigma$, $U/L_\text{vis}$, $f$, and $\alpha$, respectively. In the current circumstances, the first and third terms are small due to the small frequency of the heating and the small Coriolis force relative to the larger second and final terms representing advective acceleration and friction. The reduced equation $Uu' = -p'/\rho_0 - \alpha u'$ allows two types of dominant balance. With no friction, velocity and pressure are anticorrelated as in inviscid flows with a Bernoulli equation constraint: low pressure is associated with faster wind. With large friction ($\alpha$), the velocity correlates with local pressure gradient rather than pressure itself. Clearly from Figs. 8 and 9, the latter balance is a better description. That is, the heat-generated pressure gradients are causing wind perturbations in opposition to strong surface friction.

We conclude that the basic elements of the mean evaporation-induced disturbance can be understood as a simple response to vertically distributed cooling in the presence of weak stability, weak winds, and strong friction.

d. Implications for water resource management

Averaged over the full extent of the HR domain, incorporation of MODIS data led to a 3.1-fold increase in evapotranspiration over the length of the simulation relative to default inputs (Fig. 10; Table 2). Such a difference has dramatic implications for model-based evaluation of water resources in this portion of the Euphrates Basin. For example, the HR domain was defined to include the entire watershed of the Khabur River (Fig. 1), a tributary of the Euphrates with mean natural discharge of $1.78 \times 10^9$ m$^3$ yr$^{-1}$ (Beaumont 1996). In the MM5-CON simulation total evaporation from the Khabur watershed was only $4.51 \times 10^8$ m$^3$, or 25% of the natural discharge. For MM5-MOD, however, ET in the Khabur watershed summed to $1.66 \times 10^9$ m$^3$, or 94% of the annual natural discharge that was consumed over a 5-month period, primarily by irrigated agriculture. Significantly, the Khabur River ran dry for the first time in recorded history in the summer of 1999 and went dry again in the summers of 2000, 2001, and 2002. This catastrophe came on the heels of 20 yr of steady expansion of irrigated agriculture in the watershed and can almost certainly be attributed to overutilization of surface water and shallow groundwater that would otherwise sustain flow in the river.

The HR domain also included the Harran Plain, the centerpiece of Turkey’s Southeastern Anatolia Project (GAP). A total of 141 500 ha are planned for irrigation in the Harran Plain. According to government figures, 119 000 ha were actively irrigated in 2002, and in our MM5-MOD simulation for summer 2000, 121 500 ha were classified as irrigated, accounting for a total of $9.60 \times 10^8$ m$^3$ in ET. In the MM5-CON only 9900 ha were classified as irrigated, with $1.13 \times 10^8$ m$^3$ consumed in ET. Natural flow in the Balikh River, a Euphrates River tributary that flows southward out of the Harran Plain, is $3.00 \times 10^8$ m$^3$ yr$^{-1}$. The majority of water consumed in irrigation is diverted into the Balikh watershed via the Urfa tunnels, which draw water from Lake Ataturk on the upper Euphrates. The tunnels are designed to import $1.48 \times 10^9$ m$^3$ of water per year;
according to MM5-MOD this maximum rate of import is sufficient but not excessive to maintain both the irrigation projects and normal flow in the Balikh.

5. Conclusions

The incorporation of MODIS-derived vegetation fraction and irrigation land-use classification changed MM5-Noah predictions with regard to the surface energy balance, near-surface meteorology, and hydro-meteorologic fluxes. Impacts on lower-atmosphere temperature and humidity were found to be modest for current land use in the study area. Model predictions indicate that large irrigated areas in Turkey and Syria have the potential to cause systematic modifications of diurnal wind patterns, to influence the height and stability of the afternoon PBL, and to contribute a plume of water vapor to the lower atmosphere that is coherent up to at least 800 mb. No impact on precipitation was observed, however, either locally or in downwind regions, and we observed no differences in total cloud water over the length of the simulation.

This small impact on relative humidity and precipitation could be specific to our modeling approach, but we believe that it is primarily a product of summertime mesoscale conditions in the Middle East. Irrigated features of similar or smaller spatial scale than those included in this study area have been found to stimulate development of fair-weather cumulus clouds and to alter the precipitation pattern of midlatitude storm events in other semiarid regions (e.g., Moore and Rojstaczer 2002; Perlin and Alpert 2001). Three factors combine to prevent such an impact in the Euphrates Basin. The first is broad summertime subsidence in the lower atmosphere, driven by the descending branch of the Hadley cell and by a heat-driven circulation from the Iranian Plateau to the east (Evans et al. 2004; Warner and Sheu 2000). Descending air prevents rapid lifting of wet air from the evaporating surface and limits the potential for precipitation feedbacks. The second factor is a strong background wind that limits the residence time of terrestrial introduced water vapor within the local PBL: humid air is not allowed to build up over irrigated features for more than a few hours, limiting the depth of organized circulations and the possibility of cloud formation. The role of the background wind is obvious from a simple box-model calculation: the amount of water vapor added to a well-mixed column of air (Δρ\(_w\)) during its transit across a water vapor source (i.e., a well-watered field) is a function of evaporation rate (E), distance across the feature (L), depth of the column (D), and the rate of advection (U): Δρ\(_w\) = E × L/U × D. For a negligible background wind, an afternoon evaporation rate of 0.35 kg m\(^{-2}\) h\(^{-1}\)—a representative midsummer value for our simulation—would contribute 1–2 kg m\(^{-2}\) water to a column the height of the PBL (1600 m) over the course of an afternoon. Given a background wind of 5 m s\(^{-1}\), however, a column of air will cross the largest irrigated features in our study area (40 km) in 2 h, limiting the total vapor contribution to 0.7 kg m\(^{-2}\), or less than 2% of the saturation mixing ratio for midday temperatures. The third, related factor limiting the impact of irrigation is that the background air is fairly dry—the average near-surface relative humidity at meteorological stations in the region was 35% over the length of our study. An atmosphere on the verge of moist convection might be tipped by a modest increase in specific humidity, but in this region a larger input of water vapor is required. These background conditions do not preclude the possibility of land–atmosphere influence on precipitation in the Euphrates Basin, but they suggest a certain resistance to such processes in summer. In transitional seasons, when subsidence dissipates, the land surface may have a more significant influence on precipitation (Perlin and Alpert 2001).

From the perspective of water resource planning, however, the influence of MODIS data and a modified irrigation scheme was substantial. Whereas MM5-Noah with default inputs and no irrigation scheme predicts minimal summertime evaporation from terrestrial sources in the study area, and MM5-Noah with default inputs and the irrigation scheme in place (MM5-CON) predicts substantial but sustainable consumption of water, MM5-Noah with modified irrigation and MODIS data (MM5-MOD) indicates that surface waters are currently oversubscribed. The observed change along the Khabur River is an obvious indicator of this hydrologic shortfall, and dropping water tables throughout the Euphrates Basin speak to an impending crisis in groundwater reserves. GCM simulations suggest that global change will only intensify this crisis in the Middle East, as the region is predicted to become significantly warmer and dryer as a result of greenhouse gas forcing on the global scale (Ruosteenoja et al. 2003). Accurate simulations of water consumption and atmospheric feedbacks on the local to regional scale could provide useful predictions for water management and preparedness for climate change in this volatile and water-stressed region.

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