Modeling the large-scale water balance impact of different irrigation systems

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[1] In this study, two parameterizations for different irrigation techniques have been implemented in a regional climate model. These implementations allow for a comparative study of water use and land–atmosphere interactions associated with traditional flood irrigation—a widespread but highly water-inefficient practice—and water-conserving drip irrigation. Both parameterizations yield realistic results for coupled climate simulations, and do so without the need to reproduce an entire crop model within the climate model. Simulations with drip irrigation exhibit ~30% less irrigation season evapotranspiration and ~60% less water demand overall relative to simulations with flood irrigation. Examination of the water balance for various irrigation zones in Syria and Turkey demonstrates that planned Syrian irrigation expansion in the Euphrates watershed is only feasible if accompanied by modernization. Even then, planned expansion in the Khabur watershed, a major tributary of the Euphrates, would only reach sustainability if there is significant irrigation water runoff into Syria from Turkey. Thus Syria has a window of opportunity within which it can reap the benefits of investing in modernization and expansion of irrigation. That window begins now, with the Syrian governments recent commitment to modernize its irrigation infrastructure, and in the absence of an international water-sharing agreement, ends when increased water demand and/or decreased precipitation causes the Turkish government to invest in modernizing its own irrigation systems. Such a precipitation decrease is predicted to occur in the Middle East by mid-century if greenhouse gas emissions are not curbed substantially.


1. Introduction

[2] In many countries of the world, growing populations maintain pressure to increase agricultural production. This increase is achieved either through expanding the area dedicated to agriculture or by implementing more intensive agricultural practices. In areas with relatively high aridity, such as the Middle East, agricultural production is often limited by water availability and increasing production requires increasing irrigation. In the Euphrates River watershed of Turkey and Syria this has largely meant increasing the area cropped under flood irrigation, the cheapest to implement but least water efficient irrigation method. As the area irrigated increases, the remaining available water resources decreases, and in the upper Euphrates watershed water demand will outstrip supply in coming years.

[3] While international negotiations concerning the sharing of Euphrates and Tigris waters between Turkey, Syria and Iraq have been occurring for decades, no permanent treaty has been achieved (see Gruen [2000] for a discussion). Turkey is home to the Euphrates headwaters and thus has first opportunity to utilize the water. Downstream neighbors like Syria already face an overall water deficit; that is, less precipitation falls over Syria than the total water used there. Thus Syria is dependent on water that flows into the country across international borders. The most important trans-boundary river is the Euphrates, whose flows have diminished because of Turkey’s rapid increase in the number of dams and area irrigated. Recognizing this pressure on the water supply, Syria established a national plan for irrigation modernization focused on improving the water use efficiency of agriculture. While suggestions for investment in water efficient irrigation technologies in Syria can be traced back to at least 1966 [FAO, 1966], they went unheeded until recent years. In 2006, the Syrian Ministry of Agriculture launched an irrigation project to move the sector toward modern irrigation techniques, investing US$420 million. The total area to be modernized is approximately 1.25 million hectares over 4 years while the amount of irrigated land will also be increased 38% over the next ten years.

[4] This large and rapid conversion of irrigation techniques away from the traditional flood irrigation to modern sprinkler and drip irrigation systems will have a significant impact on the regional water balance. Khan and Abbas [2007] investigated potential water savings achieved by converting from flood to sprinkler irrigation schemes using the SWAP (Soil–Water–Atmosphere–Plant) model and GIS over an Australian catchment. They found savings of...
up to 38% in the required irrigation water. Their study used atmospheric forcing to drive the agro-hydrological model and as such it did not allow any feedback between the land surface and atmosphere. These feedbacks may result from changes in local evaporation and albedo or the influence of surface cooling on mesoscale circulations and the stability of the lower atmosphere [Zaitchik et al., 2005; Perlin and Alpert, 2001]. These feedbacks can in turn effect evaporative demand of the crops and hence the required irrigation water. The net impact of these feedbacks will depend on landscape characteristics, the dominant precipitation mechanism and the spatial scale of irrigation [Piekkle et al., 1991] and in order to capture these effects a coupled land–atmosphere model, such as a regional climate model, must be used.

[5] Modeling the land surface has gained more attention in climate and numerical weather prediction models over recent years. These models still rely on coarse biome classifications, though some are moving to plant functional type classifications. At GCM scales irrigation is essentially ignored. At the regional scale cropland is usually split into rainfed or irrigated crops. Noah (Land Surface Model (LSM) in MM5 and WRF) specifies irrigation as an area initiated with high soil moisture but does not add water after that. RAMS and RegCM both use BATS which treats the irrigated area like the Noah scheme. ISBA also acts similarly to BATS and Noah with respect to cropped and irrigated land. Betts [2005] presents the case for closer integration of climate and crop models. de Noblet-Ducoudre et al. [2004] assimilated some variables from a detailed crop model into a dynamic global vegetation model (coupled to a climate model) and found significant changes such as a drying out of the atmosphere at the end of summer and during autumn over Western Europe. Ozdogan et al. [2007] introduced a simplified irrigation scheme to uncoupled land surface models for continental and global scale simulations. Their results indicate the importance of accounting for irrigation in land surface models, and demonstrate the potential for these parameterizations to influence land–atmosphere interactions in the coupled context. Their irrigation scheme was designed to mimic sprinkler irrigation, typical for cash crops in the United States, but relatively uncommon in the Middle East and other regions in the developing world.

[6] Here we implement two irrigation algorithms that can be added to any land surface scheme in climate models that contain an irrigation land use class. The schemes allow for a realistic representation of the hydrology without the computational expense of adding an entire crop model. All feedbacks between the land surface and atmosphere associated with irrigated agriculture are maintained. By implementing a water inefficient (flood) irrigation scheme and a water efficient (drip) irrigation scheme, bounds on the improvements in water use possible by deploying today’s best practice systems and technology are quantified. This is achieved within a fully coupled land surface – atmosphere system and includes any related changes in the feedbacks between these systems.

[7] The regional climate model (RCM) used is described in section 2, along with the implementation of irrigation schemes implementation, the satellite-based identification of irrigated areas, and the model simulation setup. Section 3 presents the results of the simulations which are discussed in section 4 with particular attention to water balance and some economic implications. The main conclusions are summarized in section 5.

2. Model Description and Setup

2.1. MM5-Noah

[8] The PSU/NCAR (Pennsylvania State University/National Center for Atmospheric Research) mesoscale modeling system MM5 is described in Dudhia [1984, 1989] and Grell et al. [1994]. MM5 is a limited-area nonhydrostatic model that uses a terrain-following vertical coordinate system. It has 2-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 MRF planetary boundary layer scheme [Hong and Pan, 1996], and the Rapid Radiative Transfer Model (RRTM) radiation scheme [Mlawer et al., 1997].

[9] 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].

[10] One limitation 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 additional water is introduced during the simulation. This may be appropriate for 2–3 d 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 simulate two distinct irrigation regimes that span the range of water use efficiencies of systems in use today. A “flood” irrigation scheme as an example of worst practice in terms of water use efficiency, and a “drip” or “perfect” irrigation scheme that represents best practice.

[11] It should be noted that the model is applied at horizontal resolutions much larger than field scale. The highest resolution in this study has 9 km² grid cells. Thus every grid cell represents many fields and many crops. The vegetation parameters chosen for the “irrigation” land use type, such as thermal inertia, roughness length, emissivity, etc., were chosen as representative values for a mix of irrigated crops. That is, the “irrigated” class does not represent a particular crop but rather the mean response of a mix of irrigated crops. Each parameter value was determined using various combinations of satellite data, field studies and literature review as discussed in Chen and...
Soil moisture and is given by equation (2).

\[ F_1 \text{ with } 1 \text{ representing the least canopy resistance to} \]

where \( R_{\text{cmin}} \) is the minimum canopy resistance, LAI is the leaf area index, \( F_1 \) is the solar radiation effect, \( F_2 \) is the vapor pressure deficit effect, \( F_3 \) is the air temperature effect and \( F_4 \) is the soil moisture effect. All \( F_i \) vary between 0 and 1 with 1 representing the least canopy resistance to transpiration. Only \( F_4 \) is directly effected by changes in soil moisture and is given by equation (2).

\[ F_4 = \frac{\sum_{i=1}^{3} \left( \frac{\theta_i - \theta_w}{\theta_{\text{ref}} - \theta_w} \right) d_i}{d_1 + d_2 + d_3} \]

Where \( i \) represents the current soil layer, note that the sum is over the three soil layers in the root zone, not the entire soil column. \( \theta \) is the fraction of unit soil volume occupied by water, \( d_i \) is the depth of soil layer \( i \), \( w \) is the wilting point and \( \text{ref} \) is the reference field capacity soil moisture and represents the minimum soil moisture at which there is no soil moisture stress.

In the drip irrigation scheme the canopy resistance is calculated twice, once as-per-usual given the current soil moisture status and once with \( F_4 \) set to 1, ensuring that there is no soil moisture stress. The first value is used to calculate the amount of current soil moisture used for ET, while the second value is used to calculate the ET that occurs if there is no soil moisture stress. This is the amount of ET that actually occurs in the simulation. The difference between the first value and the second gives the amount of irrigation water that must be added to a grid cell to avoid any soil moisture stress under drip irrigation. Thus the drip irrigation system supplies irrigation water in a continuous, "on-demand" schedule.

It should be noted that the root zone in the Noah model is static and does not account for crop roots being shallow early in the season. That is, the Noah model allows crops to access moisture that is deeper in the soil column than would be accessible to early stage crops. Thus less DRIP irrigation water is needed by the model than might otherwise be the case at this early phenological stage. This however only has a small effect on the DRIP irrigation as it is not applied to the soil as such, but directly to the plants roots without any concern for soil layer, and the early part of the irrigation season has much lower irrigation water demand than later.

2.2. 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-d 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-d 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 data set that is currently operational for MM5. In the linear method VF is defined as

\[ VF = \frac{(\text{NDVI} - \text{NDVI}_0)}{(\text{NDVI}_{\text{Max}} - \text{NDVI}_0)} \]

\[ \text{NDVI}_0 = \frac{\text{NDVI}_{\text{Max}} - \text{NDVI}}{(\text{NDVI}_{\text{Max}} - \text{NDVI}_0)} \]

\[ \text{NDVI} = \frac{(\text{NDVI} - \text{NDVI}_0)}{(\text{NDVI}_{\text{Max}} - \text{NDVI}_0)} \]

\[ \text{NDVI}_{\text{Max}} \] and \[ \text{NDVI}_0 \] are the index for each pixel, \[ \text{NDVI}_0 \] is the scene minimum terrestrial NDVI, representing bare soil in this region, and \[ \text{NDVI}_{\text{Max}} \] is the maximum vegetation index in the scene. In winter and spring images the \[ \text{NDVI}_{\text{Max}} \] was often found in deciduous forests, while summer \[ \text{NDVI}_{\text{Max}} \] was generally found in irrigated cotton fields. The resulting 8-d VF data sets 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 data set. Noah converts 8-d 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 investigated 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 aggregated to overwrite the operational U.S. Geological Survey (USGS) 30-s land-use classification for the high resolution domain as follows: all 3-km pixels that were 30–70% irrigated according to MODIS analysis (i.e., 11–25 500 m MODIS pixels) were classified as “Mixed Dryland/Irrigated Crop and Pasture,” and all pixels that were more than 70% irrigated (i.e., 26–36 MODIS pixels) were
classified as “Fully Irrigated Crop and Pasture.” This classification was performed using images from 1–9 September as this week corresponds to the minimum in natural vegetation in the region, facilitating the VF-based classification of irrigated areas.

2.3. MM5 Setup

[17] Simulations performed using the “flood” and “drip” irrigation algorithms described in section 2.1 will be referred to as FLOOD and DRIP respectively in the remainder of the paper. For both DRIP and FLOOD simulations, MM5 was applied at 27 km horizontal resolution in an outer, low-resolution (LR) domain that includes southwest Asia and portions of its surrounding water bodies (Figure 1). 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 12 months of model simulation (1 November 1999), 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 1 day of advection from these features, according to the mean wind.

[18] 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. This two-domain (MR + HR) system was spun up for two months (Nov–Dec) and then run for the 2000 calendar year. All three domains were run with 23 vertical levels. The vertical coordinate in MM5 (s 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 in the HR domain.

[19] In the HR domain, MM5 default inputs for vegetation fraction and land cover type were replaced with MODIS-derived fields, which provided a substantially more realistic map of summertime irrigated agriculture and associated vegetation density [Zaitchik et al., 2005]. The DRIP and FLOOD simulations differ because of the irrigation scheme implemented. It should be noted that precipitation in the region displays high inter-annual variability and 2000 was the third driest year in the region since 1981 and hence represents a “worst case” scenario in terms of irrigation water demand.

3. Results

[20] It should be noted that previous simulations have been performed using the FLOOD irrigation scheme over the LR domain [Evans and Smith, 2006] as well as the nested domains used here [Zaitchik et al., 2005]. In each case the simulations performed well when compared to observations. Use of MODIS data substantially improves the recognition of irrigated areas and the designated vegetation fraction associated with them as shown in Zaitchik et al. [2005]. This section presents results of the simulations in terms of the surface water balance and feedbacks to the atmosphere. The annual total water balance components for irrigated pixels in the HR domain are given in Table 1.

[21] Table 1 Shows that precipitation is nearly identical in the two simulations, as is expected given the identical driving conditions. Dramatic differences are seen in the remaining water balance variables however. The DRIP scheme uses only ~37% as much irrigation water as the FLOOD scheme. The runoff is negligible using the DRIP scheme. In the FLOOD scheme there is some runoff, albeit a small amount. This low-level flow stemming from FLOOD irrigation can be observed today in some locations, such as downstream of the Harran plain irrigation district. Using DRIP the water loss due to ET is almost one third less than that found using FLOOD. FLOOD irrigation also produces an increase in soil moisture throughout the entire soil profile including almost 70 mm of water being lost to deep drainage. This deep drainage represents losses from the top 2 m of soil. Often this water is trapped within shallow aquifers below the flood plain, from which it either is pumped in subsequent irrigation applications or is lost to streamflow and groundwater. These irrigation “return waters” often become an important water resource in downstream locations; this is particularly the case for the Balikh and Khabur watersheds of Syria, as will be discussed in section 4. In contrast to FLOOD, DRIP produces a decrease in moisture throughout the soil profile with almost no deep drainage thus the mean soil profile evolves similarly to non-irrigated areas.

[22] Once the irrigation season has ended, the FLOOD irrigated soil contains much more moisture than the DRIP irrigated soil. This difference effects the simulation for several months after the irrigation has ceased. From the end of the irrigation season until the end of the calendar year there is twice as much runoff and ~4.5 times more ET under FLOOD irrigation than under DRIP. Most of this difference occurs within two months of the season end.

[23] In Figure 2, it can be seen that once the irrigation season begins (day 151) the two simulations diverge rapidly, especially in terms of the soil moisture. The periodic application of irrigation water in the FLOOD simulation can be clearly seen in the top soil layer, SM1, and this effect is present though smaller, in the next two layers. Overall, all three root zone layers are able to maintain a fairly steady and reasonably high level of soil moisture throughout the irrigated season using the FLOOD technique. At the same time the DRIP simulation experiences a summer-long drying similar to that experienced by nearby non-irrigated pixels. This does not reflect a similar decrease in the water available to the plants but rather it is a decrease in the mean soil moisture over the entire irrigated pixel, most of which is not close to the plant roots where the DRIP irrigation water is applied. This is demonstrated by the fact that ET increases under DRIP while this decrease in soil moisture is occurring. A closer look at ET during the irrigation season reveals a similar pattern of increases through July and subsequent decreases for both irrigation schemes. The FLOOD simulation however always produces more ET than the DRIP simulation. Much of this difference is water evaporating from bare soil between and around the crops rather than differences in transpiration of the crops themselves. It is also worth noting that at the end of the irrigation season the DRIP simulation experiences a rapid drop in ET since the mean soil profile is very dry, while the decrease simulated...
Figure 1. (A) MM5 domains, which have horizontal resolutions of 27 km (D01), 9 km (D02), and 3 km (D03). (B) MODIS-derived 16-d vegetation index for D03 recorded 28 August to 12 September 2000, with high vegetation index shown as dark. Features discussed in the text are: (a) the Harran Plain, located at the headwaters of the Balikh river, (b) the Euphrates River floodplain, (c) the Ras-s-al-Ain irrigation development, and (d) the Khabur River. The dotted line is the boundary of the Khabur watershed.
under FLOOD is much more gradual since it starts with a wet soil profile that is depleted gradually.

[24] The monthly mean difference in ET at 1200 local time is shown in Figure 3. Clearly seen are the irrigation areas especially the Harran plain, Euphrates river floodplain and the Ras–Al–Ain irrigation development. Note that the difference remains large in October after irrigation has ceased, demonstrating the lasting influence of a moist soil column under FLOOD irrigation. This difference has decreased dramatically by November. It can also be seen that the difference between irrigation methods in August is relatively small. This is because the DRIP irrigation scheme supplies more water when there is higher evaporative demand, while the FLOOD scheme supplies similar amounts regardless of demand hence when the demand is highest the difference between the two schemes is small. September is the month with the greatest difference since half of this month is immediately after the end of the irrigation season, when DRIP ET has almost stopped and FLOOD ET, though falling, is substantially higher than DRIP (Figure 2).

[25] There are two major ways that land–atmosphere feedbacks can effect the surface water balance: by changing the near surface environment in a way that impacts ET; or by changing the larger environment in a way that impacts precipitation. In terms of the near surface environment the main changes that impact ET include changes in temperature, humidity and turbulent mixing (wind speed). Under the DRIP scheme more of the net radiation is converted into sensible heat when compared to the flood scheme. This results in higher near surface temperatures for irrigation regions using the DRIP scheme, and hence lower temperature differences between the irrigated and non-irrigated areas. While the “sea breeze” type wind perturbation discussed in Zaithchik et al. [2005] is present under both irrigation schemes, it is weaker with the DRIP scheme. Thus while the near surface temperatures are higher with the DRIP scheme, suggesting a possible increase in potential evaporation, they actually cause a decrease in the turbulent mixing (wind perturbations), somewhat negating this temperature effect. Figure 4 shows the mean monthly difference in 2 m relative humidity. FLOOD irrigation consistently has higher low-level humidity than the DRIP irrigation. This higher humidity causes a decrease in the potential evaporation compared to the DRIP case. Thus with the DRIP scheme there is higher near surface temperature and lower near surface relative humidity but some decrease in the local winds. Overall these changes increase the potential evaporation compared to the FLOOD scheme. The actual ET however displays the opposite change, with the FLOOD scheme producing more than the DRIP scheme (see Figure 2 and Figure 3). This is because ET under the DRIP scheme is always water limited, while the FLOOD scheme does not have this limitation during and just after a flooding episode and is able to come closer to reaching its potential evaporation.

[26] Local precipitation feedbacks in this region during summer are inhibited by the large-scale atmospheric processes. These processes include large-scale subsidence caused by the descending arm of the Hadley cell reinforced by the Rossby wave effect of the Indian Monsoon as discussed by others [Staubwasser and Weiss, 2006, and references therein]. Thus any potential feedback processes are likely to be found within the planetary boundary layer (PBL). The PBL height is lower over irrigated areas compared to the surrounding non-irrigated land for both irrigation schemes. The daily evolution of the PBL height differs between the schemes however. Higher temperatures associated with the DRIP scheme lead to faster PBL growth and a deeper midday PBL. During the afternoon however the FLOOD PBL decays more slowly because of its higher low-level atmospheric water vapor content. This diurnal PBL evolution for August is shown in Figure 5; similar PBL characteristics exist from July through November. The persistence of high ET past the end of the irrigation season in the FLOOD case means that there is more low-level moisture in the atmosphere in late September and October. This in turn means that the FLOOD case produces more precipitation in October than the DRIP case though this increase was small and not significant to the overall water balance.

[27] A feedback mechanism between soil moisture state, which differs between the two irrigation schemes studies here, and precipitation was proposed by Eltahir [1998]. This theory makes the connection between surface conditions and precipitation through the energy in the PBL as given by the moist static energy (mse) given in equation (3).

$$\text{mse} = \frac{g}{C_0} z + C_P T + L q$$  \hspace{1cm} (3)

Where g is gravity, z is elevation, $C_P$ is the specific heat capacity at constant pressure, T is the temperature, L is the latent heat of vaporization and q is the water vapor mixing ratio.

[28] Eltahir [1998] examines the relationship between mse and precipitation and concludes that PBL mse plays an important role in the dynamics of storms at all scales. It is the density of this mse in the PBL that provides the energy required to initiate local convective storms. The difference (FLOOD–DRIP) in the PBL mse density during daylight hours in August is shown in Figure 6. For most of the day little difference exists between the two schemes. However, at the end of the day, when the PBL height is decreasing, the extra low-level moisture present in the

### Table 1. Water Cycle Component Totals for Irrigated Pixels in the HR Domain (mm)

<table>
<thead>
<tr>
<th>Time</th>
<th>Scheme</th>
<th>Precipitation</th>
<th>Irrigation</th>
<th>Runoff</th>
<th>ET</th>
<th>Change in Total Soil Moisture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irrigation season</td>
<td>FLOOD</td>
<td>&lt;1</td>
<td>676</td>
<td>2.6</td>
<td>482</td>
<td>122.8</td>
</tr>
<tr>
<td>(30 May to 14 September)</td>
<td>DRIP</td>
<td>&lt;1</td>
<td>250</td>
<td>0.4</td>
<td>333</td>
<td>-86.5</td>
</tr>
<tr>
<td>After irrigation season</td>
<td>FLOOD</td>
<td>114</td>
<td>0</td>
<td>6.7</td>
<td>123</td>
<td>-9.8</td>
</tr>
<tr>
<td>(15 September to 31 December)</td>
<td>DRIP</td>
<td>124</td>
<td>0</td>
<td>3.8</td>
<td>27</td>
<td>97.0</td>
</tr>
</tbody>
</table>
FLOOD case manifests itself as higher mse density. According to Eltahir [1998], this produces a greater tendency to produce precipitation. This precipitation is not produced here due largely to the large-scale subsidence dominating the region which inhibits convection. If this large-scale subsidence were to weaken in the future due to global warming, as has been found in some simulations [Evans, 2008b], then the FLOOD scheme would be more likely to produce local convective storms though this currently seems unlikely given the large-scale dynamics involved.

4. Discussion

Irrigated agriculture is a vital resource in many parts of the world. It is driven or limited both by water availability and capital investment in irrigation-related infrastructure including large-scale dams and canals and, at smaller scales, field-based sprinkler or drip systems. Because of the large costs involved in the construction of large-scale infrastructure, such as new dams, time periods of 50 years or more may be considered the necessary timescale to recuperate costs of the investment. These multi-decade timescales are the same timescales over which some areas of the world are potentially going to experience significant changes in precipitation due to global warming. This introduces a new layer of uncertainty into these long-term investment decisions. Alternatively, investments directed at improving irrigation water efficiency can be made at smaller scales and with shorter planning horizons. When considering future investment in irrigation infrastructure then, one must consider the current and the probable future state of the surface water balance in physical terms, as well as the likely costs and benefits of the infrastructure required.

In the analysis below the results of the FLOOD simulation represents the situation if all irrigation uses the traditional surface flooding technique which is the dominant

Figure 2. Mean ET and root zone soil moisture for irrigated pixels from just before the irrigation season until the end of the year. SMi indicates soil moisture in level i, 1 is topmost.
irrigation method for the region. The DRIP simulation represents the situation if all irrigation were “perfect”—that is, that all water added was used directly by the crops. While it is anticipated that improvements in irrigation technology and methods will eventually allow farmers to approach this limit, in practice today perhaps only 50% of the water savings predicted by the DRIP simulation may be achievable. In the analysis below this is referred to as DRIP50.

**Figure 3.** Mean difference in latent heat at 1200 local time (FLOOD–DRIP).

**Figure 4.** Mean monthly difference in 2 m relative humidity (FLOOD–DRIP).
Figure 5. Mean daily evolution of PBL height during August.

[31] In the real world, the decisions of individual farmers to use a particular type of irrigation system are important factors in determining the irrigation water use. However, in terms of water use efficiency, this choice will always lie somewhere between the inefficient FLOOD irrigation scheme and the efficient DRIP irrigation scheme. The simulations discussed here, where every farmer simultaneously chooses the least efficient or most efficient schemes provide the outer bounds for irrigation water efficiency at the large-scale. In practice there will probably always be a mix of irrigation systems in use and hence the irrigation water use will fall somewhere between the FLOOD and DRIP simulations.

[32] Similarly, individual farmers often choose different crop types, sometimes on a field by field basis. Given the limitations of computation power available it is not possible to simulate the region at a field resolving horizontal resolution. Instead, a model grid cell is 9 km² and the crop modeled is a mean over this area. Given this limitation the study assumes that the crop type does not change, only the irrigation system changes. As such, any assessment of the sustainability of irrigated agriculture in this study does not consider the possibility of farmers switching to a crop requiring less water.

4.1. The Water Balance

[33] In this study the FLOOD simulation represents the current situation in the region and the DRIP (or DRIP50) simulation represents a possible irrigation infrastructure investment scenario. Over the HR domain, on an annual basis, there is a significant water deficit with ET being twice as much as precipitation in the FLOOD case and 1/3 greater than precipitation in the DRIP case. This extra water is brought into the domain by pumping from deep aquifers or by transport from reservoirs outside the domain. The Harran plain is the centerpiece of Turkey’s Southeastern Anatolia Project (GAP) and has its water piped in from Lake Ataturk via the Sanliurfa tunnels. For the summer of 2000, the FLOOD scheme requires $9.82 \times 10^8$ m$^3$ of H$_2$O to be supplied for irrigation. This compares with $10.1 \times 10^8$ m$^3$ of H$_2$O reported by the Turkish State Hydraulic Works (DSI) as released from the Sanliurfa tunnels for the purposes of irrigation [Ozdogan et al., 2006]. This good agreement between model and State report does carry some caveats. For one, the State figure is already corrected for discharge, so the total volume of water released is actually higher than that reported. Some of this extra water is lost in conveyance, which is not included in the model. On the other hand, FLOOD does represent a “worst case” estimate of water usage for irrigation, so actual on-field efficiencies may be somewhat better. If the same area was instead irrigated using the DRIP scheme, the total irrigation water required would be $3.77 \times 10^8$ m$^3$ or about one third as much as DSI currently releases. DRIP50, which may be practically achievable, would require $6.80 \times 10^8$ m$^3$ of irrigation water or ~2/3 of the current irrigation requirement.

[34] The total irrigated area in the Harran plain has continued to increase since 2000. It is planned eventually to irrigate 141500 ha [Beaumont, 1996], this is almost a 50% increase over the area reported by DSI to be irrigated in 2000. Such an increase in irrigated area would increase irrigation water demand to such an extent that the Sanliurfa tunnels would be reaching their supply limit of $14.8 \times 10^8$ m$^3$ year$^{-1}$. In the short term, this supply limit may force the introduction of more water-efficient irrigation technologies. In the longer-term changes in precipitation in the upper Euphrates may further force the issue. Analysis of the GCM results used in the recent IPCC 4th Assessment report reveal that by 2050 this precipitation could decrease by ~40 mm per year [Evans, 2008a]. Such a decrease represents more than 7% of the current total precipitation, i.e., more than $24 \times 10^8$ m$^3$ year$^{-1}$. Because of the presence of other reservoirs and water uses within the upper Euphrates watershed, the change in the amount of water reaching the Ataturk lake may be even greater. Changes of this magnitude, which are predicted to be even larger by the end of the century, may make the water savings available by switching to an efficient irrigation system a necessity, even for Turkey.

[35] Downstream of the Harran plain, return flow enters Syria in the Balikh river. Extensive irrigation occurs within the Syrian Balikh catchment. Irrigation just south of the border and along the river relies primarily on the river flow and pumping from shallow aquifers. This flow is fed in summer partly by a natural spring and partly through irrigation drainage from the Harran plain. Under the FLOOD irrigation scheme ~$3.0 \times 10^8$ m$^3$ of H$_2$O is required to irrigate this region. This is more than the outflow from the Harran plain and the contribution of natural springs combined (~$1.0 \times 10^8$ m$^3$), with the deficit presumably drawn from groundwater. If Syria is able to convert to DRIP50 type irrigation systems in this region then ~$2.0 \times 10^8$ m$^3$ water would be required. This level of irrigation in the Syrian upper Balikh is potentially sustainable since it is equal to the river flow plus the Harran plain losses to deep drainage (aquifer recharge) of ~$1.0 \times 10^8$ m$^3$. If Turkey modernizes irrigation in the Harran plain, this will decrease the river flow of the Balikh to ~$0.7 \times 10^8$ m$^3$ and the aquifer recharge to $0.05 \times 10^8$ m$^3$ thus making the currently irrigated area unsustainable. While modernization of Turkish irrigation in the Harran plain is likely to be
problematic for irrigation in the Syrian upper Balikh, it does mean more water remaining in the Euphrates river and potentially made available to irrigate other parts of Syria such as the lower Balikh development zone. Withdrawals for irrigation are a necessity for any agricultural production in this region, as precipitation is insufficient for the production of rainfed crops [USDA, 1979]. Recall that the irrigation water for the Harran is supplied via pipes that originate on the main-stem Euphrates. If however Turkish irrigation modernization occurs only because of precipitation decreases accompanying global warming there will be a significant decrease in water available for irrigation in the Syrian upper Balikh without any associated increase in Euphrates water. 

The neighboring Khabur catchment is much larger than the Balikh and contains the remainder of the GAP related irrigation projects in Turkey. The main scheme is the Mardin–Ceylanpinar project which is planned to irrigate 334,900 ha, some from groundwater but most using Euphrates water piped into the catchment. Another smaller project in the east, Nusaybin–Cizre–Idil, will irrigate 89,000 ha using water from the Tigris river. In 2000 we estimate a total of ~81,000 ha was irrigated, representing only ~20% of the planned total area. Under the FLOOD irrigation scheme 5.97 × 10^8 m^3 of water is used in the Turkish Khabur catchment. If irrigated water demand scaled linearly with irrigated area then the Turkish irrigation would eventually use ~25 × 10^8 m^3 of water in the Khabur watershed.

Specific water demand is however expected to decrease with increasing density of irrigation due to a reduced humidity deficit associated with irrigation-induced cooling and humidification of the boundary layer [Bouchet, 1963; Morton, 1965]. Ozdogan et al. [2006] suggest that this effect could lead to a 40% decrease in specific irrigation water demand as irrigation increases in Central and Eastern Turkey. Their analysis focused on the Harran Plain, which is the most densely packed, coherent irrigation zone in the region, and examined the phenomenon using a model that had a resolution of 100 km^2. Satellite data shows that irrigation zones in general are not as densely packed or coherent as the Harran plain, and that fields are scattered on a scale much smaller than 100 km^2, in part because well-water irrigation encourages a sparse distribution of fields in comparison to canal-based irrigation [Hole and Zaitchik, 2007]. This more scattered irrigation field arrangement leads to more local mixing of spatially close high and low humidity areas, such that the humidity deficit decreases are likely to be less than that found in Ozdogan et al. [2006], with a correspondingly smaller impact on specific irrigation water demand. If we assume that specific water demand decreases by ~20% on the regional average, then irrigation in the Turkish Khabur catchment would eventually use ~20 × 10^8 m^3 of water. This expected irrigation water demand is similar in magnitude to the expected decrease in precipitation because of global warming by 2050. Under DRIP irrigation 1.77 × 10^8 m^3 of water is used in 2000 and a total of ~7 × 10^8 m^3 would be used if all the planned

Figure 6. The difference (FLOOD–DRIP) in the mean Moist Static Energy Density in the Planetary Boundary Layer during the day in August. Local times are shown.
irrigation is implemented. Thus only a small increase in water use is required to implement the expansion if it is accompanied by modernization of the irrigation systems. The more achievable DRIP50 irrigation would use $3.87 \times 10^8$ m$^3$ of water in 2000 and a total of $15 \times 10^8$ m$^3$ if all planned irrigation is implemented. While this is almost 3 times more than is currently used it represents a water savings almost equal to the total current irrigation water use in the catchment. Given the expected decrease in precipitation due to global warming such efficiency may prove vital.

[35] In Syria the Khabur River is the major tributary of the Euphrates. It is fed largely by waters emanating from the large karstic springs at Ras–Al–Ain on the border with Turkey. These springs supplied an annual flow of $1.5 \times 10^8$ m$^3$ to the Khabur. The rest of the flow entering Syria comes from precipitation and, increasingly, irrigation drainage waters from Turkey and totals over $8 \times 10^8$ m$^3$. Approximately $6.27 \times 10^8$ m$^3$ is used in Syrian irrigated agriculture in the upper Khabur, most associated with the Ras–Al–Ain development area. During 2000 there was little irrigation occurring in the lower Khabur region. This is anomalous, and was a side-effect of upstream dam construction and reservoir creation on the Khabur that was occurring at the time. Ultimately, plans call for water from that reservoir is to be used to irrigate 70,000 ha in the lower Khabur. This represents almost a doubling of the area under irrigation in the Syrian Khabur relative to 2000 and a likely irrigation water demand of $10^8$ m$^3$, which is more than the flow of the river. Such an expansion may be possible as Turkey continues to expand its irrigation and hence increases the supply of irrigation drainage waters to Syria. Converting to DRIP irrigation reduces the present irrigation demand in the lower Khabur to $1.79 \times 10^8$ m$^3$ and the future demand, under full implementation of the lower Khabur development zone, to $3 \times 10^8$ m$^3$, well within the expected river flow. The more realistic DRIP50 scenario means irrigation demand in the upper Khabur would be $4.03 \times 10^8$ m$^3$ and once the lower Khabur development zone is complete demand would reach $8 \times 10^8$ m$^3$. This level of demand is equal to the total river flow and its long-term sustainability may depend on increasing irrigation drainage entering the catchment from Turkey. Like irrigation in the upper Syrian Balikh, even fully modernized irrigation in the Syrian Khabur will be threatened when Turkey modernizes its own irrigation.

[39] Since the year 2000 was a particularly dry year, most years would exhibit irrigation water demand that is lower than that found in these simulations. Thus it seems that current and planned future Syrian irrigation in the Balikh and Khabur catchment should be successful as long as Turkey continues to expand irrigation areas while using flood irrigation methods, and Syria modernizes most of its irrigation. Two major, likely future occurrences threaten this success. First, decreasing precipitation due to global warming could, by 2050, make conditions in the year 2000 look more like an average year than an unusually dry year. This would mean that in dry years there may not be enough water to irrigate the entire area though in wet years it would still be viable. Second, such a decrease in precipitation is likely to spur modernization of irrigation techniques and infrastructure in Turkey, decreasing the irrigation drainage waters that supply some of the Syrian irrigation areas on these Euphrates tributaries. Thus if precipitation in the region does decrease as predicted because of global warming, Syrian irrigated agriculture in the Khabur catchment would need to be scaled back and Syria would need to rely more directly on Balikh and Euphrates water for irrigation. These water sources are somewhat more reliable because of the Turkish reliance on hydroelectricity generated at the Ataturk Dam (on the Euphrates) and in the Sanliurfa tunnels (which feed water to the Balikh).

[40] While the simulations performed do not explicitly deal with inter-annual variations in climate, differences in how the FLOOD and DRIP irrigation perform as the region dries over the summer can be used to infer relative performance between wetter and drier years. During dry years the entire soil column will dry out. This necessarily increases the water required by FLOOD irrigation as it must saturate the top layer and eventually moisten the entire column. The DRIP irrigation on the other hand, supplies only what the crops require and does not waste water moistening the soil column unnecessarily. That is, during dry years the evaporative demand of the atmosphere will increase. FLOOD irrigation must meet both the transpirative demand of the crops and the evaporative demand from the wet soil. DRIP irrigation only supplies the transpirative demand of the crops and simply allows the rest of the soil to dry out. Additionally, DRIP irrigation supplies just enough moisture to allow the crops to transpire without stress, while the FLOOD irrigation makes substantially more moisture available to the crops, leading to higher transpiration rates. Hence as conditions become drier ET under FLOOD irrigation increases more rapidly than ET under DRIP irrigation. This is in fact seen during the season as conditions become drier later in summer.

4.2. Economic Implications

[41] Implementing water efficient irrigation systems, like drip irrigation, often results in increases in yields along with decreases in water use [Mehmet and Bicak, 2002]. Despite this fact, and despite calls for irrigation modernization by international institutions such as the FAO, there has been little movement in this direction. A primary reason for this inertia is the cost of installing modern drip irrigation systems. The initial rehabilitation and modernization costs can vary substantially depending on location and level of technology implemented. Modernization with limited automation in the Beni Obeid, Egypt in 1998 cost ~US$900 ha$^{-1}$, while full modernization in the Lugan Sur project, Argentina cost ~US$3000 ha$^{-1}$ [Wakil, 2006]. Cetin et al. [2004] found that introduction of drip irrigation to olive plantations in Turkey required an initial investment of US$2244 ha$^{-1}$. Estimating a cost of US$2500 ha$^{-1}$, planned modernization of 1.25 $\times 10^9$ ha of irrigated land in Syria would cost in excess of US$3 billion. This is considerably more than the US$420 million allocated by the Ministry of Agriculture for this task, which provides only US$336 ha$^{-1}$. As a point of comparison, construction of the Ataturk dam in Turkey—a massive infrastructure project—cost ~US$1.25 billion.

[42] Nonetheless, modernizing irrigation repays the initial investment by increasing yields and allowing an increase in irrigated area with the same water resources. Within the Khabur, for example, modernization of irrigated areas would cost ~US$213 million (at US$2500 ha$^{-1}$). If the
lower Khabur development zone is implemented with cotton as a dominant crop, and yields and prices remaining at the average from 2000 to 2005, then over US$21 million worth would be produced per year. This simplistic analysis would suggest that costs for modernization of the Khabur could be recovered in just over a decade.

Additionally, a conversion to modern drip irrigation improves resilience to inter-annual variability in precipitation. Such resilience is a primary motivation for irrigation in this region, as rainfall in the Middle East frequently fails because of inadequate precipitation. The development of large flood irrigation schemes, including numerous storage reservoirs, provides some improvement in this regard, as stored water can be utilized in dry years. Because of its inefficiency however flood irrigation depletes reservoirs much faster than drip irrigation. In a particularly dry year, flood irrigation may exhaust the economically viable water reserve before the end of the growing season, resulting in reduced crop yields. This effect is exacerbated by the fact that irrigation water demand for flood irrigation increases dramatically under dry conditions because of water wasted in evaporation (section 4.1). By reducing irrigation demand, the implementation of drip irrigation extends the effective capacity of the reservoir system—an advantage that becomes critical during drought years that would overwhelm an irrigation infrastructure based on flood irrigation. Of course, if a dry period lasts long enough, even a drip irrigation system will use the entire reserve water capacity and experience decreasing yields. Even so, a larger area of successful crops can still be supported using drip irrigation than can be supported using flood irrigation.

These inter-annual variations can cause considerable loss of production. For example the dry year of 1999 decreased the value of wheat and barley production in Syria by US$500 million compared to the previous year [FAOSTAT, 2007] Bringing greater stability to agricultural production faced with this inter-annual variability would also improve the welfare of the rural population involved. The predicted decrease in precipitation due to global warming by 2050 will increase the frequency of dry years and the corresponding losses in agricultural production. In a sense Syria currently has a window of opportunity in the Khabur catchment. Rapid investment in modernization and expansion of irrigation now would earn back its cost by 2020 to 2025. After this it would continue to add value to the country’s overall production. By around 2040 however the decrease in precipitation due to global warming would likely drive an irrigation modernization effort in Turkey, decreasing the overall flow into the Khabur and making some fraction of the irrigated area of Syria nonviable.

5. Conclusions

In this study two parameterizations for different irrigation techniques have been implemented in a regional climate model. This allows the hydrologic effects of irrigation to be investigated, including the coupling between the land surface and atmosphere, without trying to reproduce an entire crop model. One of these techniques is very water inefficient, flood irrigation, while the other is very water efficient, drip irrigation. Using drip irrigation instead of flood irrigation decreased irrigation season ET by ~30% and irrigation water demand by 60% overall. The irrigation season runoff was also several times higher under flood irrigation than under drip. The largest differences in ET were seen immediately after the irrigation season since the flood irrigation left the soil column wet while drip irrigation left the soil column relatively dry.

Examining the water balance for various irrigation zones in Syria and Turkey demonstrates that planned Syrian irrigation expansion in the Euphrates watershed is only feasible if accompanied by modernization. Even then the expansion planned in the Khabur basin will only reach sustainability if there is significant irrigation water runoff into Syria from Turkey. This in turn requires Turkey to keep expanding its irrigated area while keeping flood irrigation as the primary technique. As long as this remains the case in Turkey, Syria has a window of opportunity within which it can reap the benefits of investing in modernization and expanding irrigation. Two future occurrences are likely to threaten the sustainability of even modernized Syrian irrigated agriculture. A decrease in precipitation, possibly due to global warming, and a decrease in irrigation runoff from Turkey due to Turkey modernizing its irrigated agriculture. Given Turkey’s position as the upstream neighbor with control over the headwaters of both the Euphrates and Tigris rivers, it will likely take a long-term decrease in precipitation before Turkey places any significant funding into modernizing its irrigation systems. Thus the two factors that threaten the sustainability of a modernized and expanded Syrian irrigated agricultural sector are likely to occur at approximately the same time, as climate change induced decreases in precipitation trigger a change in Turkish irrigation strategy.

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