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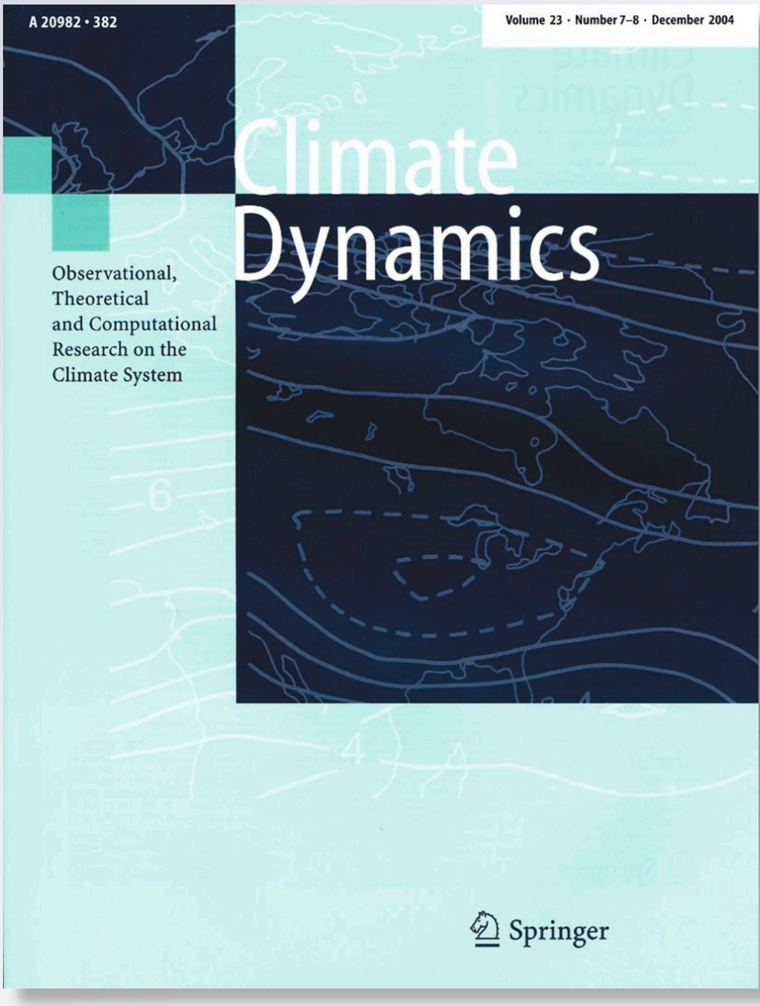

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Influence of irrigated agriculture on diurnal surface energy and water fluxes, surface climate, and atmospheric circulation in California

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Abstract The impact of land use change on regional climate can be substantial but also is variable in space and time. Past observational and modeling work suggests that in a 'Mediterranean' climate such as in California's Central Valley, the impact of irrigated agriculture can be large in the dry season but negligible in the wet season due to seasonal variation in surface energy partitioning. Here we report further analysis of regional climate model simulations showing that diurnal variation in the impact of irrigated agriculture on climate similarly reflects variation in surface energy partitioning, as well as smaller changes in net radiation. With conversion of natural vegetation to irrigated agriculture, statistically significant decreases of 4–8 K at 2 m occurred at midday June–September, and small decreases of ~1 K occurred in winter months only in relatively dry years. This corresponded to reduced sensible heat flux of 100–350 W m^{-2} and increased latent heat fluxes of 200–450 W m^{-2} at the same times and in the same months. We also observed decreases of up to 1,500 m in boundary layer height at midday in summer months, and marginally significant reductions in surface zonal wind speed in July and August at 19:00 PST. The large decrease in daytime temperature due to shifts in energy partitioning overwhelmed any temperature increase related to the reduced zonal sea breeze. Such changes in climate and atmospheric dynamics from conversion to (or away from) irrigated agriculture could have important implications for regional air quality in California's Central Valley.

Keywords Regional climate model · Land use change · Irrigated agriculture · Diurnal cycle · Energy fluxes · Atmospheric circulation

L. M. Kueppers, and M. A. Snyder contributed equally to this work.

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1 Introduction

Anthropogenic land-cover and land-use changes have dramatically altered the earth's surface, with agriculture and pasture land occupying approximately 43 million km^2 or ~34% of Earth's ice-free land area (Ramankutty et al. 2008). Conversion of natural ecosystems to cropland alters the surface roughness of vegetation, albedo, leaf conductance, and other properties that affect exchanges of water and energy between the land surface and atmosphere (Pielke et al. 1998, 2002). As a result, a wide variety of weather and climate changes have likely occurred in many parts of the world (Foley et al. 2005). Cropland management practices including the timing of harvest, tillage practice, and irrigation may also have a significant biophysical impact on the atmosphere (Cooley et al. 2005; Lobell et al. 2006).

Many global modeling studies have investigated the atmospheric impacts of historical or hypothetical land cover change, with results dependent on geographic location and conversion type (Bonan 1997; Feddema et al. 2005a; Snyder et al. 2004; Zhao and Pitman 2002; Bounoua et al. 2002). For example, land cover changes associated with the expansion of agriculture produced net

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global reductions in air temperature of 0.09–0.22°C in an intermediate complexity model, due to the increase in albedo associated with crops (Matthews et al. 2003), while a full complexity model sensitivity study yielded very little near-surface air temperature change (+0.05°C) with conversion to cropland due to regional differences in the sign of temperature change largely canceling each other (Chase et al. 2000). Several studies have also noted the possibility that land cover change can affect large-scale and regional atmospheric circulations through effects on tropical convection and surface winds (Chase et al. 2000; Zhao and Pitman 2002). Including interactions between future land cover change and greenhouse gas increases is critical for projecting future global climate (Feddema et al. 2005b).

One of the most significant land use changes globally, both in terms of area affected and degree of biophysical alteration, is arguably crop irrigation. Global modeling investigations of cropland management find that irrigation decreases surface air temperatures, increases relative humidity, and changes the temperature profile of the troposphere, with geographic variations in the strength of these effects, but not the sign (Boucher et al. 2004; Lobell et al. 2006; Sacks et al. 2009). The irrigation cooling effect appears to overwhelm or reinforce other biophysical effects from cropland conversions or management, such as changes in leaf area and albedo, in most regions (Lobell et al. 2006). This is probably because irrigation is most widely utilized where growing season rainfall is low or risks of drought are relatively high, leaving surface soils under natural vegetation relatively dry. Thus irrigated soils are 'unnaturally' wet, and a significant source for evapotranspiration during otherwise dry times of the year. However, globally the net cooling effect of irrigation is typically small or nearly zero due to temperature increases in some regions (e.g., due to secondary hydrological and circulation changes) that offset the cooling (Sacks et al. 2009)).

At the regional scale, where summer convective storms occur, conversion of natural vegetation to agriculture can alter both temperature and rainfall through large changes in surface energy balances. In a large portion of south Florida, the draining of once extensive wetlands followed by conversion to agriculture and increases in urban areas, has likely led to increased summer maximum surface air temperatures, decreased minimums, changes in mesoscale circulations, and decreased rainfall (Marshall et al. 2004; Pielke et al. 1999). These changes were attributed to the effects of land cover change on surface energy partitioning between latent and sensible heat, and the importance of the land surface-ocean contrast in generating sea-breeze circulations, which direct convective precipitation. The rainfall changes projected by one numerical model were consistent with observed changes in rainfall over the twentieth century (Marshall et al. 2004).

In a more arid region, conversion of short-grass steppe to irrigated agriculture in the Midwest US had more dramatic effects on growing season surface air temperature, water vapor levels, and precipitation than conversion to dry land crops, although both had detectable influences (Adegoke et al. 2003; Pielke et al. 2007; Stohlgren et al. 1998). Observations and modeling studies suggest that conversion of tall grass prairie to irrigated agriculture in regions to the south and east of the short-grass steppe, has increased rainfall under conditions otherwise suited for thunderstorm formation (Barnston and Schickedanz 1984; Pielke et al. 2007; Segal et al. 1998).

The semi-arid Western US is dominated by irrigated as opposed to rain-fed agriculture. A large fraction of the West's irrigated land lies in California, where 81,000 hectares in 1878 expanded to 3.3 million hectares over the course of the twentieth century (Bonfils and Lobell 2007; USDA 2004). Irrigation water is derived from highly engineered capture and redistribution of snowmelt, and from groundwater, which is recharged by winter and spring runoff from many mountain ranges. In California's 'Mediterranean' climate, precipitation is sparse (near zero) in the hot summer months, and relatively abundant in the cool winter months. Regional climate modeling studies and observational analyses suggest that conversion of natural vegetation to irrigated agriculture in California's Central Valley has decreased mean and maximum 2 m air temperatures in the dry season, with few effects in the winter rainy season, when soils were otherwise wet (Bonfils and Lobell 2007; Kueppers et al. 2007, 2008; Lobell and Bonfils 2008). At seasonal to decadal scales, these effects appear to be large and persistent, and more pronounced in dry than wet years (Kueppers et al. 2007).

The large changes in energy fluxes and temperature seen in past studies raise the question of whether higher frequency variation (e.g., diurnal variation) in the climate fingerprint of irrigated agriculture can be observed, and what the implications of those changes are for atmospheric structure and circulation on a range of timescales. Changes in both temperature and atmospheric dynamics have potentially strong leverage on ground level ozone in areas such as California's Central Valley, which is struggling to meet national air quality standards (US Environmental Protection Agency 2006; San Joaquin Valley Air Pollution Control District 2005). Here we present additional analyses of the regional climate model sensitivity study first reported in Kueppers et al. (2007). We evaluate changes in surface energy and water fluxes on diurnal timescales and report consequences for atmospheric structure and dynamics. We then discuss the relevance of our findings for interpreting and modeling variations in regional air quality. While our simulations included simple parameterizations for urban and suburban land cover, the few scattered pixels

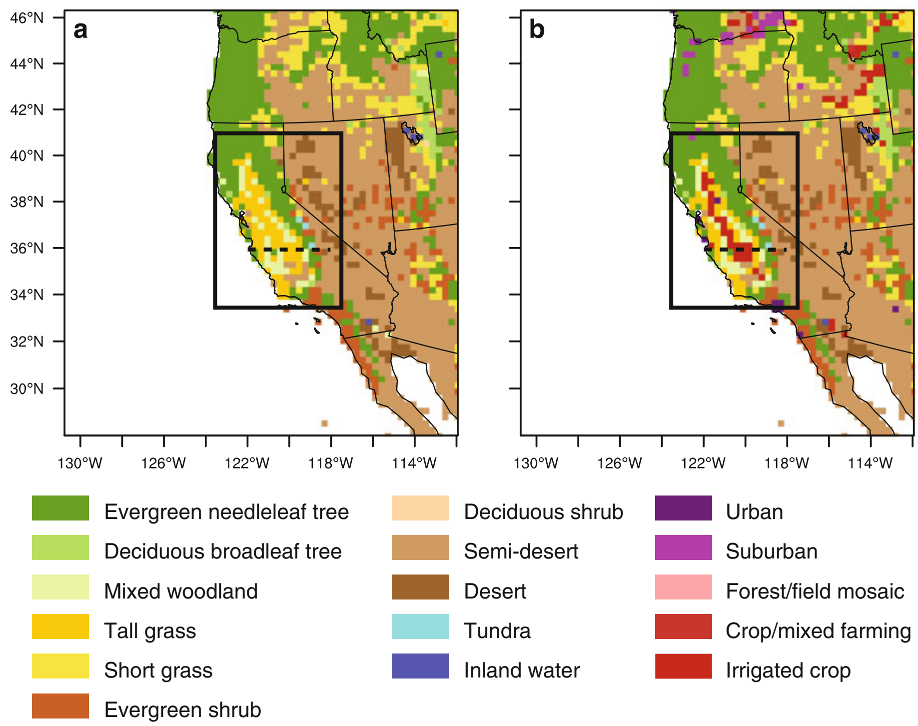

Fig. 1 Full domain and land cover and use as represented in the **a** NAT and **b** MOD model runs. *Black rectangles* bound the California Central Valley subdomain used in analyses. Spatially aggregated differences reported in the text and shown in subsequent figures were calculated using an irrigated crop land-use mask in the subdomain (*red pixels* inside *black rectangle* in panel (**b**)). *Dashed line* indicates position of East–West transect used in Fig. 5

in these land cover classes combined with their negligible climate effects at the regional scale (Kueppers et al. 2008) have led us to focus this analysis on conversion of natural vegetation to irrigated agriculture in California's Central Valley, the largest coherent area of converted land in our Western US domain.

2 Materials and methods

The model simulations are described in Kueppers et al. (2007), but for clarity, we summarize the model configuration and experimental design again here. We used the International Center for Theoretical Physics (ICTP) Regional Climate Model, RegCM3 (Pal et al. 2007), to quantify the climate effects of land use change. RegCM3 is a regional-scale climate model developed from the MM5 mesoscale model. RegCM3 shares the MM5 dynamical core, has the same radiative transfer code as CCM3 (Kiehl et al. 1996), and uses the Biosphere–Atmosphere Transfer Scheme (BATS) land surface model (Dickinson et al. 1993). For these experiments, we configured RegCM3 to use the Grell cumulus scheme (Grell 1993), utilizing the Fritsch and Chappell (1980) closure scheme, and the Holtslag boundary layer scheme (Holtslag and Boville 1993). RegCM has been validated against observations of modern-day climate in the domain studied here and captures dominant climate patterns (Bell et al. 2004; Snyder et al. 2002), although it may have a cool bias in California's Central Valley in summer months (Kueppers et al. 2008).

We performed two 22-year model runs that differ only in the characteristics of the land surface (Fig. 1). One case (MOD) used a modern vegetation distribution (circa 1990) that included both irrigated and non-irrigated agriculture, as well as urban land. We used the 1992–1993 AVHRR-based Global Land Cover Characteristics database, version 2.0 (Loveland et al. 2000), as land cover boundary conditions for the MOD simulation. The second case (NAT) used the potential natural vegetation distribution described in Kueppers et al. (2008), which assigned modern agricultural and urban pixels to natural land cover types based on a nearest-natural-neighbor approach, ensuring consistency with Ramankutty and Foley (1999).

The BATS land surface model represents vegetation as a single layer canopy. Irrigated crops have a relatively low roughness length (0.06 m), low minimum stomatal resistance (45 s m^{-1}), maximum leaf area similar to grassland and forest (6 m^2 m^{-2}), and albedo similar to deciduous broadleaf trees (0.08 in the visible range). To represent irrigation, RegCM3 maintains root zone soil moisture at field capacity at every time step. Thus, irrigated agricultural land is managed to have high water availability at all times of year. While this is an idealized case that likely overestimates the temporal duration of irrigation, in the absence of spatially and temporally explicit data, we believe this to be a useful scenario since much of the study region supports a year round growing season. To test the modeled climate sensitivity to the *amount* of irrigation, we performed an additional series of 3-year model integrations, forcing root zone soil moisture for irrigated crops to

100, 75, 50, and 25% of field capacity year round, plus one 'no irrigation' case. Where there is no irrigation, the land surface model determines soil moisture only as a function of precipitation, evapotranspiration, and soil properties, allowing drainage and runoff.

For both MOD and NAT cases and the suite of irrigation sensitivity studies, we used 30 km horizontal grid spacing, for a domain centered at 37.5N, 121.5W, spanning 28.5°N to 47.0°N and 110.5°W to 132.0°W (Fig. 1). As lateral and ocean surface boundary conditions, we used NCEP/DOE Reanalysis II (Kanamitsu et al. 2002) and National Oceanic and Atmospheric Administration (NOAA) Optimally Interpolated Sea Surface Temperatures (OISST) (Reynolds et al. 2002). We held atmospheric CO_2 constant at 355 ppm. We discarded the first 2 years of the simulations (1979 and 1980) to allow for model equilibration, and report results from January 1981–December 2000. For the 3-year irrigation sensitivity cases, we ran the model using the same domain and lateral boundary conditions as above, but for the period October 1995–September 1998, with the first 2 years discarded and the final year (October 1997–September 1998) analyzed.

For each variable, we compared the MOD and NAT cases using a *t* test at each 3 hourly time step averaged across 20 years (n = 20). We also present results for a relatively wet year, 1998, and a relatively dry year, 1994, to illustrate the importance of interannual variability in climate sensitivity to irrigation. All times are given in local time, Pacific Standard Time (PST).

3 Results

The largest coherent area with significant climate effects from the land cover and land use change was the Central Valley of California, where grassland (NAT case) was converted to irrigated agriculture (MOD case). Thus, the following analysis focuses on this region. All area-averaged differences presented below are means across the red colored grid cells inside the Central Valley subdomain shown in Fig. 1b.

3.1 Surface energy budget and temperature

Under the NAT case, the monthly mean diurnal cycles in net radiation show peak values of 800–1000 W/m^2 from 13:00 to 16:00, May through September (Fig. 2a). Net radiation (Rnet) was 10–30 W m^{-2} lower ($p < 0.05$) under irrigated crops than natural vegetation from 22:00 to 01:00 in August and September, and from 19:00 to 4:00 in July (Fig. 2b). Net longwave (LWN) radiation was 15–50 W m^{-2} lower between 13:00 and 22:00 from June through September ($p < 0.05$), and $\sim$10 W m^{-2} lower at all other times of the day (not significant; Fig. 2c).

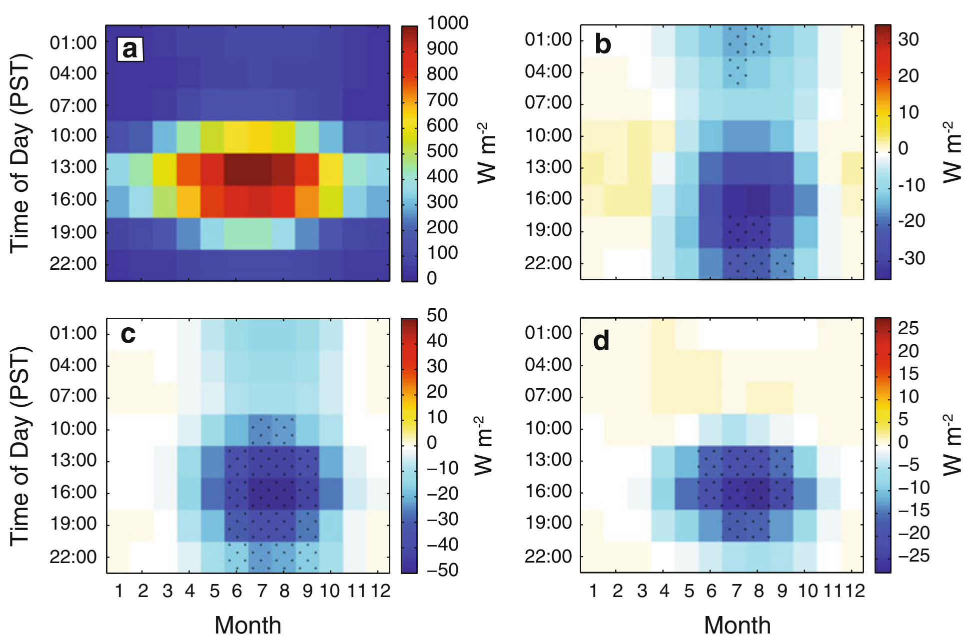

Fig. 2 Diurnal and seasonal cycle of **a** net radiation at the surface (net shortwave plus net longwave) in the NAT case, **b** difference in net radiation between the two cases (MOD-NAT), **c** difference in net longwave radiation between cases, and **d** difference in downwelling longwave radiation between cases. Months are along the *x*-axis, starting in January. Time of day is on the *y*-axis, starting at 01:00 local (PST) time. *Colors* indicate magnitude of flux or flux difference averaged over the 20 years of model run and all Central Valley grid cells irrigated in MOD. Units are W m^{-2}. *Stippled* areas indicate differences that are statistically significant at the 95% confidence level

Reductions in downwelling longwave (LWD) radiation at the surface were a primary driver of the afternoon LWN decline, decreasing by 15–30 W m^{-2} between 13:00 and 16:00 from June through September, reductions of ~8% ($p < 0.05$; Fig. 2d). 10–25 W m^{-2} declines in outgoing longwave radiation with irrigation were more smoothly distributed over the summer diurnal cycle, and were statistically significant from 13:00 to 19:00 in July and August ($p < 0.05$; not shown). Incoming shortwave radiation was not significantly affected by irrigation, with only small reductions (up to 10 W m^{-2} or <2%) between the cases at midday in summer months (not shown). Fractional absorption of incoming radiation was greater with irrigation due to wetter soils and a prescribed crop albedo lower than the grass albedo. However the resulting net shortwave radiation increases with irrigation of up to ~15 W m^{-2} were not statistically significant ($p > 0.19$) at any time of day in any month of the year (not shown). Ultimately, the decrease in incoming long-wave radiation was larger than the increase in absorption, leading to the simulated decline in net radiation.

We simulated even larger diurnal variation in effects of irrigated agriculture on energy partitioning between sensible and latent heat fluxes. NAT case diurnal cycles in sensible (SH) and latent heat flux (LH) showed strong partitioning to SH (Fig. 3a, b). With irrigation, mid-day (10:00–19:00) SH declined by 100–350 W m^{-2} from May through September ($p < 0.05$), while nighttime flux (22:00–04:00) was not affected in any month of the year (Fig. 3c). Conversely, LH increased by 200–450 W m^{-2} between 13:00 and 16:00 from May through September ($p < 0.05$), with smaller increases both earlier and later in the day and in April and October (Fig. 3d). As a consequence of the energy budget changes, 2 m surface air temperatures (T2) decreased by 4–8 K from a NAT baseline of ~298–310 K between 10:00 and 16:00,

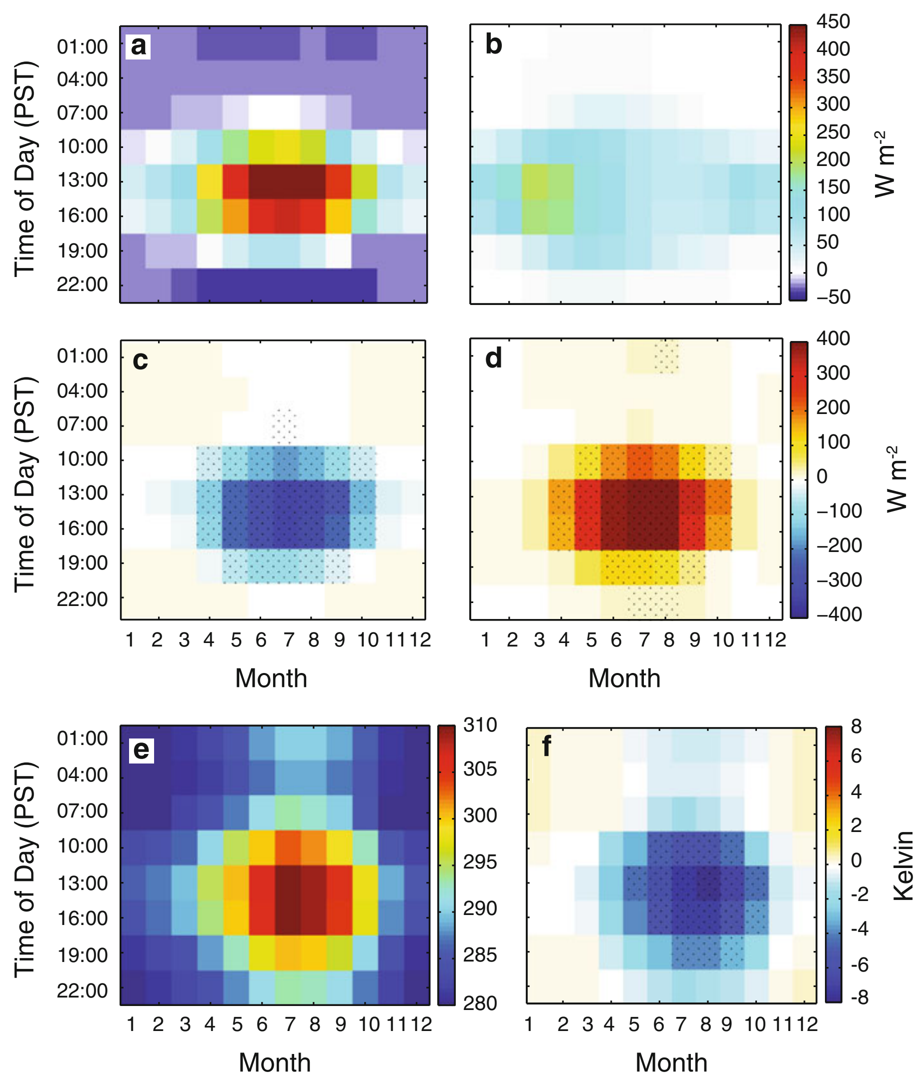

Fig. 3 Diurnal and seasonal cycle of **a** sensible heat flux in the NAT case, **b** latent heat flux in the NAT case, **c** difference in sensible heat flux between the two cases (MOD-NAT), **d** difference in latent heat flux, **e** 2 m temperatures in the NAT case, and **f** difference in 2 m temperature. Format is as in Fig. 2, except units are W m^{-2} for (**a**)–(**d**) and K for (**e**) and (**f**)

June–September ($p < 0.05$), closely mirroring the diurnal pattern of sensible and latent heat flux changes May through September (Fig. 3e, f).

While we found no statistically significant changes in mean energy partitioning in winter and early spring due to irrigation over the full 20 years of the simulations, variability in the magnitude of temperature change in normally wet months was partially related to winter precipitation. For example, January-March mean T2 differences were correlated with January-March total precipitation across years (r = 0.30), and March–April T2 differences were correlated with January–February precipitation (r = 0.49). This is illustrated by the more pronounced January daytime increases in LH, decreases in SH, and decreases in T2 in 1994's relatively dry winter (230 mm in Jan–Feb; Fig. 4a, c, e) compared to 1998's relatively wet winter (756 mm in Jan–Feb; Fig. 4b, d, f). While the influence of winter precipitation could carry forward into summer months, its importance was diminished, and year-to-year variation in summer effect sizes was relatively small, as illustrated by the 180% difference in the January T2 irrigation effect between 1994 and 1998 versus the 6% difference between years in the August T2 effect at 13:00 (Table 1). In sum, conversion to irrigated agriculture in RegCM3 led to small decreases in net radiation due to reductions in downwelling longwave radiation and large decreases in the sensible:latent heat ratio (Bowen ratio), primarily between 13:00 and 16:00 during summer months (May–September). These diurnal energy budget changes substantially reduced T2 during midday-evening in summer months. To a lesser extent, midday temperature decreases with irrigation were also observed in winter and spring months in years with relatively low precipitation.

3.2 Atmospheric structure and dynamics

Mirroring the peak in increased LH with irrigation, and perhaps helping to explain the decrease in downwelling

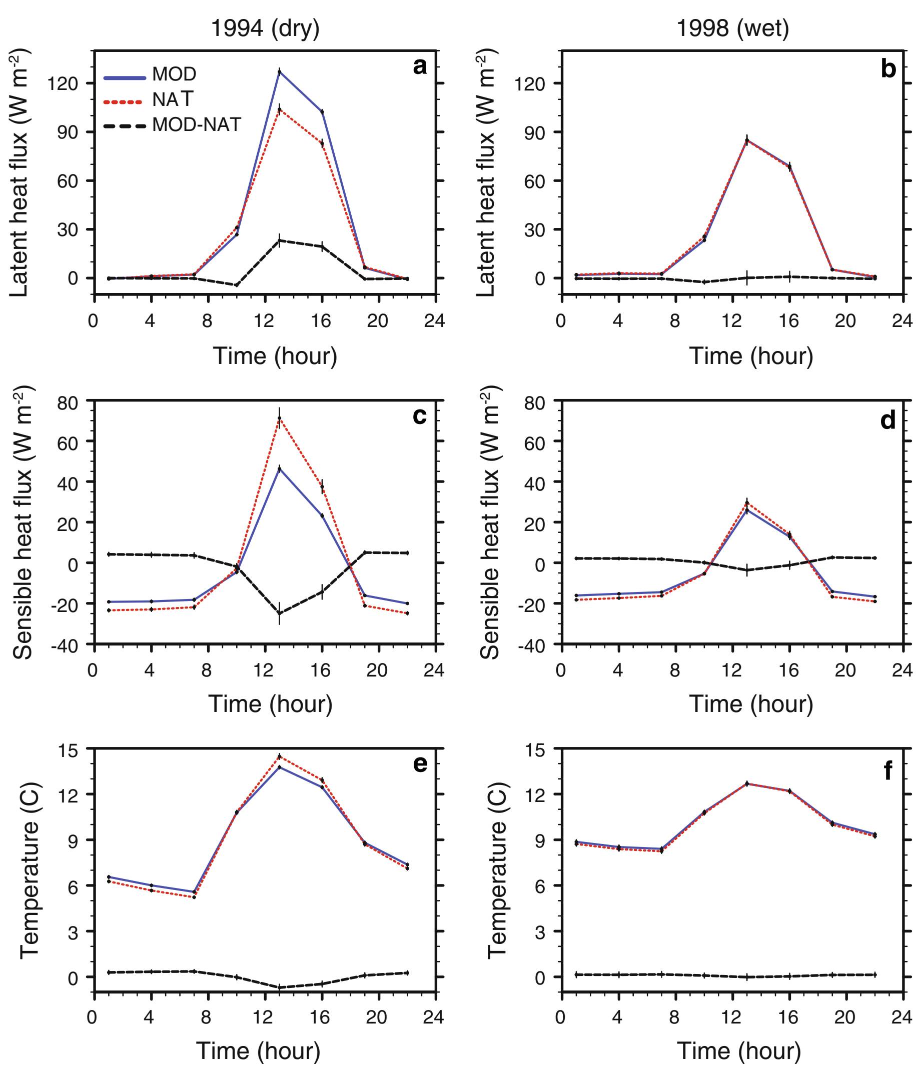

Fig. 4 Area averaged diurnal latent heat flux in **a** January 1994 and **b** January 1998, diurnal sensible heat flux in **c** January 1994 and **d** January 1998, and diurnal 2 m temperature in **e** January 1994 and **f** January 1998 for the two cases and differences (MOD-NAT) between them. Latent heat flux and sensible heat flux are given in W m^{-2} and 2 m temperature is shown in °C. *Error bars* at each time are standard errors of the mean (n = 27 pixels irrigated in subdomain shown in Fig. 1b)

Table 1 Diurnal temperature differences and daily average Bowen ratio differences between MOD and NAT (MOD-NAT) for January and August in a relatively dry (1994) and relatively wet (1998) year

Time of day	January		August	
	1994	1998	1994	1998
	2 m air temperature			
1:00	0.15	0.06	−1.53	−1.06
4:00	0.22	0.06	−1.22	−0.82
7:00	0.27	0.12	−1.80	−1.06
10:00	−0.17	−0.07	−6.32	−5.80
13:00	−0.94	−0.33	−8.39	−7.88
16:00	−0.80	−0.31	−7.82	−7.19
19:00	−0.10	−0.03	−4.79	−3.90
22:00	0.11	0.03	−2.16	−1.58
	Bowen ratio			
Daily	−0.19	−0.10	−5.95	−2.78

Averages are calculated using all grid cells irrigated in MOD. Time of day is given in local time (PST)

longwave radiation at the surface, the mixing ratio of water vapor increased substantially in the lower atmosphere at 13:00 (atmospheric model output was only saved in 6 hourly time increments), and by lesser amounts earlier and later in the day (Fig. 5). The mixing ratio difference was greatest near the surface and confined to heights below 900 mb.

The decrease in T2 and sensible heat flux to the lowest atmospheric layer led to a 1–2 mb increase in surface pressure between 13:00 and 16:00 in July and August ($p < 0.15$; not shown), and a large decrease in planetary boundary layer (PBL) height of up to 1500 m in August at 16:00 h, a reduction of almost 70% from the NAT case (Fig. 6). PBL height was at least 250 m lower from 10:00 to 19:00 h, June through September ($p < 0.05$; Fig. 6). There are few observations of variation in PBL height for comparison, but Zhao et al. (2009) report measurements between 300 and 1750 m at mid-latitude in the Central Valley. In RegCM3, some decrease in PBL height occurred in both wet and dry years (e.g., 1998 and 1994) from April to October, but was not apparent at other times or months in relatively wet years. The afternoon decrease in PBL height was greater overall (up to 1,500 m) in 1994 than in 1998, and small decreases occurred in January, March and November from 13:00–16:00 in 1994 but not in 1998 (Fig. 7).

While the Central Valley receives downslope flow from the Sierra Nevada Mountains at night, the primary mean wind direction in August is from the west or northwest at all times of day (Fig. 8). Heating over land drives this sea-breeze circulation that draws generally cooler, moist air into the Central Valley from over the Pacific Ocean. Under the NAT case in August, mean wind speeds were greatest at 16:00 and 19:00, peaking at 5–7 m s^{-1} (Fig. 8). Winds slackened to less than ~2 m s^{-1} between 01:00 and 13:00. The slight increase in surface pressure with irrigation was sufficient to cause a decrease in the ocean-valley pressure gradient, and a decrease of ~1–2 m s^{-1} in the onshore zonal wind at 19:00 in July and August ($p < 0.13$; Fig. 8).

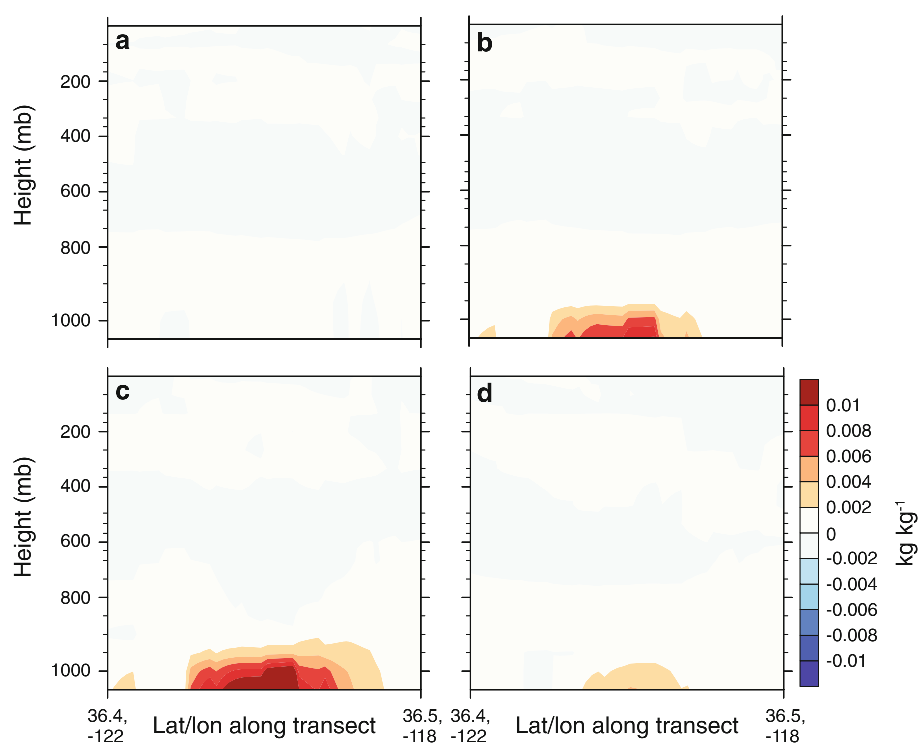

Fig. 5 Water vapor mixing ratio differences between the two cases (MOD-NAT) in August at **a** 01:00 PST, **b** 07:00 PST, **c** 13:00 PST, and **d** 19:00 PST along an East–West transect through a heavily irrigated area of the Central Valley. The location of the transect is shown with the dashed line in Fig. 1. Height along the *y*-axis is given in pressure levels (mb), and colors correspond to mixing ratio values in kg kg^{-1}

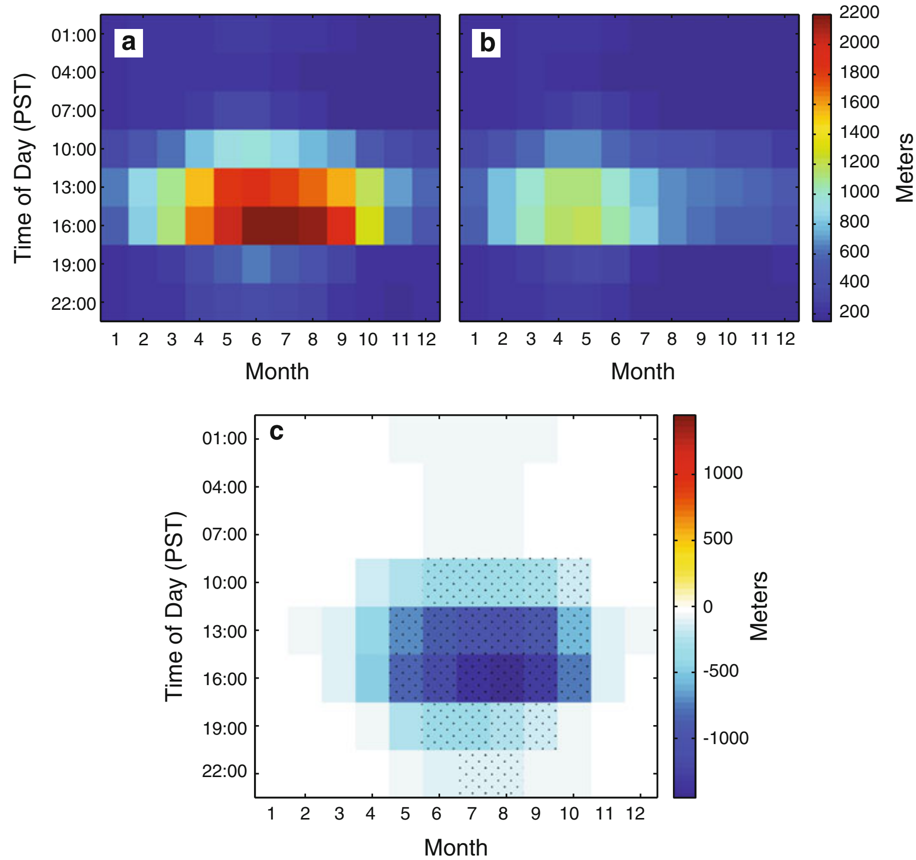

Fig. 6 Diurnal and seasonal variation in planetary boundary layer height in **a** the NAT case, **b** the MOD case, and **c** the difference between the two cases (MOD-NAT). Format is as in Fig. 2, except units are meters

3.3 Atmospheric sensitivity to irrigation amount

Irrigating 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 (Fig. 9). It was only by dropping irrigation to 25% of field capacity that the modeled irrigation cooling effect was reduced by 35 and 10% for July and August maximum temperature, respectively (−1.9°C vs. −3.0°C, and −3.7°C vs. −4.1°C). The temperature effect differences mirrored the changes in sensible and latent heat fluxes (Fig. 9), suggesting that in RegCM3, energy partitioning is only sensitive to changes in soil moisture at the dry end of the spectrum. This additional sensitivity test was performed with lateral boundary conditions from a relatively wet year (1997–1998), when the overall effect was somewhat smaller than in other years.

4 Discussion and conclusions

4.1 Diurnal variation in temperature change mirrors variation in surface energy fluxes

While conversion to irrigated agriculture was not isolated from other land use changes in our experimental design, it had an overwhelmingly dominant effect on local and regional climate in the California portion of the domain, when compared to urban and suburban land use (Kueppers et al. 2007, 2008). Diurnal patterns in the irrigation cooling effect in California's agricultural regions were a direct consequence of changes in the surface energy budget, with the most pronounced effects occurring during mid-day in summer months when incoming radiation was at its diurnal and seasonal peak, and soils were dry under natural conditions. In wet years, when soil moisture was relatively high later into the summer, the difference between climate in a natural landscape and one transformed to irrigated agriculture was slightly smaller but still pronounced. This is because California receives very little precipitation in the summer months, as is typical for 'Mediterranean' climate regimes, meaning the natural and modern land surface still differ considerably in soil moisture even in relatively wet years. The direct decrease in daytime T2 due to shifts in energy partitioning counteracted any indirect temperature change related to a change in the winds. The simulated decrease in sensible heat flux and surface temperature resulted in a slight increase in surface pressure, which in turn decreased the pressure gradient between the irrigated region and the nearby ocean, resulting in a slight weakening of the onshore winds. As a result, we simulated less

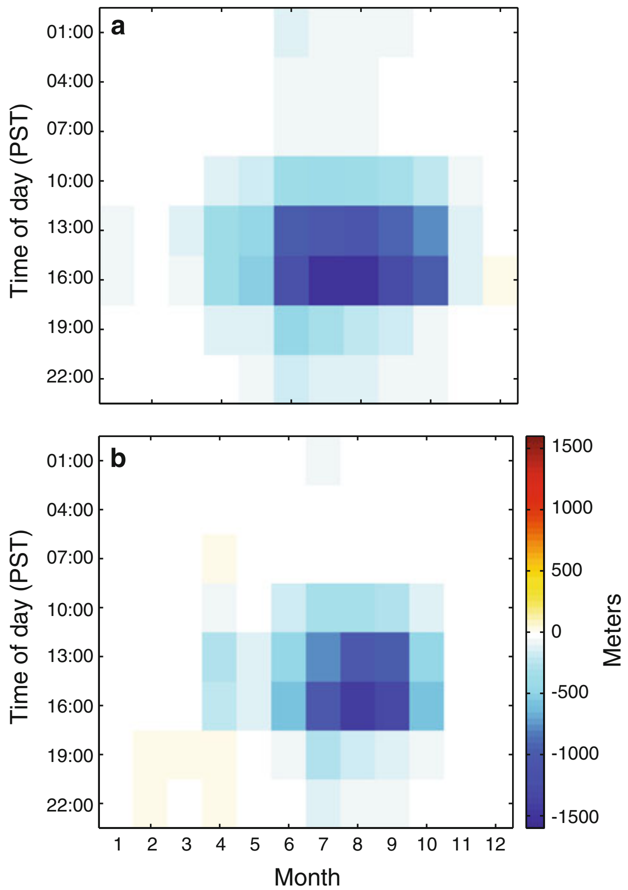

Fig. 7 Diurnal and seasonal variation in planetary boundary layer height difference between the two cases (MOD-NAT) in **a** 1994, a relatively dry winter, and **b** 1998, a relatively wet winter. Format is as in Fig. 2, except units are meters

transport of cooler coastal air into the Central Valley. This would tend to raise temperatures, while our results showed only strong cooling as a result of irrigation.

We found no evidence in our model simulations for significant nighttime warming associated with irrigation, a mechanism proposed to explain increases in minimum temperatures over time in Central Valley temperature records (Christy et al. 2006). While we found slight, but non-significant, increases in nighttime sensible heat flux in winter (Fig. 3c), and significant decreases in boundary layer height at 22:00 in July and August (Fig. 6), neither change translated into statistically significant nighttime temperature increases in irrigated areas at any time of year over our 20 year experiments (Fig. 3f). In fact, we found slight (non-significant) *decreases* in summer nighttime temperatures that corresponded with significant decreases in nighttime net radiation, due to reductions in net long-wave radiation (Fig. 2). Thus, we conclude that observed increases in minimum temperatures throughout the year in this region are not due to irrigation, but are likely due to other causes such as urbanization in the proximity of weather stations (Lobell and Bonfils 2008), or aerosol and greenhouse gas increases (Bonfils and Lobell 2007).

Consistent with studies of dynamic atmospheric responses to irrigated agriculture elsewhere, such as in the Indian summer monsoon region (Lee et al. 2009), we found that irrigated agriculture altered the land-sea pressure gradient. However, while we found that irrigation has consequently reduced late afternoon and early evening surface winds, and reduced boundary layer height, we

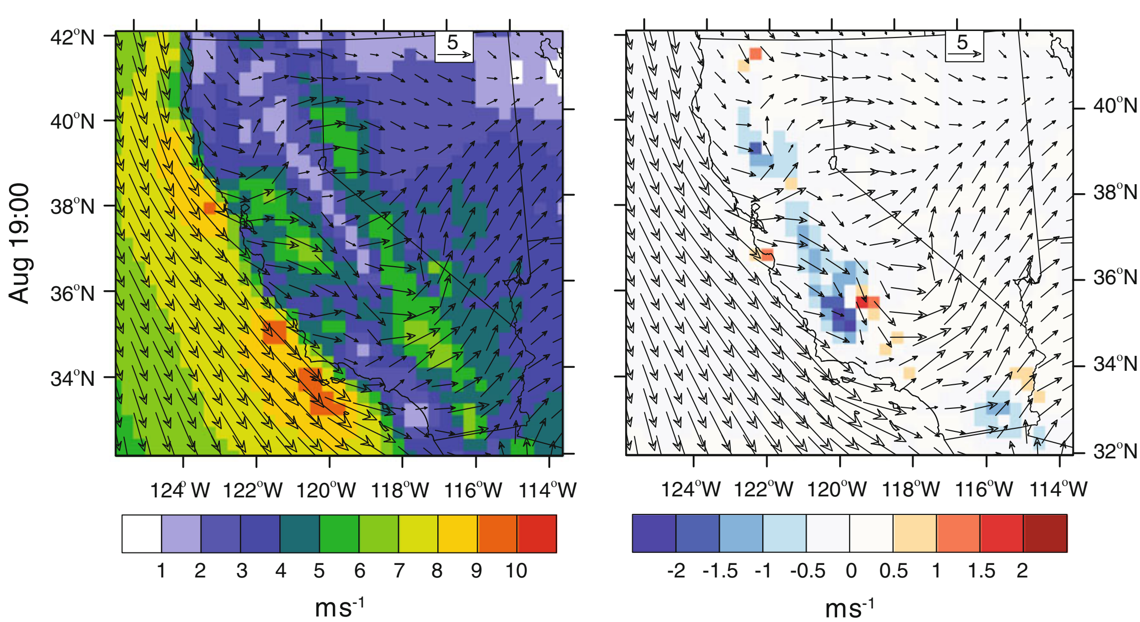

Fig. 8 20-year average August wind speed and direction at 10 m above the surface for **a** the NAT case and **b** the difference between the two cases (MOD-NAT) at 19:00 PST. Wind vectors in (**b**) are for the MOD case. *Color bars* and wind vector lengths give wind speed in m s^{-1}

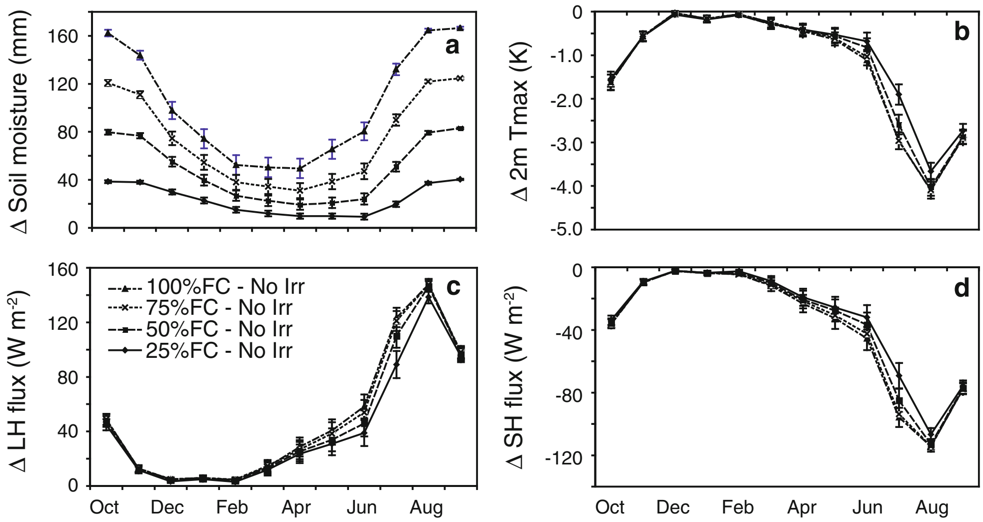

Fig. 9 Monthly differences in **a** soil moisture, **b** maximum 2 m surface air temperature, **c** latent heat flux, and **d** sensible heat flux between 1-year simulations at varying irrigation levels ranging from no irrigation (No Irr) to full field capacity (100% FC), as described in the text

found no effect of irrigation on precipitation. The Midwestern US, Florida, and India, where irrigation has likely led to changes in summer precipitation as well as temperature (Pielke et al. 2007; Lee et al. 2009), thus differ from California, where the very low incidence of summer convective storms means less opportunity for an irrigation effect on summer rainfall. Large-scale storm systems from over the Pacific Ocean dominate winter precipitation, also minimizing the role of the land surface in winter precipitation. In fact, neither total nor convective precipitation differed significantly between the NAT and MOD cases at any time of year. This highlights the fact that the climatic setting preconditions the regional response of climate to land use change, even for a relatively dramatic land surface changes such as the widespread addition of irrigation (Lobell et al. 2009).

4.2 Comparing RegCM3 irrigation effects to other models and observations

In comparison with other RCMs conducting similar, but shorter duration experiments (Kueppers et al. 2008; Jacobson 2008; Sorooshian et al. 2011), RegCM3's shift in energy partitioning in response to irrigation led to large temperature changes. Are evapotranspiration rates and 2 m temperature changes in response to irrigation realistic in RegCM3? Where we specified irrigated crops as the land cover type, 100% of the vegetation was irrigated crop over a 30 × 30 km pixel. Further, by supplementing soil water at every time step in the model, soils did not dry down, but were always at their maximum wetness (field capacity), such that evapotranspiration could take place at or near its potential rate year round. While these model assumptions of 100% coverage of irrigated crop and continuous, year round irrigation to field capacity were spatial and temporal overestimates, RegCM3 appears to produce reasonable estimates for evapotranspiration when compared to field-based reference values, which are indicative of evaporative potentials. Averaged over all Central Valley irrigated grid cells and 20 simulated years, RegCM3 evapotranspiration ranged from 25 mm in December to 210 mm in July. Reference evapotranspiration estimated over well-watered grass using meteorological variables and a modified Penman model ranged from 27 mm in December to 213 mm in July averaged over 30 San Joaquin Valley stations (California Irrigation Management Information System—CIMIS—data available online at http://www.cimis.water.ca.gov). This indicates that RegCM3 captures the relationship between available soil water and evapotranspiration quite well for well-watered crops.

Does the simulated increase in evapotranspiration, and therefore latent heat flux, lead to a reasonable estimate of temperature change? While RegCM3 appears to have higher temperature sensitivity to full irrigation than some other models, it seems to have a temperature sensitivity to 100% irrigation within the range of current observations (Lobell and Bonfils 2008). In a direct comparison with the Davis Regional Climate Model (DRCM), which applied water episodically through the growing season to mimic fluctuations in soil water, DRCM had latent heat fluxes nearly identical to those in RegCM3 for the Central Valley during the months when soil moisture was the same (August and September), but nearly half the change in maximum temperatures (Kueppers et al. 2008). Yet, extrapolating from historical observations, Lobell and Bonfils (2008) estimated that conversion to 100% cover by irrigated agriculture would lead to an average 5.0°C decrease in daily maximum temperature (with a 95% confidence interval of 2.0–7.9°C) averaged over summer months in California. This estimate agrees surprisingly well with our results showing peak midday cooling of 4–8°C June through August (Fig. 3f). In contrast to those observations, which show a cooling effect only in spring (MAM) and summer (JJA), RegCM3 produced statistically significant cooling May through October. This is likely due to the fact that RegCM3 did not capture the diminished irrigation following harvest of row crops in August and September. Consistent with other climate models (Lobell et al. 2009), RegCM3's temperature sensitivity to irrigation was only substantially reduced when irrigation amount was reduced to 25% of field capacity (Fig. 9), a model feature that can't be validated with currently available observations. Future simulations that more accurately represent temporal variation crop management and extent of irrigated agriculture on the landscape will likely yield temperature responses more closely matched to observed temperature variation. For example, a recent study in the Central Valley of California found a smaller cooling effect when using higher spatial resolution (4 km vs. 36 km), and therefore a more accurate extent of irrigated area (Sorooshian et al. 2011). In addition, more extensive joint observations of soil moisture, 2 m temperature, and energy fluxes established under varying irrigation regimes would aid in accurately quantifying the climate effects of land use change and support better model parameterizations.

4.3 Implications of irrigation effects on climate and atmospheric dynamics for air quality

Changes in land use can both directly and, via effects on climate and atmospheric circulation, indirectly affect air quality. Increased temperatures in August led to increased ozone concentrations in this region in one study, particularly near areas with high anthropogenic emissions (Steiner et al. 2006), suggesting that decreased temperatures resulting from irrigation could be holding down ozone concentrations. However, the temperature-ozone relationship is nonlinear such that on days with temperatures between 295 and 310 K the slope is $\sim$2–3 ppb K^{-1}, but on days with the highest temperatures (>312 K), ozone concentrations may not change much with temperature or could even increase with slight cooling (Steiner et al. 2010). Land use induced changes in boundary layer height and circulation patterns may also increase ground-level ozone concentrations via concentration in a shallower boundary layer and stagnation of circulations that bring clean air from over the Pacific Ocean into the Central Valley, an effect seen in short-term atmospheric chemistry simulations by Jacobson (2008). Increases in absolute humidity resulting from irrigation may also influence ozone concentrations, although the availability of NOx likely determines whether ozone increases or decreases as a consequence (Steiner et al. 2006).

While current land use in the Central Valley is dominated by irrigated agriculture, upward trends in urban and suburban development have been reducing irrigated cropland area locally, and are projected to continue (Theobald 2005). As a consequence, temperatures would be expected to rise locally as irrigation extent is diminished and due to the urban heat island effect (although irrigated urban vegetation may mitigate the change to some degree (Pouyat et al. 2007; Pataki et al. 2011). Rising greenhouse gas concentrations and additional sources for ozone precursors that come with urbanization could exacerbate reductions in irrigated cropland, further pushing up temperatures and ozone. Deteriorating soil fertility and high salinity in irrigation drainage water in the southwestern part of the Central Valley may also reduce irrigated acreage in coming years (Schoups et al. 2005). On the other hand, the pace of emission control standards will likely lead to significant reductions in ozone by the year 2050 (Steiner et al. 2006). To fully understand the complex influences of land use change and climate on atmospheric chemistry, both additional observations and more fully interactive simulations are required. Since the regional scale climate and atmospheric effects of irrigated agriculture are most pronounced at midday in summer when ozone production is highest and the region shows clear evidence of strong land–atmosphere coupling, large-scale changes in land use may have particularly strong leverage on Central Valley air quality.

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