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Final Technical Report on the Project of

Impacts of Irrigation on regional climate, hydrology variability

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Abstract

Irrigation is the largest human hydrological activity. With increasing demand for agricultural products and the application of advanced technologies, irrigated acreage in the world is continuously expanding. This proposal has investigated high-resolution (~4~10km) regional climate model (RCM) to study irrigation's influences on regional climate, and hydroclimate. The study is focused on the Central Valley, California. The PSU/NCAR Mesoscale Model (MM5) is coupled with a modified Noah land surface model to investigate the impact of irrigation on the hydroclimate. The main results from our studies include: (1) The results from our modified Noah land surface model match the In-situ observation very well both in offline and in coupled model. (2) Irrigation caused irrigation area temperature decreased up to ~5 °C at day time. However,night time temperature can not be identified partly due to the biases of model results which is inconsistent with some previous study. (3) The effect of the irrigation on regional scale is not as much as that previous studies indicated most possibly that the previous studies over added water in the model soil. (4) Irrigation may cause surface income solar radiation decrease from 1-5 W m^{-2} due to cloud and air humidity increase. However, model outputs have positive biases at about 10-30 W m^{-2} in comparison with CIMIS data. (5) Assimilation is a promising way to improve land-atmospheric interaction.

1. Introduction

California agriculture is one of the highest productive regions in the U.S. However, precipitation in California is not enough to match the need of crop growth. Irrigation becomes one of the main methods to keep crop yields not reducing due to the lack precipitation. In California, irrigated farmland includes 8.7 million acres, mostly in the Century and Imperial Valleys (Fig. 1). Irrigation practices have both direct and indirect consequences for regional/local climate. Irrigation alters surface roughness of vegetation, albedo, leaf conductance and other properties that affect surface water and energy exchanges (Pielke et al. 2002). Irrigation may also result in decreased temperature and increased relative humidity. As early as 1990s, Pielke Sr. and Avissar (1990) suggest that the temperature change due to landscape change has about the same magnitude as that due to the greenhouse gas increase at regional/local scale. Irrigation also affects ground water recharge and soil moisture.

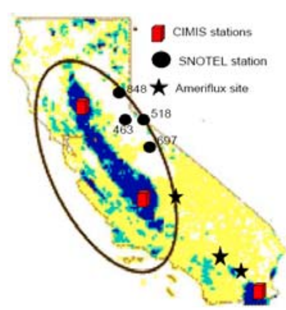


Fig. 1. California Irrigation regions (blue).

A lot of studies have investigated the impact of irrigation on weather, climate and hydrology at locale, regional, and even global scale. Although these studies can simulate some phenomena caused by irrigation processes using numerical models, the models have not described irrigation process realistically in most of the studies. For example, Seal et al. (1998) investigated the irrigation on summer rainfall in North America using MM5 at the resolution of 90-km and weekly scale. In their irrigation scheme, the daily prescribed evapotranspiration is used to describe water usage in the irrigation grid fraction. Adegoke et al. (2003), using RAMS with 10 km resolution, investigated the irrigation effect on weather in Nebraska. In their irrigation scheme, the fraction of irrigation grid cell is set up to be saturated at 00:00UTC each day. Kueppers et al. (2007) using RegCM3, have simulated effect of irrigation on regional climate in Central Valley, California. To mimic the effects of irrigation, they force RegCM3 root zone (top 1 meter) soil moisture to field capacity at every time step, year round. Kueppers et al. (2008) compared the effects of irrigation on regional climate with specific to summer temperature based on different regional climate models (RCMs) and found that the model behaviors depends on model physics and irrigation configurations. Among these models, the soil moisture is set to saturation in Regional Spectra Model (RSM), and field capacity in RegCM3, none specific description in MM5-CLM3, and 4.822 $\times 10^{-8}$ m/s in DRCM when top soil layer temperature is larger than 12^{o}C and zero when less than 12^{o}C. These assumptions overestimate the irrigation water usage in comparison with the documents by Hanson et al. (2004) and thus may overestimate the effect of irrigation on regional climate. Kanamaru and Kanamitsu (2008) have investigated the effects of irrigation on regional climate via prescribing root zone soil moisture in saturated and half saturated condition each time step, separately. Their results suggest that soil moisture prescription that is too high will cause cool bias. Besides investigating the effect of irrigation on regional/local weather and climate, some researchers have also studied the effects of irrigation on hydrology. Haddeland et al. (2006) estimated the effects of irrigation on river basin's water and energy balance. In their study, they assume that root zone soil moisture is field capacity at each time step. Tang et al. (2007) also investigated the effects of irrigation on basin water balance via adding water in the SIB2-based grid cell model. In their model, the irrigation starts when the soil moisture was below the wilting point level and continued until soil moisture reached the field capacity, which is close to realistic irrigation. Although different RCMs can qualitatively simulate pattern of the effects of the irrigation on local/regional climate. The results vary depending on the models (Kueppers et al. 2008) and few studies are quantitatively compared their results with observations (Lobell et al. 2008), possible because of observation resolution issue (Kueppers et al. 2008).

In our study, we have modified Noah land surface model (LSM) through implementing a real irrigation scheme into Noah LSM. The irrigation scheme is used in California and recommended by Hanson et al. (2004). After the model modification was done, we performed the following work:

(1) Offline Noah LSM parameter tests using available parameter data to be applied in California irrigation. We performed in Amerflux sites in California to check the surface fluxes.
(2) Following the first step, offline Noah LSM runs with/without consideration of the irrigation scheme. We performed in California irrigation area and compared with observation from California Irrigation Management Information System (CIMIS).
(3) The same as (2) but used in Nebraska Ameriflux sites, where irrigation applied in the warm season.
(4) Assimilating remote-sensing and In Situ data into Noah LSM to improve the profiles of soil moisture and temperature.
(5) Coupling the modified Noah LSM back into MM5 to investigate the effect of irrigation on regional/local climate and hydrology.
(6) Incoming surface solar radiation features in the irrigation region based on observation and modeling results.

2 Methodology and data of this study

For saving water and keeping the yield in California, Hanson et al (2004) have documented when to irrigate and how much water to be irrigated based on field experiments and theoretical methods. Their recommendation is that irrigation should start when the available soil moisture (SW in equation 1) in the root zone is less than the maximum allowable depletions (SW_m). The former is decided by soil state (θ) and soil physics ($\theta_{fc}, \theta_{wilt}$) while the latter is decided by crop type. For example, SW_m for Alfalfa is 50-55; SW_m for Onions is 25; SW_m for wheat is 90.

$$SW = [(\theta - \theta_{wilt})/(\theta_{fc} - \theta_{wilt})]*100 \qquad (1)$$

When the available soil moisture is less than the maximum allowable depletions and no irrigation applies, the yields will reduce.

Irrigation water amount is not only dependent on soil type and vegetation type, but also affected by weather and climate conditions. In order to obtain specific weather and climate conditions at the irrigation region, the California Irrigation Management Information System (CIMIS) has been managing a network using over 100 automated weather stations in the state of California. In each CIMIS station, the routine meteorological variables, including solar radiation, surface pressure, wind, humidity, air temperature, precipitation and soil temperature, are measured hourly. Currently, the data are mainly used to support the farmers making decisions for irrigation time and water usage amount.

Based on the concept of irrigation recommended by Hanson et al (2004), we have taken four steps to integrate the scheme into Noah: (1) Estimating the average water usage in Sacramento Valley, San Joaquin Valley and Imperial Valley, separately, at monthly scale based on crop types and crop growth period. (2) Estimating maximum allowable soil moisture tensions and allowable soil water depletions based on crop types and soil types each Valley. (3) Checking the crop types, crop growth period, and soil types at each Valley. And (4) starting irrigation (i.e. adding water to field capacity at the root zone layers) if the soil water content is less than a criteria that is given on soil type and crop types at each Valley.

The dataset to be used as model input and model output validation includes, CIMIS data, Ameriflux data, SNOTEL data, NARR data, NLDAS data and MODIS data.

3. Some results

3.1 Offline land surface model modification

2.1.1 The effect of wilting point on latent heat

Over the arid/semiarid California, especially the southern California, the soil experiences a long time without rainfall and the soil moisture is very low and close to the wilting point. We found that the wilting point from different soil types is different between the Noah model default values and the CA in situ observation. Thus, we have tested its effects on evaporation and compared it with Ameriflux values. When using the wilting points observed in California, the model results are much improved in comparison with the result using Noah default wilting point values. And this improvement is consistent in all three sites. Fig. 2 is an example of the latent heat flux time series at Tonzi and Oaks-old Standing and Oaks-Yong Standing in 2002. The location is labeled with a star in Fig. 1. We also have tested as long as three years at the two locations (Tonzi, and Oaks-Old-standing). The results improved consistently in comparison with results using the default model wilting point (not shown).

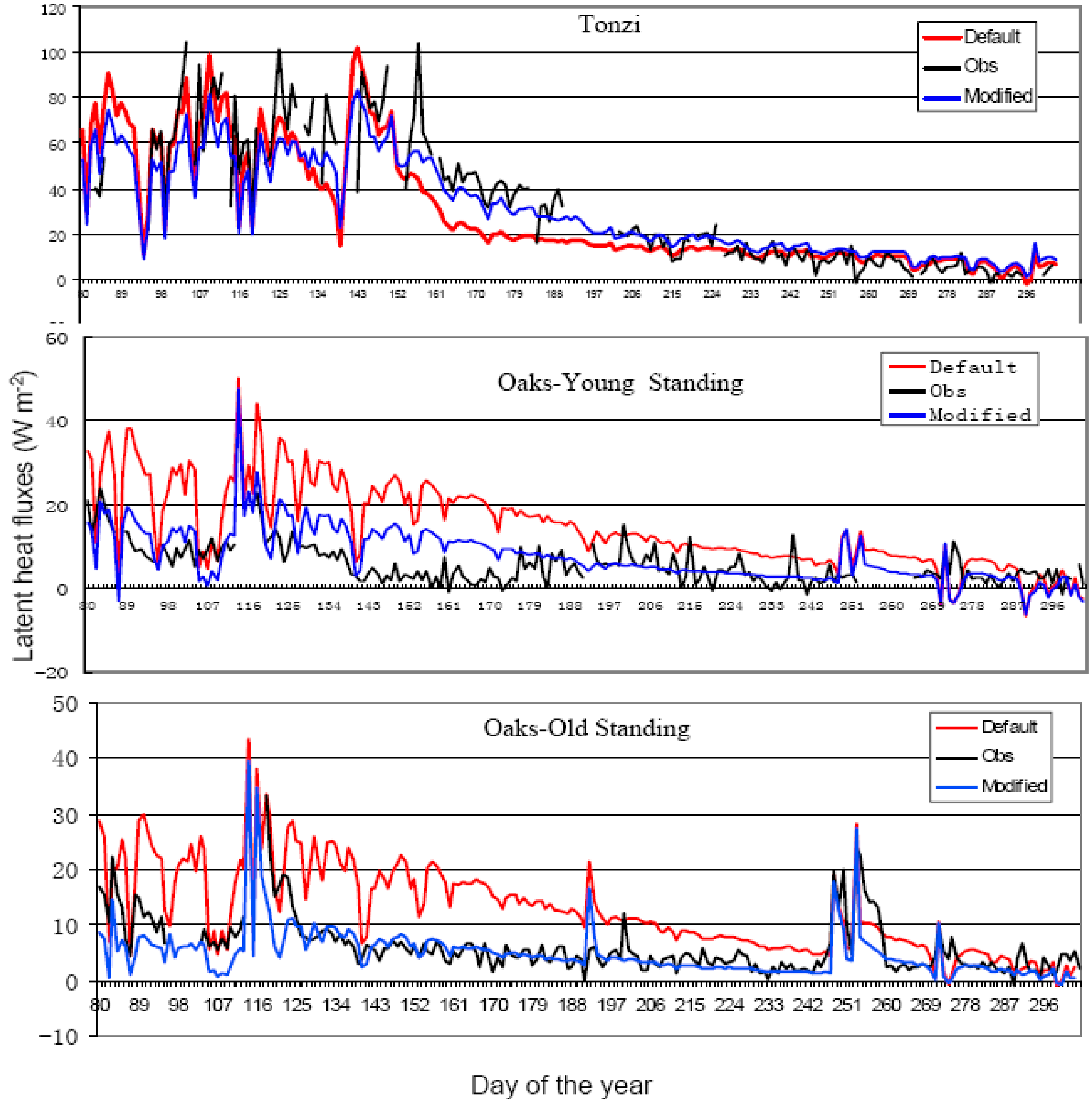


Fig. 2: Latent heat flux comparisons at Tonzi (38.43°N, 120.97°W)), Oaks-young- standing (33.377°N, 116.62°W), and Oaks-old-standing (33.37°N, 116.61°W) locations. Dark, red, and blue lines represent observation, model result with default wilting point and model result with changed wilting point.

Fig. 2 indicates that adjusting the Noah LSM default wilt-point to the Hanson et al recommended ones can improve the surface latent heat flux estimation. This result is especially clear during the seasonal transient from wet to dry. We also checked the sensible heat variation after changing wilt-point, we found that the sensible heat flux variation is not clear.

This test is only performed in the California Ameriflux site, where no irrigation occurs.

3.1.2 Noah offline tests with irrigation scheme implemented in California

California has built over 100 sites for Reference Evapotranspiration (ET), weather and crops data for the state-wide management of irrigation, i.e. CIMIS data system. To examine whether the modified Noah LSM improves the result in irrigation region, using the CIMIS data as forcing data, including wind, surface pressure, solar radiation, precipitation, relative humidity, and temperature (the Noah LSM needed downward long wave radiation is from NLDAS data), we have run the modified model and default Noah model separately over 18 CIMIS sites that located in Central Valley and Imperial Valley.

The only data that can be used to validate model performance is soil temperature. In general, the model results based on modification are improved in comparison with that based on default Noah. Totally there are about 18 sites that are identified as irrigation grid cells in MM5. In the 18 sites, 9 of them improved consistently, 7 of them improved some of the time and degraded at other times, and 2 sites got worse. Fig. 3 is an example 15-cm deep soil temperature without irrigation considerations from the three Valleys.

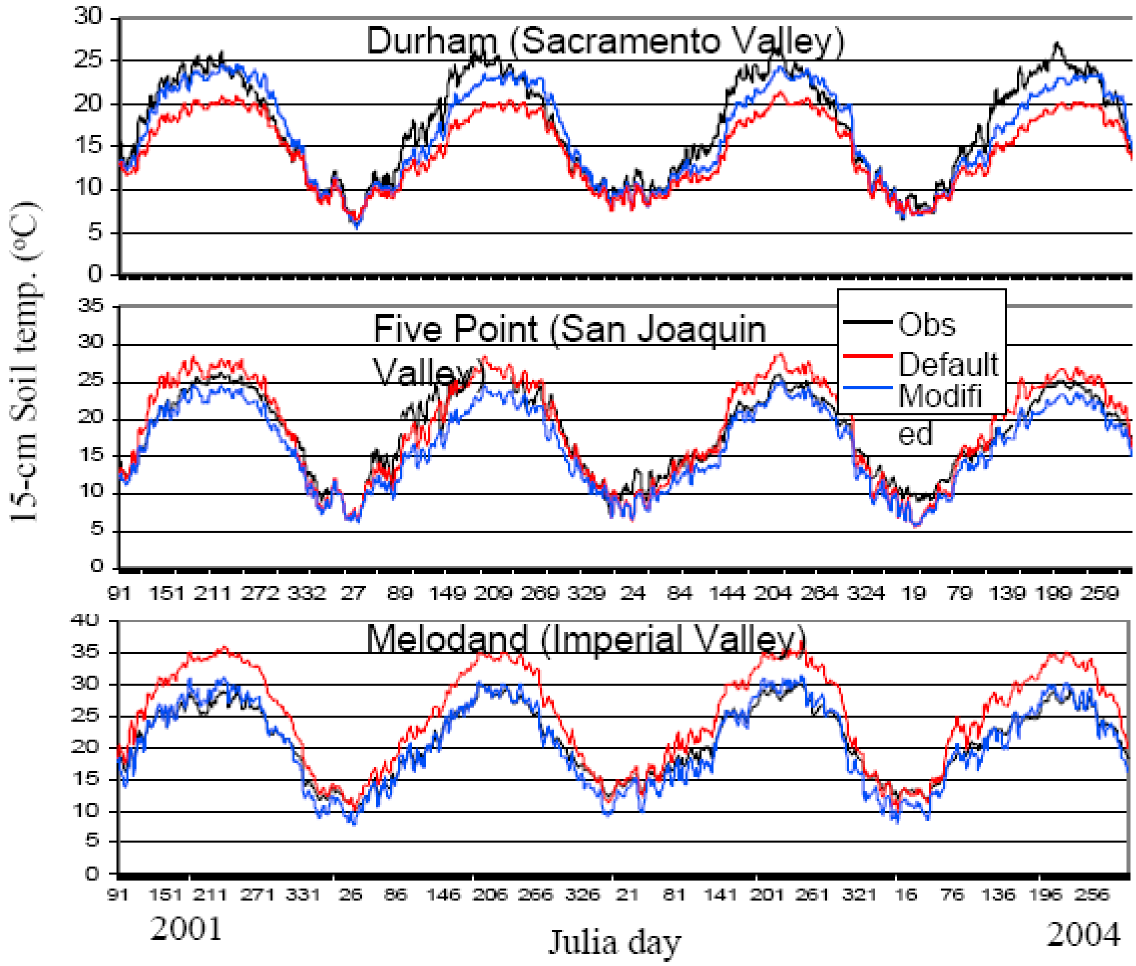


Fig. 3: The comparisons between observation and model results at Meloland, the Imperial Valley. The dark, blue and read lines represent observation, model result with default run and model result with irrigation process added and wilting point changed.

We have analyzed results of sites where model output get worse and/or inconsistent in comparison with the observation. We noticed that the vegetation type is inconsistent between Noah LSM mapped and the real world. As we mentioned, all of the 18 CIMIS sites are irrigation sites and MM5 at 4-km resolution also categorizes them as irrigation land use. The Offline Noah LSM mapped them at some other vegetation types. This difference may be one of the possible reasons that caused the model result to be inconsistent with the observation.

From Fig. 3, we also notice that the modified Noah LSM still generates low bias over the Sacramento Valley. This low bias sustains there even in the coupled model results.

3.1.3. Application to other locations

Since CIMIS only measured soil temperature, we can not further examine the model performance. We apply the modified Noah LSM to Nebraska Ameriflux sites where surface fluxes and top layer soil moisture and temperature are observed. In these two sites, the irrigation occurs in warm season.

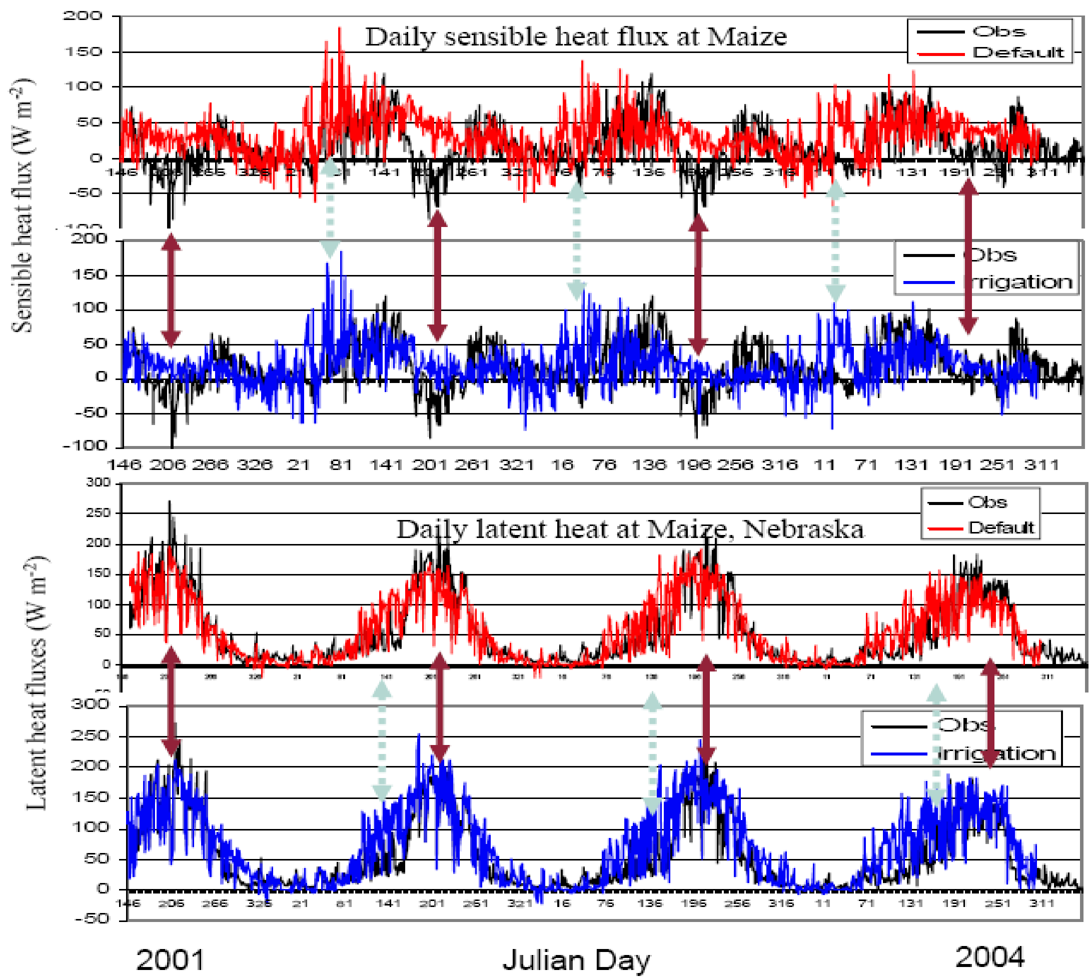


Fig.4a: Sensible heat flux (top two) and Latent heat flux (bottom two) comparisons at Maize (41,16^{o}N, 96.47^{o}W) Amerflux site, Nebraska. From Top to Bottom, the 1st figure is sensible heat flux comparison between observation (dark) and Noah result (red) with default run. The 2nd one is

sensible heat flux comparison between observation (dark) and Noah result (blue) with irrigation scheme run. The 3rd one the latent heat comparison between observation (dark) and Noah result (red) with default run. The 4th one is the latent heat comparison between observation (dark) and Noah result (red) with irrigation scheme run.

Fig. 4a is the surface sensible heat and latent heat flux comparison between observation and Noah model results without/with irrigation scheme integrated in at Maize, Nebraska. This figure indicates the adding irrigation scheme in Noah can improve sensible heat as well as latent heat during the warm irrigation season, the periods where the brown double arrows point in the figure.

The model overestimates latent heat and underestimates sensible heat flux at snow melting season, where the green arrows point. This model deficiency is not the main object of the project and will be discussed later.

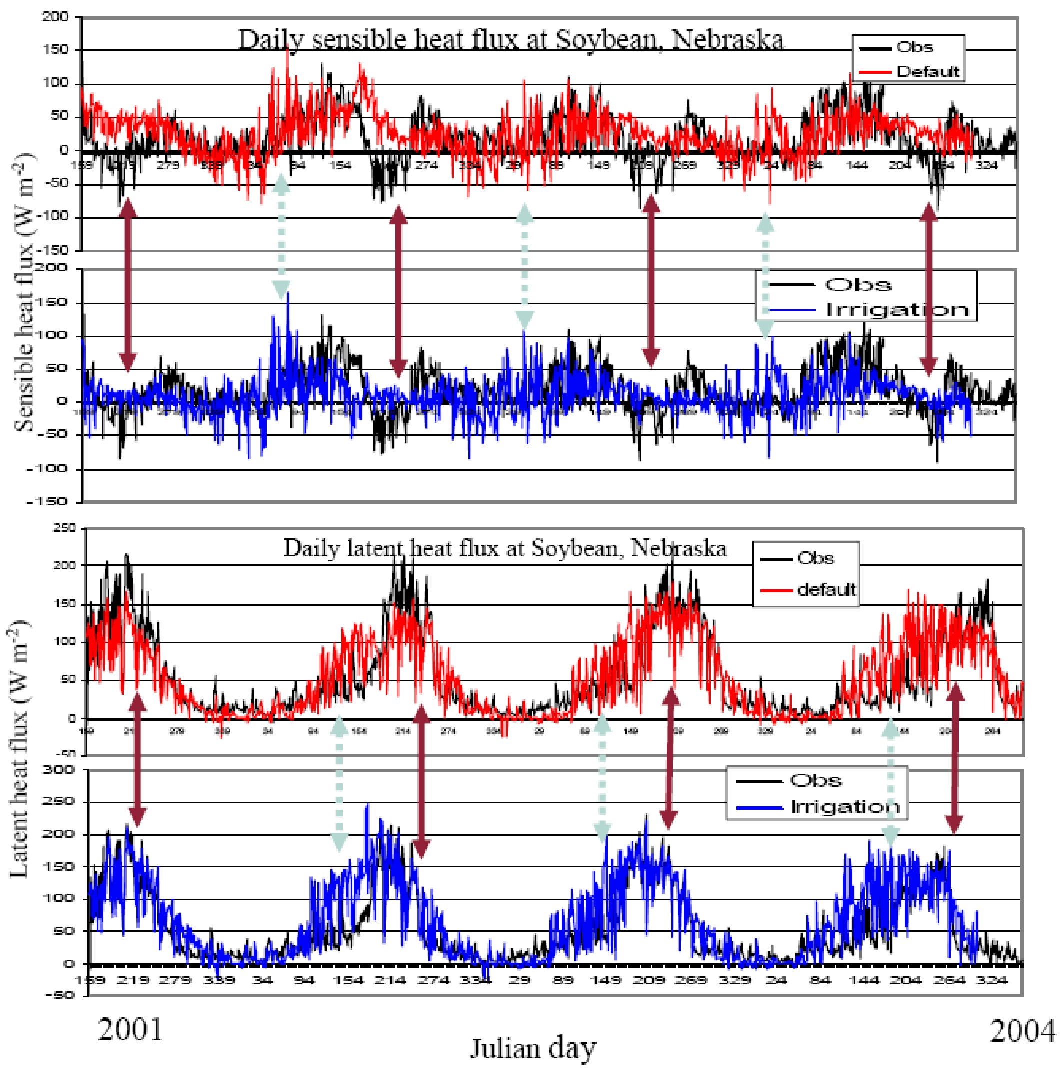


Fig.4b: The same as Fig.4a but for Soybean (41,16°N, 96.47°W) Ameriflux site in Nebraska.

Fig. 4b is surface flux comparison in another Ameriflux site, Nebraska. And the result is the same as Fig. 4a. Model has consistently improved both surface sensible heat and latent heat during the irrigation period.

From this test, we can conclude that: (1) the irrigation scheme to be used in California real time irrigation can be applied to other place; (2) The modification of Noah LSM for irrigation process is successful in some extents.

3.2. Assimilating In situ and remote-sensing data into land surface model

We tested another way to improve soil moisture then improving understanding the effect of soil moisture on weather and climate. We have using Sequential Monte Carlo method to assimilate remote-sensing and In situ data into Noah LSM.

3.2.1 Assimilating In situ soil moisture and remote-sensing soil moisture to into Noah improve surface flux at Ameriflux sites in California

We know that the EnKF is capable of providing uncertainty estimation through ensemble members meanwhile prevent from using Jacobian matrix to calculate state innovation and update. EnKF calculates Kalman gain through the ensemble member and use the calculated gain to update all ensemble members through the newly available measurement. Similarly, the use of Sequential Monte Carlo (SMC) sampling techniques in the process analysis is another progress that can apply data assimilation method to the nonlinear and non-Gaussian process. The SMC filters have been shown to be very powerful and flexible for assimilating data in numerical model predictions. As partly supported by this project, we have assimilated soil moisture into Noah LSM using SMC. We selected Varia and Tonzi Ameriflux sites (see Fig.1) as examples.

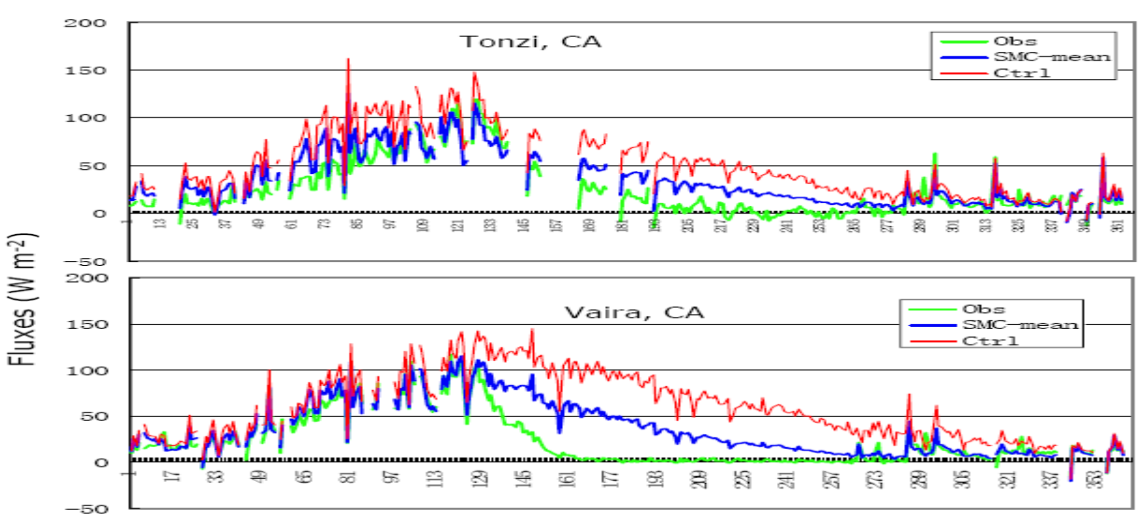


Fig. 5: Latent heat flux comparison between Observation (green) and model control run (red) and the sample mean (blue) with using Sequential Monte Carlo (SMC) method. The forcing data are combined NLDAS forcing and Amerflux observation. The runs begin Jan. 1, 2006 to May 30, 2008. The date shown in the Figures is from Jan. 1 to Dec. 31, 2007.

Fig 5 is the surface latent heat flux comparison between observation model result with and without SMC assimilation. Fig.5 indicates that assimilating In situ soil moisture into Noah LSM can slightly improve model latent heat flux. However, the biases in the two sites are apparent, especially during the transient period. Sensible heat flux at the 2 sites is also checked. The results indicate that it is improved in Vaira Ranch (38.4067°N, 120.9507°W); it is no significant change in Tonzi Ranch (38.4316oN, 120.966°W). We also applied the SMC method to two Ameriflux sites (Audubon-31.59°N, 110.51°W; Santa Rita Mesquite-31.82°N, 110.87°W) in Southern Arizona. The results are similar, which means the improvement is very limited. We have analyzed the results and found that observed soil moisture is very small most of the time it is recorded as close to 0, which is smaller than the model defined wilt-point value. If this case happens, the model will automatically reset the soil moisture to the wilt-point. This process is more like a irrigation. Although transpiration does not occur when soil moisture is equal to wilt-point, the evaporation scheme in model still works, which cause model the overestimate to the latent heat flux.

We have tried to assimilate 25-km resolution remote-sensing soil moisture (to be downloaded from http://www.falw.vu/~jeur/lprm/) into Noah LSM to examine whether the surface fluxes can be improved. Unfortunately, we found that the result from remote-sensing data assimilation is even worse than that from In situ data assimilation, to all the 4 sites. Remote-sensing data resolution can be another reason that causes a little gain using assimilation method.

To prove the concept that soil moisture data assimilation can not be performed in the dry area where soil moisture is close to or even lower than wilt-point, we have performed data assimilation in the SNOTEL station (See Fig.1) where soil moisture is above wilt point. We still use SMC assimilation method. Unfortunately, at SNOTEL, no surface flux is observed but the profiles of soil moisture and temperature are measured.

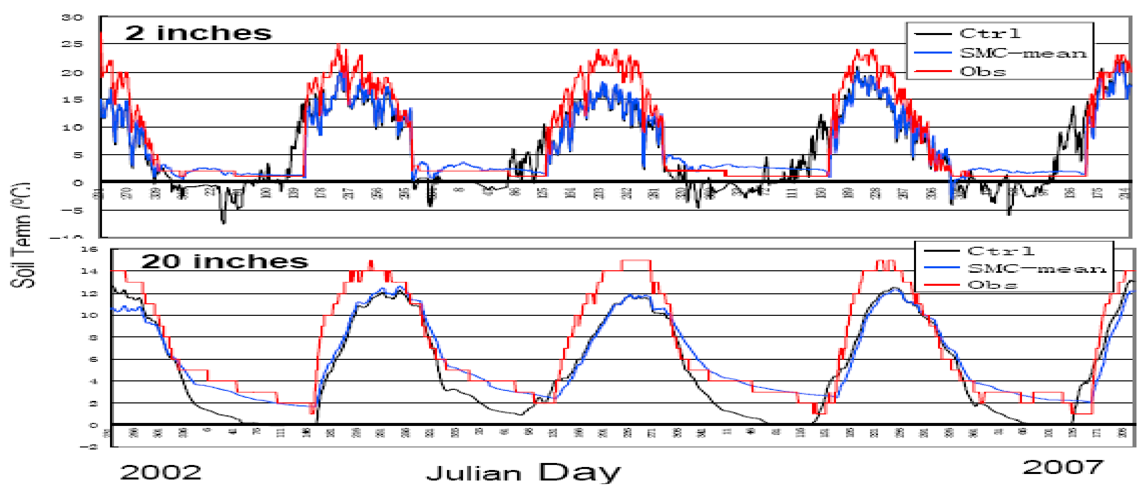


Fig. 6: SNOTEL ID 463 soil temperature comparison between observation (red) and model results with (blue; and sample mean) and without (black) SCA assimilation.

Fig. 6 is the example of soil temperature comparison at 2 inches and 20 inches at SNOTEL ID463 (36.85N, 120.08W) when MODIS Snow Cover Area (SCA) is assimilated into Noah. Fig. 6 indicates that assimilation snow information into Noah can improve soil temperature at different depth, especially during the cold season. However, during the warm season (snow-free season) there is not improvement at al, which hints us that we need assimilate some other measurable field into Noah to improve the soil profiles.

Figs. 7a and b show the soil profiles of moisture and temperature when Snow water equivalent(SWE) is assimilated into (when SWE is available) and 2-inch soil moisture is assimilated into Noah (when no snow cover). The results indicate that SMC works very well at this site (SNOTEL ID 518) both for soil moisture and soil temperature.

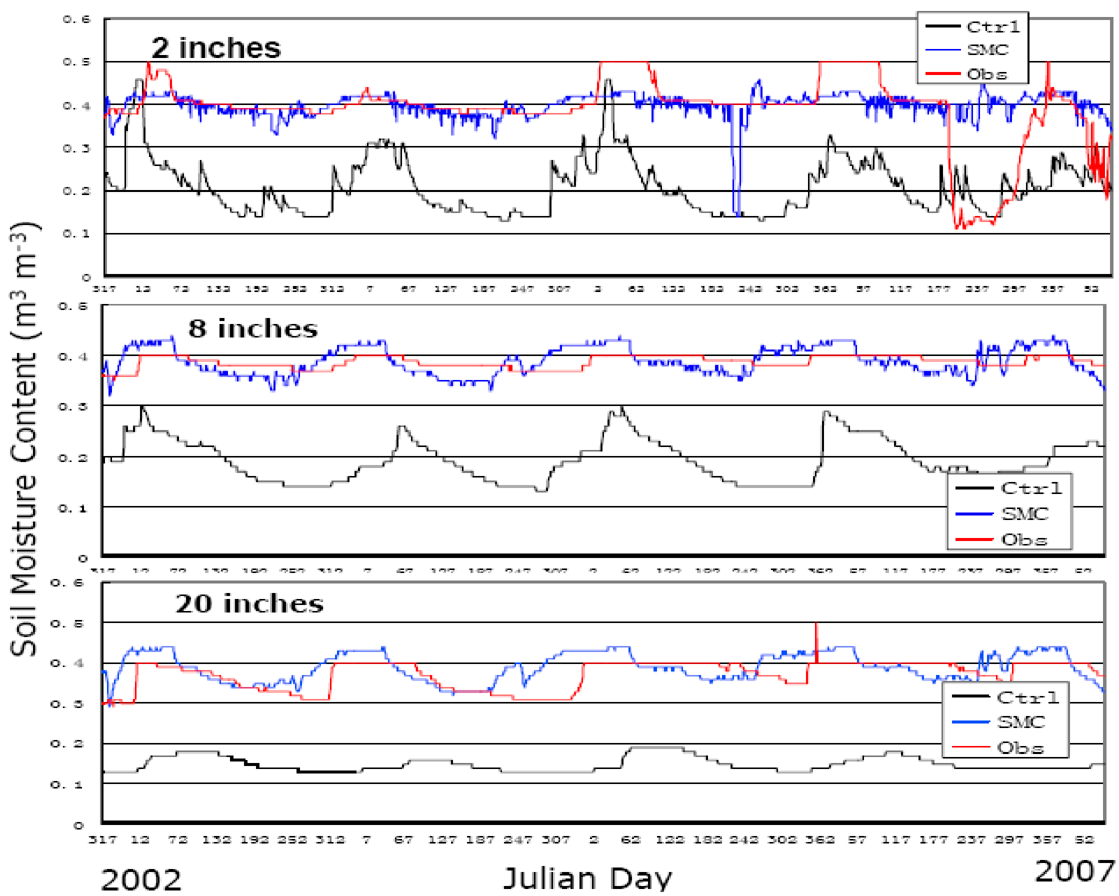


Fig. 7a: soil moisture comparison at different depths between observation (red) and model outputs with (blue, and sample mean) and without SMC assimilation.

Fig. 7a indicates that without data assimilation the model generates very low soil moisture although the model can somehow reproduce the soil moisture trend. Through assimilation, the model can generate the trend; at the same time, the model can improve the moisture in magnitude also.

Fig. 7b shows the soil temperature comparison with different depths between observation (red) and model outputs with (blue, sample mean) and without (black) data assimilation. We can see that soil temperature with data assimilation at different level is improved in comparison with observation although the biases are still there in comparison with observation.

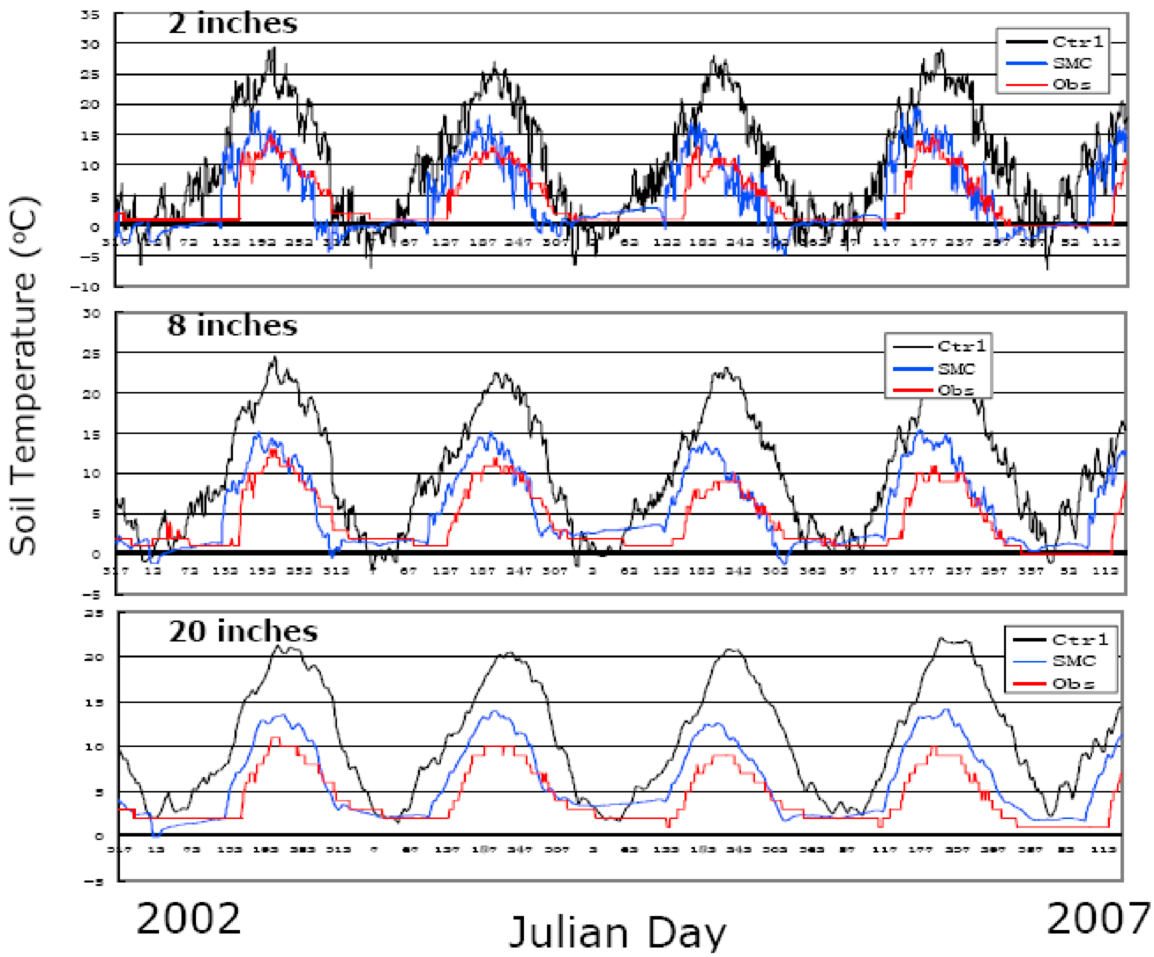


Fig. 7b: The same as Fig. 7a but for soil temperature.

We have performed the data assimilation using SMC technique in all other SNOTEL stations similar to that of Fig.7. However, analysis finds that not all of the stations have improvement in depth soil layers, which seems depending on soil type.

In the soil assimilation study, we notice that high-resolution and high quality remote-sensing soil moisture is helpful. Thus, following we mainly present the results through physical modification.

3.3. Result from Coupled modified Noah LSM and MM5

Using the modified Noah, we also have examined for coupling model. The result is consistent with previous results at signs, i.e. irrigation will cause surface local cooling, but something new is found.

In this study, we mainly focus on the Central valley, California. We design that the 4-km resolution domain only covers the Central Valley, nearby mountains and waters. The 12-km resolution covers the western U.S. and the eastern Pacific and 36-km resolution is domain covers western and Central U.S., northern Mexico, southern California and the Eastern Pacific.

To simulate the effect of irrigation on regional/local climate, a series of runs are designed (see Fig. 8). We take the year of 2007 as example since this summer was very dry due to below-normal precipitation in the previous winter. All runs are started at 00Z, April 1, 2007 and stopped on 00Z, October 31, 2007. For the control test, we just ran MM5 in the entire period. For the irrigation runs, our design was: after one month of model run, assuming the model irrigation scheme is triggered (i.e. if the irrigation condition is satisfied, the model will automatically add water to the field capacity in the irrigation grid). We also tested integrating MODIS albedo and NDVI into MM5 and sensitivity of model physical schemes on irrigation.

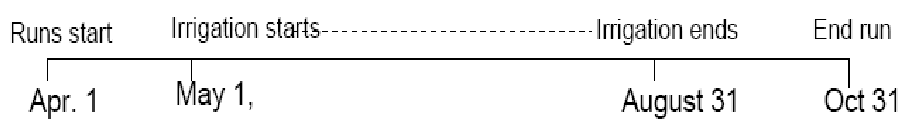


Fig. 8: Model run configuration.

In total, we have 16 runs and here we just summarize some of the results.

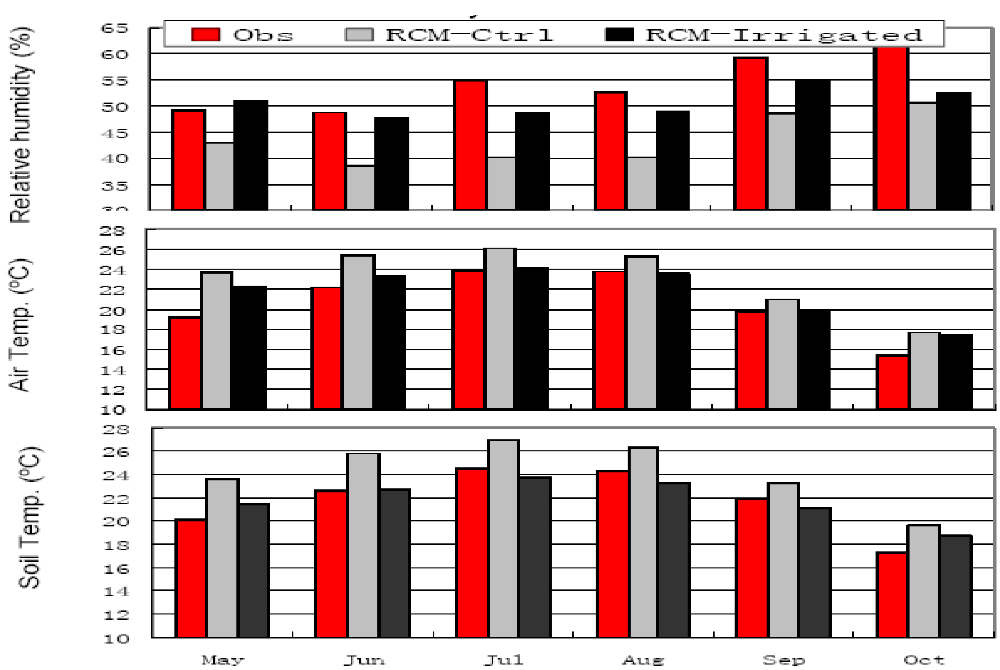


Fig. 9 is the monthly mean comparison between CIMIS observation (red) and with (black) and without (gray) irrigation scheme in the model

Fig. 9 is the comparison between model and observation for the 18 irrigation stations at the monthly mean. In the figure, RCM-ctrl represents data from MM5 default run, RCM-irrigated indicates the data from MM5 output with irrigation process added, and the Obs means CIMIS observations. Clearly that irrigation caused atmosphere cool and wet which is consistent with previous studies. In comparison with CIMIS data, MM5 control-run dry dry and warm biases in the Central Valley. The results from irrigated-run indicate that in May, although 2-m relative humidity is even a little larger than the observation, the temperature has warm bias possibly related to the model spinup issue since model irrigation starts from May. From June to August, the modeled 2-m temperature of the irrigation-run is very close to the observation. Soil temperature is also improved from May to Septempber.
The relative humidity is a slightly lower than the observation. The results from September to October indicate that irrigation causing surface air wet and cool may last about one-month at this study's model configuration.

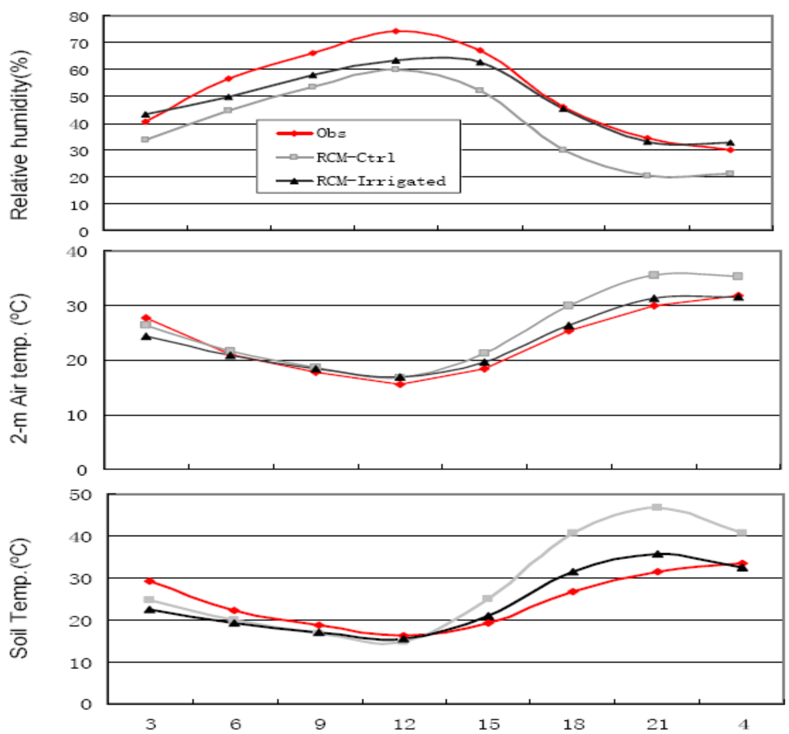


Fig. 10: The comparisons of diurnal cycle between CIMIS data (red), and model output with (black) and without (grey) irrigation scheme in the model.

Fig. 10 is the comparison of diurnal variation of 2-m air temperature, relative humidity and soil temperature. The data are the average from June, July and August. Again, with adding the irrigation scheme, the model result is much closer to the observation, in comparison to the default run. Note that the model results get worse at around 3 UTC. This may be related to adding water abruptly at that period. In irrigation modeling, to avoid irrigation occurs at large solar radiation flux period, that the assumption of solar radiation less than 50W m^{-2} is made when irrigation starts besides matching available soil moisture criteria. At around 3UTC (19PST), that over-irrigation causes high relative humidity and cool surface temperature biases, and results in that the outputs from model irrigation run is worse than those from the control run. The reason that modeled relative humidity is much lower than observation during nighttime is not fully clear. It may be related to the differences of wind fields between observation and model output (see Fig.11). Within the nighttime stable PBL, modeled large wind velocity, relative to observation, favors land surface moisture evaporating from soil horizontal diffusion while observation wind velocity does not.

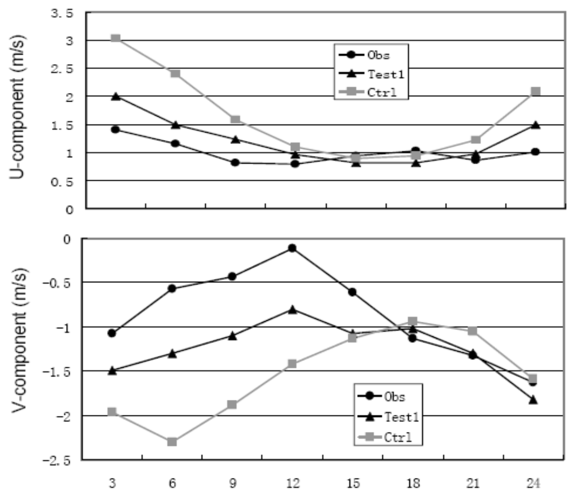


Fig. 11: The same as Fig. 10 but for 10-m wind at U and V direction.

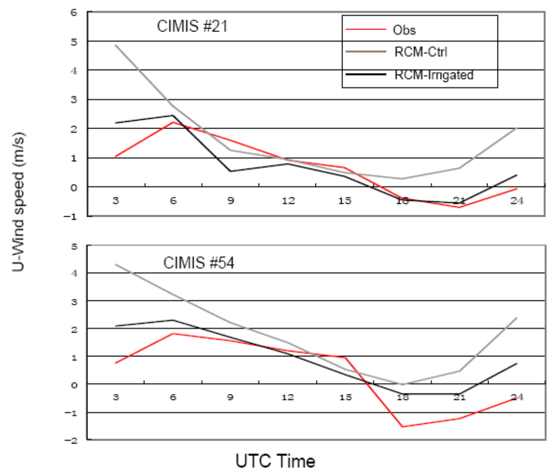


Fig. 12: The same as Fig. 11 for U-component at CIMIS ID #21 (top) and 54 (bottom)

Fig. 12 is the mean wind component variation from June, July and August. There is still a big difference between observation and modeling results although model irrigation run has some improvement in comparison with the observation possibly because of the high localization features of the surface wind fields. The differences reflect the model deficiencies and they are also may be because that the observation is one specific point result while model output is about 4 by 4 km mean. Fig. 12 is the same as Fig. 5 but two specific stations' mean U-component diurnal cycle (CIMIS ID #s, 54, and 21 in San Joaquin Valley). It clearly indicates that adding irrigation process in RCM can improve wind field diurnal cycle.

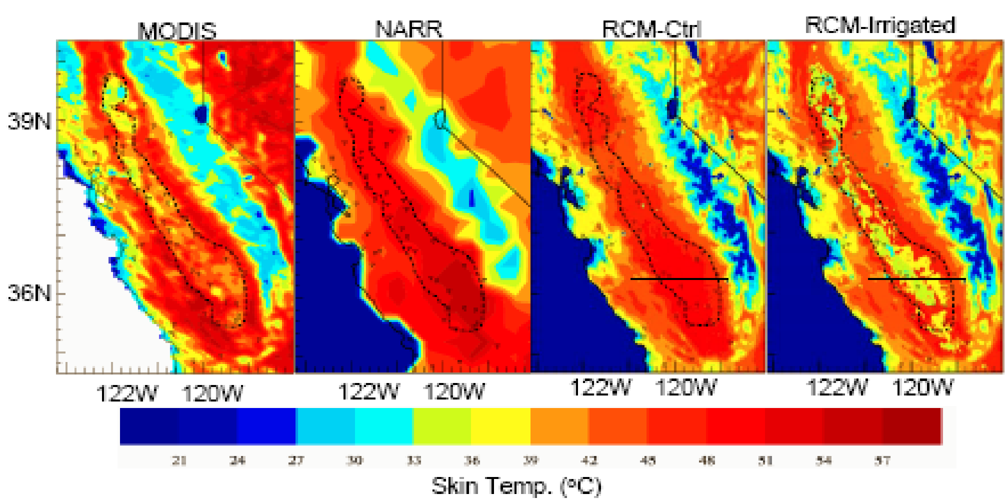


Fig. 13: Skin temperature comparison at 21:00UTC among different sources. Data are averaged from June, July and August. Triangle in the figure indicates the CIMIS stations. The dashed line is the irrigation boundary. The Bold black line will be explained later. MODIS indicates the MODIS skin temperature. NARR indicates skin temperature from NARR output.

Fig. 13 is the comparison of mean surface temperature at 21UTC and remote-sensing skin temperature at 21:30 UTC (13:30 LST). The results from NARR and MM5 control run only show the terrain-caused climate pattern and do not show the irrigation-caused surface temperature variation indicated in the MODIS data. When irrigation process is added in the MM5, the irrigation-caused surface temperature variation is reproduced by the model. Note that in comparing with the MODIS data, MM5 outputs have a cool bias. This bias needs more data to verify. As shown in the top slide of Fig. 4, in comparing with CIMIS 2-m air temperature, both MM5 control run and MM5 irrigation run have warm bias at the time of 21:00UTC. If we take the ground observation is "true", MM5 model surface temperature has warm possibility.

Fig. 14 is the cross-section distribution of the differences temperature and relative humidity between irrigation run and control run. The result indicates that irrigation will cause boundary-layer cool and wet. The highest values could be about 5°C differences in temperature and 5-6 g per kg for mixing ratio.

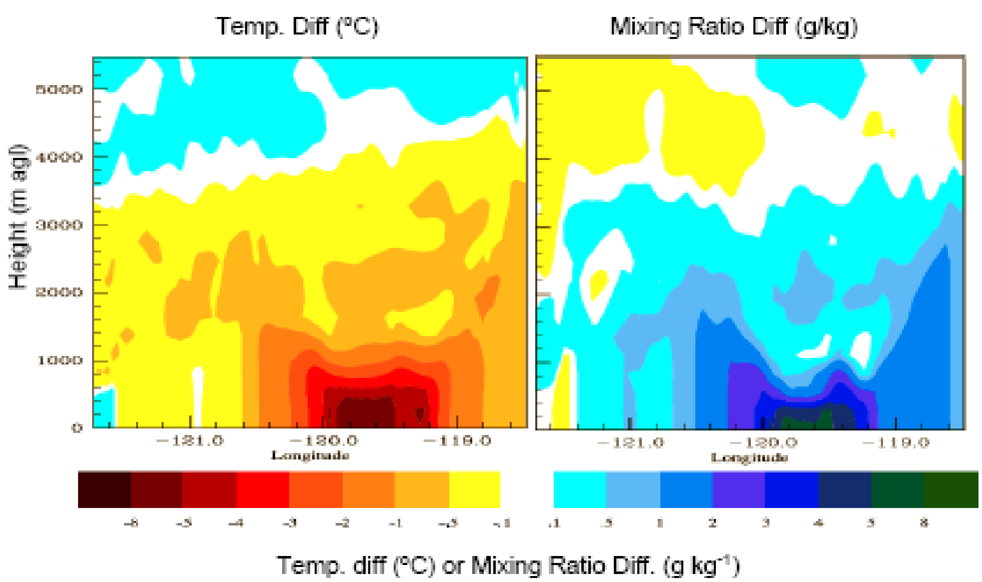


Fig. 14: Cross-section distribution of the difference between irrigation run and control run: left: air temperature (°C), right: relative humidity (%) at 21:00UCT. Data are mean of July 2007. The location of the cross-section is labeled as bold line in previous Figure (Fig. 13)

Above, we have mainly discussed how irrigation affects the weather and climate at local scale and how irrigation impacts the climate in the irrigation areas. To investigate the effect of irrigation on regional scale or on the nearby regions of irrigation area, we have compared the model temperature and observation in these areas.

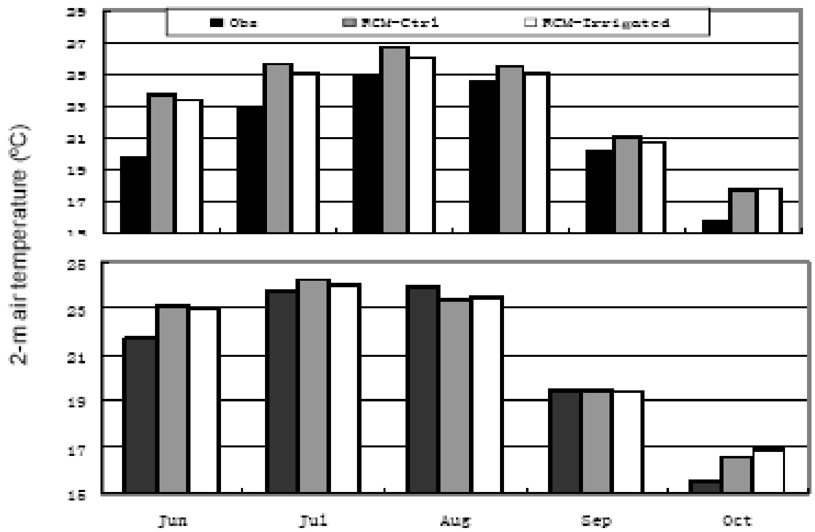


Fig. 15: 2-m monthly mean air temperature comparison between models and observations
Top: between 27 CIMIS stations in Central Valley and model grid closet to the station but not irrigation grid identified.
Bottom: between two Ameriflux sites-Tonzi Ranch(38.4136N,120.966W) and Vaira Ranch (38.4067N,120.9507W) (see Fig.1) and model output closest to the site.

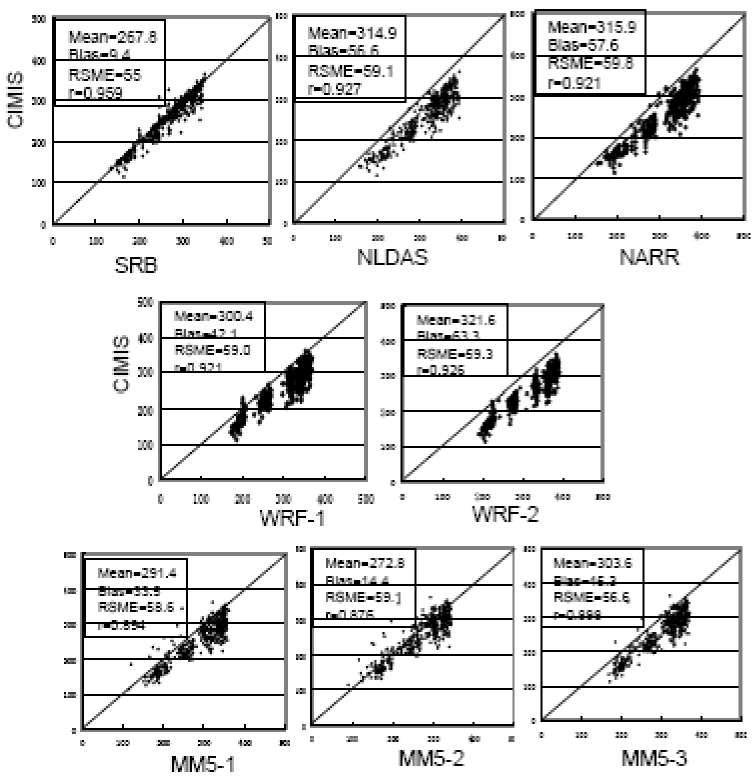
The irrigation-induced cool and wet phenomena can affect in the boundary-layer (Fig.14), and thus may affect the surrounding areas through modifying local and mesoscale circulations. To examine to what extent that irrigation can affect the surrounding region, we also analyzed the surface meteorological fields based on observation and models. Fig.15 is the 2-m temperature comparison. As mentioned in the previous section. In Central Valley, there are 27 CIMIS stations which are irrigation areas in real world but corresponding model grid cells at 4-km resolution are categorized not the irrigation areas. The top in Fig. 9 is the temperature comparison between the 27-station CIMIS observation and model output with/without irrigation at corresponding grid cells. The figure shows that irrigation causes very small cool temperature differences (<1ºC), which means that the effect of irrigation on surrounding region is pretty small at current model configuration. The differences in the top of Fig. 15 between model and observation are due to irrigation in CIMIS data and no irrigation in the model. To further examine this result, the bottom slide of Fig. 9 plots the temperature comparison between two Ameriflux site mean and model output with/without irrigation. The Ameriflux sites are located in the east of the large irrigation areas (<100-km in distance) and is about 50km distance to the closest CIMIS station. The result shows that there is only slight cool during model irrigation while the bias is larger than the model differences between model irrigation run and control run. We also checked the humidity variation and surface wind with/without irrigation in the same place as indicated in Fig.15. The differences between with and without irrigation are also small (Figures not shown). The results indicate that irrigation-induced cool and wet effects mainly occur in local scale. The effect of irrigation on weather and climate at regional scale are small. Previous studies may have overestimated the effect partly due to unrealistic representing the irrigation process or soil moisture.

3.4 Incoming Solar radiation in the irrigation regions

Since CIMIS observed surface incoming solar radiation, we also compared solar radiation in the irrigation areas.

We analyzed the solar radiation differences with and without the irrigation at the same test group, and found there is about 1-5 W m^{-2} differences, Especially in July. However, in comparison with CIMIS observation, all of the model outputs have positive biases and thus it is difficult to make conclusion quantitatively how much solar radiation has been changed due to irrigation.

Fig. 16 is the solar radiation comparison among different sources. In comparison with CIMIS solar radiation, all other solar radiation data overestimated in some extent. In the Figure, SRB indicates the UMD satellite solar radiation; NLDAS indicate NLDAS solar radiation; NARR indicate solar radiation from NARR; WRF-1 and WRF-2 indicate the short-wave radiation output from WRF with 2 different radiation schemes. MM5-1, MM5-2 and MM5-3 indicate the short-wave radiation output from MM5 with 3 different radiation schemes. How irrigation affects solar radiation is still under investigation.



4. Summary and discussion

In this project, the effects of irrigation in Central Valley of California on local/regional climate is investigated by incorporating more realistic irrigation processes suggested by Hanson et al.(2004), into MM5 Noah land surface model. Relative to the results from model default run, the model results with irrigation process indicate that the surface meteorological fields are much improved in comparison with observations from the California Irrigation Management Information System (CIMIS) network. The resulting improvement is especially clear at the daytime when the interaction between land-PBL is active. At nighttime, the model has deficiency in simulating surface wind fields. NARR data have warm and dry biases in the irrigation region of the Central Valley.

With realistic irrigation incorporated into MM5/Noah LSM model, the model can simulate the irrigation-induced local weather and climate features very well at monthly scale in comparison with both ground observation data and remote-sensing data. However, in contrast to previously reported studies, the result from this study indicates that irrigation-caused regional weather and climate feature is not significant. The possible reason is that the previous studies add too much water into soil (usually the root zone soil moisture is prescribed to field capacity or even saturation).

CIMIS network also observes surface solar radiation and 15-cm soil temperature. Our preliminary analysis indicates that MM5 slightly overestimates surface solar radiation even at clear sky, when compared with CIMIS observation. It is also noticed that solar radiation, as well as the other meteorological fields in the model, vary depending on the radiation scheme used.

5. Education and publications

One of our Ph.D. students is funded by the project.

Published papers:

J. Li, S. Sorooshian, W. Higgins, X. Gao, B,. Imam, and K-L Hsu, 2008: Influence of Spatial Resolution on Diurnal Variability During the North American Monsoon. *J. Climate*, **21(16)**, 3967-3988.

J. Li, X. Gao, and S. Sorooshian, 2008: Model performance of downscaling 1999-2004 hydrometerological fields to Upper Rio Grande River basin at different forcing datasets. *J. of Hydrometeor.*, **9(4)**,677-694.

J. Li, 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. Hydrometeor.*, **8**, 805-824.

Conference presentation

J. Li, K. Hsu, and S. Sorooshian: Improving Soil Moisture and Temperature Estimation of NOAH LSM through Assimilation of In-Situ and Remote Sensing Measurements. *AGU Fall meeting,* San Francesco, California, December 13-18, 2009.

J. Li, X. S. Sorooshian**,** and X**.** Gao: The impact of model resolution on rainfall over the Western Mexico. *Mountain Hydroclimate workshop,* Boulder, Colorado, October 13-15, 2007.

S. Sorooshian**, J. Li,** X. Gao, G. Park, and Michael Ek: Improving land surface model to simulate California Irrigated land surface processes. *NASA Energy and Water Cycle Study (NEWS) PI Meeting,* Huntsville, Alabama, September 19-21, 2007.

Papers in review

1) Sorooshian, S and J. Li: How significant is the impact of irrigation on local hydroclimate in California's Central Valley ? submitted in Geophysical Research Letter

2) Li J., B. Imam, X. Gao, K. Hsu, and S. Sorooshian: Comparison of Satellite and Ground-based Observation of Surface Solar Radiation in the California irrigated agricultural regions Submitted into J. Geophys. Res. (atmos.)

Papers in preparation

1) Li, J. et al. Radiation comparison between CIMIS data and model output from different WRF radiation schemes in the Central Valley

2) Li, J. et al. Integrating a realistic irrigation scheme into offline Noah LSM to improve soil hydrology and groundwater recharge estimation in Imperial Valley

3) Li, J. et al. the effect of irrigation on boundary structure and boundary climte