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Influence of irrigation schemes used in regional climate models on evapotranspiration estimation: Results and comparative studies from California's Central Valley agricultural regions

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[1] The agricultural sector is the largest consumer of water in California. The impacts of irrigation on local and/or regional weather and climate have been studied and reported in recent literature. However, because of the lack of observations and realistic irrigation schemes employed in the numerical models, most previous studies fall in the category of sensitivity tests, focusing on temperature variations. The results being reported in this paper are obtained by incorporating into the MM5/Noah land surface model an irrigation method practiced in California's farming sector. The proposed irrigation scheme is based on the principle that irrigation occurs when available soil-water content is less than the maximum allowable water depletion (SW_m), which depends on both soil type and crop type. The study's focus was to evaluate the impact of a more realistic irrigation scheme on surface fluxes, especially evapotranspiration (ET). It is demonstrated that more accurate amounts and patterns of ET in the Central Valley are realized, as compared to ET estimates (in terms of amounts and spatial distribution) obtained from remotely sensed observation as well as in situ ground data. It is demonstrated that significant discrepancies of ET estimates between different irrigation schemes used in regional hydroclimate modeling exist, which may result in erroneous conclusions about the impact of irrigation on regional water balance, especially over and near agricultural areas.

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1. Introduction

[2] Agriculture is one of the important sectors of California's economy and a major provider of agricultural products to the United States and the global markets. However, given the semiarid nature of California's agricultural region and lack of sufficient precipitation, irrigation has been the main method of meeting the water demand and ensuring high crop yields. Viewed in the context of California's overall water management, irrigation is the largest consumer of water. However, current water management decision-making models assume that the consumptive use of water for irrigation is fixed and ignores interannual variations (see review by *Tang et al.* [2009]). Better estimation of irrigated crop's ET and other climate variables presumably could lead to more efficient use of water in arid and semiarid California areas.

[3] Crop water use depends on surface atmospheric conditions, crop characteristics, the type of irrigation, as well as soil moisture. The relationship between large-scale irrigation (i.e., water use) and land surface energy and mass flux exchanges (depending on atmospheric conditions) has also received much attention, especially in recent years (see the reviews of *Pielke et al.* [2007] and *Sacks et al.* [2009]). Qualitatively, irrigation practices have been identified as having both direct and indirect consequences on local and regional climate (e.g., see the review by *Pielke et al.* [2007]) through land cover and land use changes (LCLUS). The types of irrigation schemes have also impacted the ecohydrological processes in the water-limited environments through modifying the soil water contents (e.g., see the review by *Newman et al.* [2006]). Many studies have quantitatively investigated the impact of irrigation on weather, climate, and hydrology at different scales. Such studies have relied mainly on the use of physics-based numerical models [e.g., *Segal et al.*, 1998; *Adegoke et al.*, 2003; *Kueppers et al.*, 2007, 2008; *Kanamaru and Kanamitsu*, 2008; *Lobell et al.*, 2009]. However, such studies have shown results which disagree on the magnitude and spatial pattern [*Sacks et al.*, 2009]. For example, most authors of these studies have usually fixed the root zone soil moisture within the models to either field capacity or saturation in the runs [e.g., *Adegoke et al.*, 2003; *Haddeland et al.*, 2006; *Kueppers et al.*, 2007; *Kanamaru and Kanamitsu*, 2008]. Consequently, the reported

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results of previous studies may not accurately represent the effects of irrigation on surface fluxes and on the regional/local climate and surface hydrology.

[4] The question of how much water should be added into climate models' assumed soil zone in order to account for irrigation is still unresolved and has typically been decided based on some sensitivity studies. For example, *Kanamaru and Kanamitsu* [2008] investigated the effects of irrigation on regional climate by prescribing the Oregon State University land surface model (LSM) root zone soil moisture to saturated and half-saturated conditions for each time step separately. Their results suggested that the soil moisture prescription is too high and, hence, causes cool bias. *Sacks et al.* [2009] prescribed a specific amount of water into the model (CLM3.5) irrigation grid based on leaf area index (LAI) and mean estimated annual irrigation water amount to investigate the effect of irrigation on global climate. However, *Sacks et al.* [2009] mentioned that their method assumes that the irrigation water usage has no seasonal and interannual variation as well as being independent of crop type. On the other hand, *Lobell et al.* [2009], using the community atmospheric model (CAM3.3), which is coupled with CLM3 LSM, and through prescribing the top 30 cm soil moisture at the irrigation grid for 90%, 50%, 40%, and 30% of soil saturation, respectively, found that the impacts of irrigation on air temperature and latent heat fluxes (i.e., ET) are "extremely insensitive" to soil moisture increases beyond 30% saturation. The same results were done by *Kueppers and Snyder* [2011], who also claimed that "irrigation to 50, 75, or 100% of field capacity did not result in detectably different effects on afternoon maximum temperatures in any month of the year in RegCM3," which is coupled with BATS LSM. Most recently, using the Noah LSM offline, *Ozdogan et al.* [2010] studied the ET variation at the Five Points site (grass farm) in California as well as the Mead (previous name of the station Soybean) Ameriflux site (bean crop) in Nebraska and found that ET is improved by setting the maximum allowable water depletion (SW_m) of soil moisture at the fixed value of 50% for the two sites studied.

[5] While the study of *Ozdogan et al.* [2010] showed improvement in ET estimates for a fixed SW_m, there is a plausible explanation for their reported underestimation of ET at Five Points in California and overestimation at the Mead Ameriflux site in Nebraska [*Ozdogan et al.*, 2010, Figure 7]. This is partly due to the fact that the recommended SW_m values for bean crop are 0.45 and 0.50–0.55 for alfalfa or grass. According to *Hanson et al.* [2004], the maximum allowable water depletion changes depending on a wide range of vegetation (crop) types. For example, SW_m values as high as 0.90 for wheat (ripening) and as low as only 0.15 for strawberries have been recommended. In short, fixing the SW_m to a specific value may still result in inaccurate capturing of the effect of irrigation on ET, etc.

[6] There are also a number of reported studies where the Noah LSM has been employed to study irrigation impact on regional and local hydroclimate [e.g., *Ozdogan et al.*, 2010]. Often, all crops in the Noah LSM, especially in the coupled MM5/Noah LSM, are categorized as one type of land use, and the related vegetation parameters are kept the same. In a recent study by *Sorooshian et al.* [2011, hereinafter S2011], using the Noah LSM in offline mode, the SW_m at each irrigation grid or site (point) was set to values recommended by *Hanson et al.* [2004]. We note that *Hanson et al.* [2004] recommended that SW_m values, which are based on crop types, be prescribed for optimal (i.e., minimum) use of water without affecting maximum crop yield. It should be recognized, however, that, in the real world, it is difficult to control and monitor two factors. The first factor is the practicality of maintaining SW_m at the exact recommended values. The second factor is the potential inexactness of information about crop types as they change from season to season and annually. The combination of these two factors introduces some error in the model simulations because of prescribed irrigation assumptions that may not reflect the exact conditions. In coupling runs performed by S2011, the SW_m values used for the two major irrigation areas of the Sacramento and San Joaquin valleys were the average from all crops within the respective irrigation areas based on monthly data provided by *Hanson et al.* [2004]. The results from S2011 indicate that the integrated model using the averaged SW_m can reproduce observed meteorological fields as compared to ground observation as well as remote sensing data at the intraseasonal scale.

[7] In this paper, we extend the study of S2011, which only focused on interseasonal scale, to interannual and interdecadal scales with the primary focus on ET variations. Remote sensing estimates of ET obtained from the MODIS (called MODIS-ET here) instruments, onboard Terra and Aqua Earth Observing Satellites [*Tang et al.*, 2009], were used as reference for comparison purposes.

2. Model Setup and Observation Data

[8] The mesoscale model NCAR/PENN STATE MM5, which has been used to study similar topics [e.g., *Segal et al.*, 1998; *Kueppers et al.*, 2008; *Sorooshian et al.*, 2011], is employed as the integration model. For high spatial resolution runs (only for the year 2007), the selected model physics scheme, as well as model setup, were similar to the one adopted in an earlier study [see *Sorooshian et al.*, 2011]. In brief, for the long-term run, a total of three nested domains are used. Domain 1 covers the United States, Mexico, southern Canada, and the eastern and tropic Pacific, with a 162 km horizontal grid mesh (total 52×61 grid cells). Domain 2 covers the western mountains of the United States, northwestern Mexico, and surrounding water with a 54 km grid (total 64×70 grid cells). Domain 3 is the most inner domain covering California, Nevada, and surrounding areas with an 18 km resolution (118×100 grid cells). NCAR/NCRP reanalysis data [*Kalnay et al.*, 1996] are used as forcing fields, and the modeling period dates from 1 June 1980 to 31 October 2007.

[9] For this study, three model runs are conducted. Run 1 is the "control" run (hereinafter MM5C), which is the normal MM5 simulation run without any modifications. Run 2 is called the "field capacity" run (hereinafter MM5F), where the MM5 root zone soil moisture is set to near field capacity (i.e., 0.90% of field capacity) at each time step. The conditions created for Run 2 are similar to some of the previous studies [e.g., *Haddeland et al.*, 2006; *Kueppers at al.*, 2007; *Kanamaru and Kanamitsu*, 2008]. Run 3 is called

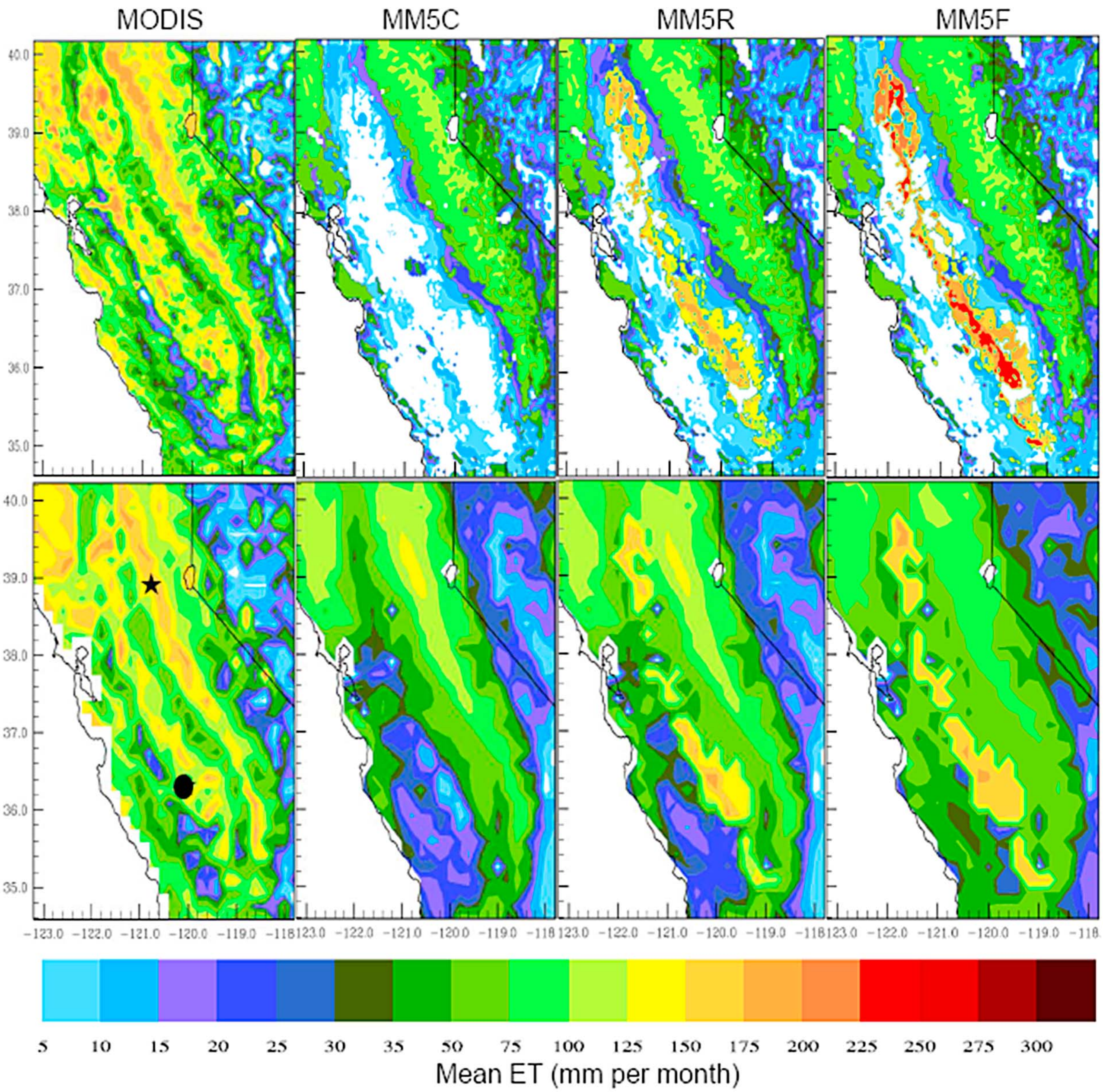

Figure 1. Mean evapotranspiration (ET) map at different resolution in June, July, and August 2007. (top) At about 4 km resolution. (bottom) At about 18 km resolution. MODIS: MODIS ET. MM5C: MM5 output at control run. MM5R: MM5 output with recommendation irrigation scheme added in MM5/Noah. MM5F: MM5 output with fixing soil to field capacity moisture in the model root zone layers. Star in the bottom left panel represents the ET observation location at Ameriflux site while circle represents the ET observation location at Five Points.

the "realistic" run (hereinafter MM5R). For this case, the soil moisture conditions are set up based on a number of conditions including the recommendations of *Hanson et al.* [2004], which are practiced closely by irrigators. In our MM5R run, irrigation water is applied when the following three conditions are satisfied: (1) the root zone's relative available soil water (SW) content is less than the maximum allowable water depletion (SW_m) of soil [*Hanson et al.*, 2004], (2) when downward solar radiation is less than 50 W m^{-2} [*Sorooshian et al.*, 2011], and (3) soil temperature is greater than 10°C for the long-term run to avoid irrigating if the soil is frozen. Irrigation ceases when soil moisture reaches field capacity.

[10] In this manuscript, we focus mainly on modeled ET variation at different time scales and compare it with available observations. The MODIS ET data are downloaded

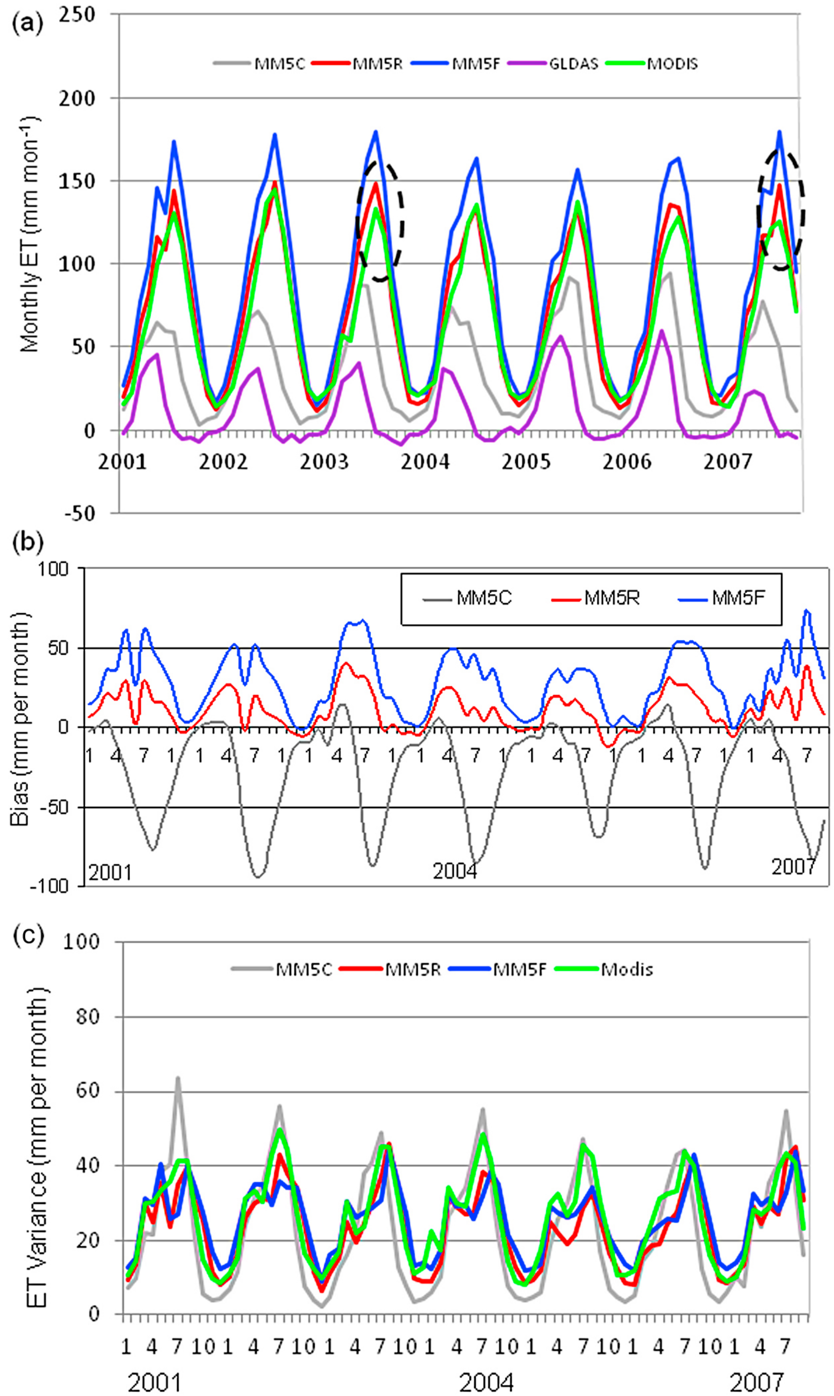

Figure 2. (a) Monthly ET (mm per month) comparison to be averaged over all of the irrigation grid cells from January 2001 to September 2007. (b) Bias time series of monthly ET (mm per month) in the irrigated regions based on grid to grid pixel from January 2001 to September 2007. (c) Variance time series of monthly ET (mm per month) in the irrigated regions based on grid to grid pixel from January 2001 to September 2007.

from the Land Surface Hydrology Research Group, University of Washington (http://ftp.hydro.washington.edu/pub/qiuhong/usa/). The data are monthly and 0.05 degree spatial resolution and cover the period from 2001 to 2008 (hereinafter MODIS). The Ameriflux ET data at the Blodgett Forest site are converted from the L-4 latent heat flux, which covers from 1999 to 2006 (hereinafter Ameriflux).

[11] For reference, we also downloaded the ET (latent heat flux) from the Global Land Data Assimilation System (GLDAS) [*Rodell et al.*, 2004] 0.25 degree monthly data

from website (http://disc.sci.gsfc.nasa.gov/hydrology/data-holdings).

3. Result Analysis

3.1. Analysis of ET Estimates Over the Irrigated Areas

[12] Figure 1 shows the map of ET distributions at two different resolutions in 2007 summer (June, July, and August). MODIS ET at about 18 km resolution was averaged from the 5 km resolution data. Compared to two resolutions of MODIS ET data, they have the similar spatial pattern, although the higher resolution data have slightly higher ET values at some locations. MM5 outputs at 4 km resolution (Figure 1, top) are from the runs in S2011, and those at 18 km resolutions are run in this paper. In Figure 1, it is observed that ET from MM5C is underestimated over the Central Valley irrigation areas when compared with those of MM5R, MM5F, and MODIS. The ET estimates from both MM5R and MM5F exhibit the same patterns (spatial distribution) as MODIS ET at the same resolution. However, MM5F overestimates the amount, in comparison with MODIS and MM5R at the same resolution. Overall, when the irrigation scheme is incorporated into the MM5/Noah LSM, the model reproduces the spatial pattern captured in the MODIS data reasonably well.

[13] A more careful examination of the irrigation areas at 4 km resolution reveals that MODIS estimates of ET capture heterogeneity in spatial distributions which correspond well with the specific meteorological conditions, soil, and crop types for the study period (June–August 2007). The model outputs from MM5R and MM5F have reproduced the detailed spatial variations over the Sacramento River basin and the southern San Joaquin Valley, especially in the case of MM5R, with only slight differences in the amount. In the northern San Joaquin Basin, both MM5R and MM5F differ slightly from MODIS ET. A plausible explanation for the difference is that, in the MM5F and MM5R simulations, the land use data employed are from the 1993 USGS data set. Needless to say, that since 1993, the land use patterns in this area have not remained static and have changed. Therefore, the simulation results do not reflect the MODIS estimates which are capturing the present conditions and represent the current conditions more realistically. Comparison of model outputs with MM5C and MODIS estimates in the 18 km resolution case reveals differences between two areas of (1) over the central Valley and (2) over the Sierra Nevada Mountains. In the Central Valley case, where a relatively large amount of irrigation water is applied to the model's soil zone, the simulated climate over the surrounding region is affected, and this result is consistent with some of the previous studies [e.g., *Kueppers et al.*, 2007]. Figure 1 also indicates (as also reported in S2011) that the selected model resolution in studying the effect of irrigation on local/regional climate and hydrology is important.

[14] Figure 2a shows the ET comparison based on the mean values from all irrigation grids from January 2001 to October 2007. The data from GLDAS show the smallest ET amount followed by MM5C with a consistent time shift for both, in comparison with ET values from MODIS, MM5R, and MM5F. It should be noted that both MM5C and GLDAS simulations assume no irrigation, and that the model-generated ET amounts are from the precipitation-caused soil moisture, which is mainly associated with rainy seasons occurring in the previous winter and spring. Lack of any significant rainfall in other time periods results in very dry air, resulting in rapid loss of soil moisture due to the high rate of ET during the summer season. This is the reason for the observed shift in the ET peak time in comparison with MODIS and MM5R/F. Because both MM5 and GLDAS simulations and their data are based on the Noah LSM, the time shifts from MM5C and GLDAS reflect a similar trend. However, the differences in ET amounts between MM5C and GLDAS are likely due to differences in resolution [*Sorooshian et al.*, 2011] and the offline mode (GLDAS) and coupled mode (MM5). When the recommended irrigation scheme is added in MM5/Noah, ET from MM5R matches with the MODIS data very well, both in time and in amount. Furthermore, results from both MM5R and MM5F show that the intraseasonal and annual variabilities are very similar to that from MODIS. However, examining Figure 2 with respect to interannual variability, the modeled and MODIS estimates show differences for the summers of 2003 and 2007, both of which followed dry winters and springs. In this manuscript, we do not consider water availability as a limiting factor and assume that, whenever irrigation is needed, irrigation water is available. However, in the real world, this assumption is not always satisfied. For example, if the precipitation in the preceding winter and spring, such as the period from winter 2002 to spring 2003 [*Li et al.*, 2007] and from winter 2006 to spring 2007 [*Sorooshian et al.*, 2011], is less than normal (i.e., dry winter and spring), the water available for irrigation is usually limited, and some crops might not get enough water in some fields. The situation of available water in actuality and model irrigation assumption which places no limit on water availability is one of the reasons responsible for the differences between modeled ET and MODIS estimates, as was experienced in the 2003 and 2007 summers (see the circled areas in Figure 2a).

[15] The grid cell to grid cell biases between modeled ET and MODIS ET in the irrigation region are also estimated and plotted (see Figure 2b). The model simulation results for the case assuming no irrigation (MM5C) indicate that the model experienced negative biases, especially during the summer, which coincides with maximum level of irrigation. For the two cases when irrigation is added (MM5F and MM5R), the biases become positive. As expected, the bias level was relatively significant for the MM5F and ranged between 30 and 60 mm per month. However, for the MM5R run, the bias is significantly reduced, with its maximum being less than 40 mm per month during the hottest summers. The variances of mean monthly ET are also calculated (Figure 2c), and the results indicate that the variation from the four ET data sets (including ET from MM5C, MM5R, MM5F, and MODIS) are very similar, except in summer 2001, when the MM5C variance is larger than the others.

[16] Two possible reasons can be used to explain the result of the high biases and variance. One might be that too much water is added or overirrigated (e.g., MM5F). Another one might be that the averaged irrigation factors, such as mean allowable water depletion in the entire irrigation region, have been used in the model, while in the real world, the allowable water depletion depends highly on the crop's type and growth season [*Hanson et al.*, 2004].

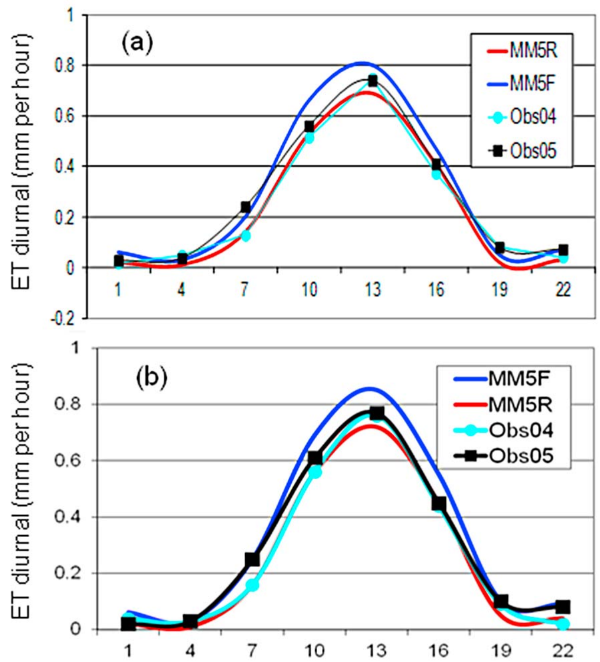

Figure 3. ET diurnal variations between observations at Five Points, California, in 2004 and 2005 and modeled at the grid closest to the observation site in 2007. (a) August and (b) June, July, and August mean.

[17] In the Central Valley irrigation region, the ground observations of ET, etc. from a number of ongoing projects are not yet available, but are expected to become available for public use after the completion of projects and publication of results by the project researchers (USDA-ARS and a number of university researchers, personal communications, 2011). However, some observational results, but for different years than the period considered in our study, were published and were available. *Ozdogan et al.* [2010] reported the results of a study examining the diurnal variation of ET at the Five Points station (36.34°N, 120.11°W) based on measurements obtained in August 2004 and August 2005 [*Ozdogan et al.*, 2010, Figures 7c and 7d]. Using the same data, we plotted the diurnal variations between our model outputs obtained with different SW_m values during August 2007 and observations from the months of August 2004 and 2005 (Figure 3a). Figure 3a shows that the measured maximum ET at the Five Points site was about 0.7 mm per hour (solid line with solid circle and solid square for different years) that occurred between the hours of 13:00 local time in both years. On the basis of the observation, it is safe to assume that it is likely that a similar mean diurnal ET pattern for the month of August in other years (including 2007, which was the focus of our study) can be expected. Diurnal variations in ET values for August 2007 from MM5F and MM5R are plotted with solid blue and red lines, respectively. Two important observations can be made by examining Figure 3a. First, the observed mean ET peak values for both years are almost identical, with the value of 0.7 mm between the hours of 13:00. Second, the MM5R underestimates ET slightly but is very close to the observed peak, while MM5F overestimates.

[18] Figure 3b shows the diurnal variations from observations at Five Points for June, July, and August 2004 and 2005 and from MM5R and MM5F models at the grid cell closest to Five Points for the same months but for 2007. Comparison shows that (1) MM5R modeled values are close to the observations, especially at the maximum, and (2) MM5F overestimates the maximum values consistently in both years. We conclude that MM5, with the modified Noah LSM, can reproduce the ET diurnal variation very realistically in comparison with available field observations made in the Central Valley.

[19] Unfortunately, lack of extended in situ ET observations in the California's Central Valley irrigation area does not allow for a more comprehensive comparison of modeled results. Nonetheless, a more extended modeling study covering the period from 1981 to 2007 and using all three model runs (i.e., MM5C, MM5F, and MM5R) were conducted. The interannual variations of annual total ET are presented in Figure 4. The MODIS ET from 2001 to 2007 is also plotted in Figure 4. On the basis of the conclusions made earlier by examining results in Figures 2 and 3, it is concluded that (1) MM5F overestimates ET, (2) MM5C underestimates the actual ET, (3) MM5R captures the quantity of MODIS ET more realistically, (4) MM5C is in opposite phase in comparison with the results from MM5R and MM5F, and (5) it is not reasonable to assume that the irrigation water amount has no interseasonal or interannual variation. Thus, it is reasonable to reach the conclusion that the previously reported studies assume that the field capacity irrigation scenarios have overestimated the effects of irrigation on regional/local climate. Specifically, models have generated wet biases.

[20] Supporting the claim about the accuracy of MM5R, we refer to our recently reported results [*Sorooshian et al.*, 2011], where other meteorological fields such as temperature, wind, and humidity were studied. It was demonstrated that, after implementing the irrigation scheme of *Hanson et al.* [2004] into MM5/Noah, the MM5R modeled values of these variables were improved, becoming more realistic in comparison with the control run and observation.

[21] Finally we draw attention to Figure 4, which shows the phase of MM5C and MM5R/F being opposite to each other. In the case of the control run (MM5C) at the annual scale, where the seasonal time shift for ET is ignored, less precipitation generated by the model over the irrigation areas results in less ET estimates. In contrast, for irrigation runs where we assume water is available whenever needed, more ET is generated. The amount of ET generated by the model is also regulated by the drier and hotter soil conditions when more water is applied via irrigation to compensate for lack of precipitation. In the real world, however, water is limited after the dry winter and spring, which can also partly explain the difference between MODIS ET and MM5R/F.

3.2. Analysis of ET Estimates Over the Mountainous Areas of the Sierra Nevada Mountains

[22] In the final part of this study, we focused on the ET estimates outside the irrigated areas, especially those provided by MM5 and MODIS over the Sierra Nevada Mountains (see Figure 1). We first note that the modified irrigation schemes' influence on ET estimates outside the irrigated areas diminishes with distance and, therefore, the three modeling

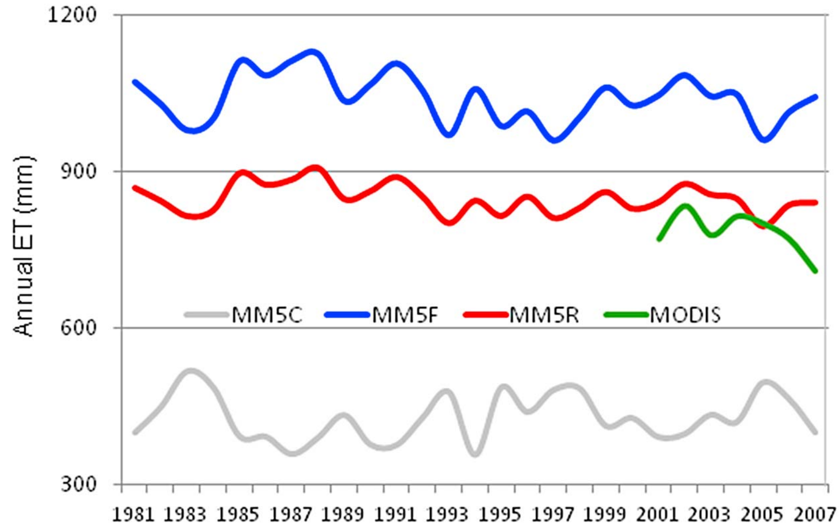

Figure 4. Time series of modeled annual ET averaged from all irrigation grids in the Central Valley.

approaches (i.e., MM5C, MM5F, and MM5R) show approximately the same ET estimates and patterns over the Sierra Nevada forest ecosystem. It is also noted from Figure 1 that the MODIS estimates of ET over the forest ecosystem are significantly larger than the MM5 modeled values and relatively larger with respect to MODIS estimates over the irrigated areas of the Central Valley. The availability of in situ ET observations from one Ameriflux site operated by UC Berkeley Goldstein's research group [*Fisher et al.*, 2005] provided the opportunity to evaluate the ET estimates of MM5 and GLDAS modeled values and the MODIS estimates. The site known as Blodgett Forest (38.8956°N, 120.6327°W) is at 1315 m above sea level and is located in an area covered with evergreen needleleaf. Monthly latent heat flux observations (L-4) are available from 1999 to 2006. Figure 5 shows the ET comparison for MM5, GLDAS, MODIS, and Ameriflux data. The MM5, GLDAS, and MODIS estimates are the average values over the grid cell closest to the Ameriflux. Examination of Figure 5 indicates that (1) compared to Ameriflux, MODIS overestimates ET, except in summer of 2006, (2) MM5 ET estimates match the Ameriflux observations very closely except in summer of 2006, and (3) GLDAS underestimates ET with a slight time shift, reaching the peak earlier than those of the others. The main conclusion from this analysis is that, while MODIS ET estimates in the Central Valley irrigation area correspond reasonably well with MM5R results, they highly overestimate over the mountainous region. This observation about the potential overestimation of ET by MODIS over higher elevations may be of interest to the MODIS scientific team which continuously seeks to improve the accuracy of their product.

4. Summary

[23] The agriculture sector is the largest user of water in California. A number of modeling studies focusing on the role of large-scale irrigation on regional climate have been reported over the years. The influence of irrigation on various hydrometeorological variables has varied, depending on the irrigation scheme and assumptions incorporated into the regional climate models. The reported study herein examines the influence of two different irrigation schemes used in the MM5/Noah LSM in terms of their ability to estimate the quantity of ET as compared to available in situ and remotely sensed observations. The irrigation schemes were (1) the scheme used in previous studies with the assumption of applying water into the model to maintain field capacity and full soil saturation and (2) our proposed use of the scheme recommended by *Hanson et al.* [2004], which is used in real practice by irrigators and when water is added based on the specific crops' need.

[24] Our tests indicate the following.

[25] 1. Integration of the irrigation scheme of *Hanson et al.* [2004] into MM5/Noah results in the model's ability to reproduce more accurate amounts and patterns of ET in the Central Valley as compared to MODIS ET observations as well as ground data.

[26] 2. It is also observed that, in general, MODIS overestimates ET values over the forest ecosystem of the Sierra Nevada Mountains. If remotely sensed estimates of ET are to

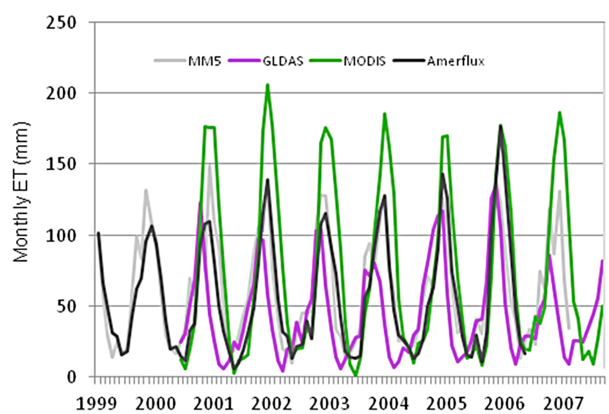

Figure 5. Monthly ET comparison at the Ameriflux site (location is shown in Figure 1).

fulfill a major gap in data for water balance studies, we caution about the ET overestimation and encourage additional studies to determine if the MODIS overestimation of ET extends to all forested ecosystems in the mountainous regions or is just exclusive to the Sierras.

[27] Finally, we believe that it is useful to quantify the significant discrepancies of ET estimates between different irrigation schemes used in regional hydroclimate modeling studies conducted to investigate the impact of irrigation on water balance and over the agricultural areas. Our calculation of the mean annual volume of ET over the Central Valley irrigation area results in approximately 12 million acre feet (ac-ft)/year estimated by MM5C, 28.5 million ac-ft/year for MM5F, 23.4 million ac-ft/year for MM5R, and the MODIS estimate of 22 million ac-ft year. The overestimation in the case of MM5F and underestimation in the case of MM5C are significant as compared to MM5R and MODIS estimates, which we consider to be much more representative of reality. Placed in the context of water resources management in the region, the overestimation and underestimation of ET amounts are not trivial and can provide erroneous information if used in water resources decision making.

[28] **Acknowledgments.** The authors appreciate Allen Goldstein and Megan McKay of the University of California, Berkeley, for their permission to use their Ameriflux data at Blodgett Forest, California. The authors also thank James Ayars at USAD ARS in California for his permission to use ground ET data at Five Points and Ozdogan of University of Wisconsin for facilitating this contact. The cooperation and information provided by Forrest Melton at NASA Ames Research Center regarding in situ field observations is appreciated. Q. Tang at of the University of Washington is to be thanked for providing the MODIS ET data. Primary support for this research was provided by the NASA ROSES programs (NNX06AF93G, and NNX09A067G) and NOAA CPO programs (NA08OAR4310876 and NA10OAR4310162). The University of California/National Labs Research Program project (09-LR-09-116849-SORS) is greatly acknowledged for its support of the PI and students.

References

Adegoke, J., R. Pielke Sr., J. Eastman, R. Mahmood, and K. Hubbard (2003), Impact of irrigation on midsummer surface fluxes and temperature under dry synoptic conditions: A regional atmospheric model study of the U.S. High Plains, *Mon. Weather Rev.*, *131*, 556–564, doi:10.1175/1520-0493(2003)131<0556:IOIOMS>2.0.CO;2.

Fisher, J., T. A. DeBiase, Y. Qi, M. Xu, and A. H. Goldstein (2005), Evapotranspiration models compared on a Sierra Nevada forest ecosystem, *Environ. Model. Softw.*, *20*(6), 783–796, doi:10.1016/j.envsoft.2004.04.009.

Haddeland, I., D. Lettenmaier, and T. Skaugen (2006), Effects of irrigation on water and energy balances of the Colorado and Mekong river basins, *J. Hydrol.*, *324*, 210–223, doi:10.1016/j.jhydrol.2005.09.028.

Hanson, B., L. Schwankl, and A. Fulton (2004), Scheduling irrigations: When and how much water to apply, *Div. Agric. Nat. Resour. Publ. 3396*, Univ. of Calif., Davis.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471, doi:10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2.

Kanamaru, H., and M. Kanamitsu (2008), Model diagnosis of nighttime minimum temperature warming during summer due to irrigation in the California Central Valley, *J. Hydrometeorol.*, *9*, 1061–1072, doi:10.1175/2008JHM967.1.

Kueppers, L. M., et al. (2008), Seasonal temperature response to land-use change in the western United States, *Global Planet. Change*, *60*, 250–264, doi:10.1016/j.gloplacha.2007.03.005.

Kueppers, L. M., and M. A. Snyder (2011), Influence of irrigated agriculture on diurnal surface energy and water fluxes, surface climate, and atmospheric circulation in California, *Clim. Dyn.*, *38*, 1017–1029, doi:10.1007/s00382-011-1123-0.

Kueppers, L. M., M. A. Snyder, and L. C. Sloan (2007), Irrigation cooling effect: Regional climate forcing by land-use change, *Geophys. Res. Lett.*, *34*, L03703, doi:10.1029/2006GL028679.

Li, J., X. Gao, and S. Sorooshian (2007), Modeling and analysis of the variability of the water cycle in the Upper Rio Grande Basin at high resolution, *J. Hydrometeorol.*, *8*, 805–824, doi:10.1175/JHM602.1.

Lobell, D., G. Bala, A. Mrin, T. Phillips, R. Maxwell, and D. Rotman (2009), Regional differences in the influence of irrigation on climate, *J. Clim.*, *22*, 2248–2255, doi:10.1175/2008JCLI2703.1.

Newman, B. D., B. P. Wilcox, S. R. Archer, D. D. Breshears, C. N. Dahm, C. J. Duffy, N. G. McDowell, F. M. Phillips, B. R. Scanlon, and E. R. Vivoni (2006), Ecohydrology of water-limited environments: A scientific vision, *Water Resour. Res.*, *42*, W06302, doi:10.1029/2005WR004141.

Ozdogan, M., M. Rodell, H. Beaudoing, and D. Toll (2010), Simulating the effect of irrigation over the United States in a land surface model based on satellite-derived agricultural data, *J. Hydrometeorol.*, *11*, 171–184, doi:10.1175/2009JHM1116.1.

Pielke, R. A., Sr., J. Adegoke, T. Chase, C. Marshall, T. Mastui, and D. Niyogi (2007), A new paradigm for assessing the role of agriculture in the climate system and in climate change, *Agric. For. Meteorol.*, *142*, 234–254, doi:10.1016/j.agrformet.2006.06.012.

Rodell, M., et al. (2004), The Global Land Data Assimilation System, *Bull. Am. Meteorol. Soc.*, *85*, 381–394, doi:10.1175/BAMS-85-3-381.

Sacks, W., B. Cook, N. Buenning, S. Kevis, and J. Helkowski (2009), Effects of global irrigation on the near-surface climate, *Clim. Dyn.*, *33*, 159–175, doi:10.1007/s00382-008-0445-z.

Segal, M., Z. Pan, R. Turner, and E. Takle (1998), On the potential impact of irrigated areas in North America on summer rainfall caused by large-scale systems, *J. Appl. Meteorol.*, *37*, 325–331, doi:10.1175/1520-0450-37.3.325.

Sorooshian, S., J. Li, K. Hsu, and X. Gao (2011), How significant is the impact of irrigation on the local hydroclimate in California's Central Valley? Comparison of model results with ground and remote-sensing data, *J. Geophys. Res.*, *116*, D06102, doi:10.1029/2010JD014775.

Tang, Q., S. Peterson, R. H. Cuenca, Y. Hagimoto, and D. P. Lettenmaier (2009), Satellite-based near-real-time estimation of irrigated crop water consumption, *J. Geophys. Res.*, *114*, D05114, doi:10.1029/2008JD010854.

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