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4 Impacts of agricultural irrigation on ozone concentrations in the Central Valley of California and
5 in the contiguous United States based on WRF-Chem simulations
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Abstract: In this study, a realistic irrigation method is incorporated into a model called Weather Research and Forecasting with Chemistry (WRF-Chem) to determine the impacts of irrigation on ozone and other pollutants over the Central Valley of California and thereafter throughout the contiguous United States. In comparison with observations, model simulations at current configurations underestimate ozone (O_3) and volatile organic compound (VOC) concentrations, especially during the elevated episode periods. The model results, however, are generally comparable with previous studies and the simulations adequately capture the spatial and temporal variability of these pollutant concentrations. In comparison with observations and model control runs, model simulations with irrigation runs are slightly improved. Our results show that irrigation increases primary pollutant concentrations in the irrigated areas under cloudless conditions, consistent with previous studies. In July and August, 2005, for instance, with clear skies, irrigation increases hourly surface [CO] up to 40 ppb with an irrigated grid average of 16 ppb or 8.3%; [VOC] up to 10 ppb with an irrigated grid average of 4.6 ppb or 21.4%; and [NO_x] up to 4 ppb with irrigated grid average of 0.72 ppb or 12.6%, especially near urban areas during daytime. On the other hand, irrigation marginally decreases ground-level ozone concentrations ([O₃]) over irrigated land: it decreases hourly [O₃] by -0.14 ppb or -0.45% and decreases daily 8 hr maximum average (DMA8) [O₃] by -0.39 ppb or -0.76%. In contrast, irrigation increases hourly [O₃] up to 5 ppb over the surrounding unirrigated areas of the San Joaquin Valley, during both daytime and nighttime. Furthermore, except for the Pacific Northwest, similar patterns of ozone variation are simulated by the model in other irrigated regions in the continental United States. The explanation is that irrigation results in cooler ground surfaces, which first decreases instability and turbulence, leading to a weakening of the vertical mixing of primary pollutants. Therefore, irrigation increases surface primary pollutant

concentrations within the irrigation zone. Irrigation also results in daytime local circulations that enhance horizontal transport of ozone and other pollutants from irrigated to unirrigated areas near the ground surface. Because our results are based on two months in 2005 and on national anthropogenic emission inventories, the magnitude of these ozone changes could vary somewhat year to year; nonetheless, the methods and results from this study can be applied to any heavily polluted and irrigated agricultural area.

Key Words: Agricultural irrigation, air quality, ozone variation, WRF-Chem simulation

1. Introduction

Land cover and land use changes (LCLUCs) occur because of both environmental changes (such as climate change, wildfires, desertification, etc.) and human activities (such as urbanization, agriculture, reforestation, etc.), and these changes will continue (Pielke Sr, et al. 2011). One of the LCLUCs is the conversion from natural land to agricultural irrigated land. In the United States (U.S.), for example, there are 61.1 million acres of irrigated land in 2005 (about 5.5% of total agricultural land) which consume 128,000 million gallons of water per day (<http://water.usgs.gov/edu/wuir.html>). As one of the world's most productive agricultural regions, the Central Valley of California has less than 1 percent of the total farmland in the United States, but produces over 10 percent of the nation's agricultural output by value. Altogether the Central Valley has about 10.2 million acres of irrigated land, half in the San Joaquin Valley. Irrigation, especially in the San Joaquin Valley, occur year-round depending on weather and crop types (Hanson et al., 2004) and consumes 80% of the water supply. The

impacts of agricultural irrigation on weather, climate and hydrology have been widely investigated in the Central Valley and other regions of the U.S. (e.g., Kueppers et al., 2008; Lobell et al. 2009; Sorooshian et al., 2011, 2012, 2014; Lo and Famiglietti, 2013; Pielke Sr., 2007, and the reviews of Mahmood et al., 2014 and the literatures therein).

The consequent question is whether and to what extent large-scale agricultural irrigation impacts air quality, such as ozone and its precursor concentrations? This is especially important for the California's Central Valley, with its 6.5 million residents, with its over 10 million acres of cropland, and with its classification as a severe to extreme non-attainment area for ground-level ozone(<http://www3.epa.gov/ozone/designations/2008standards/final/region9f.htm>). Previous studies indicate that high ground-level ozone concentrations not only adversely affect human health (Anderson 2009, Smith et al., 2009) but also reduce crop yields (Avnery et al., 2011; Chameides et al., 1999; Murphy et al., 1999). Ozone enters leaves through plant stoma during normal gas exchange and damages vegetation by reducing photosynthesis and other important physiological functions, resulting in weaker, stunted plants, inferior crop quality, and decreased yields (Anvery et al., 2011). Improved understanding of ozone variation and its causes in this region is necessary to develop effective air quality management strategies to achieve ever more stringent US air quality standards and prevent diminishing crop yields.

Agricultural irrigation certainly has indirect but consequential effects on air quality. Irrigation, firstly, modifies the meteorological conditions of air pollution. For example, irrigation-induced increases in soil moisture decrease surface air temperatures and the Planetary Boundary Layer (PBL) height (see review in Mahmood et al., 2014). Secondly, irrigation-induced decreases in air temperatures affect photochemical reaction rates (Steiner et al., 2010;

Pusede and Cohen, 2012). Finally, irrigation-induced increases in humidity could enhance the concentrations of hydroxyl radical ([HO]), a strong oxidant and critical compound in the atmospheric photochemical cycle. Among the previous studies, Jacobson (2008) has investigated the effects of agricultural irrigation on air quality in California and found that irrigation decreases air pollution in the presence of clouds and precipitation but that it increases air pollution in their absence. The author has quantitatively shown that agricultural irrigation in eastern Los Angeles increases $PM_{2.5}$ by 2% and ozone by 0.1%, but has not shown the magnitude for other regions, including the Central Valley. Therefore additional work is still “needed to better quantify the effects of agriculture on air quality” (Jacobson, 2008). In his study, the author has used the prescribed soil moisture based on actual irrigation water amounts and a multiple-scale model called GATOR-GCMOM, a one-way nested global-through-urban scale Gas, Aerosol, Transport, Radiation, General Circulation, Mesoscale, and Ocean Model, developed by the author himself. Related research on urban areas has also been conducted with similar results: that irrigation increases average near-surface primary pollutant concentrations (Jacobson, 1999).

In this study, we examine the effects of irrigation on surface ozone and other pollutant concentrations using a public domain, two-way coupled model –Weather Research and Forecasting with Chemistry (WRF-Chem, Grell et al. 2005). Furthermore, by employing statistical metrics, we examine whether WRF-Chem can be specifically used to quantitatively investigate the impacts of agricultural irrigation in the Central Valley of California and the contiguous United States, and to investigate what physical-chemical mechanisms are both important and operative within the model.

2. Methodology

2.1 WRF-Chem setup

Because it has been widely and successfully used in this region (e.g., Joe et al., 2014, Zhang et al., 2014, Li et al. 2015), we chose WRF-Chem (version 3.6.1) as the chemical-transport model. In WRF-Chem, the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008) is employed to resolve atmospheric physics and dynamical processes, while the coupled chemistry (Chem) model is used to simulate chemical processes such as gaseous and aqueous chemical reactions, dispersion, and deposition. WRF-Chem includes multiple physics and chemistry parametrization schemes; many studies have investigated the effects of these different physical/chemical schemes on model results. One of the most popular and contentious discussions is the selection of the PBL scheme (e.g., Cuchiara et al., 2014; Misenis and Zhang, 2010; Hu et al., 2013; and many others). Here, based on previous tests (Sorooshian et al., 2014; Li et al. 2014), on communication with model developers (Steven Peckham, January 2014, personnel communication), and on the WRF-Chem users' guide (Peckham et al., 2015), the modified Mellor-Yamada-Nakanishi-Niino(MYNN) surface layer and PBL schemes are used. In addition to the PBL scheme, the WRF-Chem setup consists of the following modules: the Morrison double-moment microphysics scheme (Morrison et al., 2009); the RRTMG radiation scheme (Mlawer et al., 1997); the Noah land surface model with single layer urban canopy model (Chen and Dudhia, 2001; Chen et al., 2011); and the Grell-Devenyi ensemble cumulus scheme (Grell and Devenyi, 2002) that allows subsidence and spreading at high-resolution. Land cover and land use data from the United States Geological Survey (USGS) 1 km resolution dataset are combined with the 2006 National Land Cover Database (NLCD) 3-

class urban covers to better represent the urban landscape in California. The second generation regional acid deposition model (RADM2, Stockwell et al., 1990; Gross and Stockwell, 2003) is used for gas-phase chemical reactions with aqueous chemistry included as well. The aerosol algorithms are based on the Modal Aerosol Dynamics Model for Europe or MADE/the Secondary Organic Aerosol Model or SORGAM (Ackermann et al., 1998; Schell et al., 2001) with Goddard Chemistry Aerosol Radiation and Transport or GOCART, functioning as an emissions scheme that accounts for surface wind speed, soil moisture, and soil erodibility (Ginoux et al., 2001; Zhao et al., 2010). The complete physics and chemistry parameterization schemes to be used in this study are listed in Table 1.

Three nested domains are used. The first (domain 1) has 36 km grid spacing and covers the western and central U.S., eastern Pacific, northern and central Mexico, the Gulf of California, and the western Gulf of Mexico. Nested domains 2 and 3 use grid spacings of 12 km, and 4 km, respectively. The innermost domain (4 km) grid spacing (with 150 by 180 grid cells) covers the Central Valley of California. Figure 1 displays the terrain distribution in domain 3. The vertical configuration of the model comprises 41 full layers: the lowest 15 layers are within 1500 m above ground level or a.g.l. and the first half-vertical layer above ground surface is about 14.5 m a.g.l.

2.2 Irrigation scheme

The timing and quantity of water delivery for irrigation are critical to its success and remain crucial in its realistic simulation. In previous studies, three methods have been employed: (1) Prescribing soil moisture to a specific level using real data (e.g., Segal et al., 1998; Lo and

Famiglietti, 2013). This method reasonably conserves the total water amounts being applied but does not account for the effects of weather and climate on irrigation (Kueppers et al., 2007). (2) Fixing soil moisture to field capacity or saturation (e.g., Adegoke et al., 2003; Kueppers et al., 2007). This method results in wet and cool biases (e.g., Kanamaru and Kanamitsu, 2008). And (3) mimicking realistic irrigation processes (e.g., Kanamaru and Kanamitsu, 2008; Sorooshian et al. 2011; 2012 and 2014; Vahmani and Hogue 2014). We have employed the third method because using realistic irrigation methods can produce better hydroclimatic fields than the other two, as shown by Kanamaru and Kanamitsu (2008), Sorooshian et al. (2011, 2012, and 2014), and many others. The impacts of irrigation parameterization methods on model results (mostly on meteorological variables) can be found in the literature (e.g., Lobell et al., 2009; Kanamaru and Kanamitsu, 2008; Kueppers et al., 2008; Sorooshian et al., 2011, 2012 and 2014). Jacobson (2008) used actual daily varying irrigation rates at 5 km resolution to add water to GATOR-GCMOM, perhaps the most realistic method employed so far.

In this study, we employ a realistic irrigation scheme, developed by Hanson et al. (2004) and practiced by California irrigators. Its basic concept is to use the minimum amount of water that ensures the maximum crop yield. In practice, irrigation starts when the root zone's relative available soil-water (SW) content is less than the maximum allowable water depletion (SW_m), where the magnitude of SW_m depends on soil type, crop type and crop growth period as discussed in Hanson *et al.*(2004). Irrigation ceases when soil moisture reaches field capacity. This method has been implemented into limited area models including WRF by Sorooshian et al. (2011 and 2014):In the model, when the modeled root-zone's SW is less than SW_m , water is added into root-zone layers (i.e., the top three layers) until the soil moisture reaches field capacity. In WRF, we also stop adding water whenever the downward solar radiation is greater

than 50 W m^{-2} to ensure model numerical stability during the simulations and to avoid water loss due to evapotranspiration (ET) at these higher solar radiation levels (Sorooshian et al., 2014).

This method employs the concept of a combination of flood irrigation with drip irrigation. Note that in the U.S. there are about 30.5 million acres of sprinkler irrigation, 26.6 million acres of flood irrigation, and 4.05 million acres of drip irrigation (<http://water.usgs.gov/edu/wuir.html>).

2.3 Data used for model initialization and evaluation

The biogenic emissions data are obtained from the 1-km resolution Model of Emissions of Gases and Aerosols from Nature (MEGAN, Guenther et al., 2006). The North American Regional Reanalysis (NARR; Mesinger et al., 2006) product is used for initial and boundary conditions (atmospheric and land surface [e.g., soil moisture and temperature]). NARR data are distributed on a 32-km grid with a 3-hour temporal frequency. The atmospheric chemical boundary and initial conditions are obtained from the Model for Ozone and Related Chemical Tracers Version 4)/National Center for Environmental Protections T42 (Emmons et al., 2010). The wildfire data are from MODIS (Moderate Resolution Imaging Spectroradiometer) and the emission parameterization method is based on Freitas et al. (2011).

The anthropogenic emissions are obtained from the 2005 National Emissions Inventories (NEI05) data provided by the U.S. Environmental Protection Agency (EPA) (www.epa.gov/ttnchie1/net/2005inventory.html). These data are distributed on a 4-km grid array covering the U.S. and surrounding land areas. In this study, we assume the anthropogenic emissions are not affected by irrigation.

The data used for model evaluation include measurements from the Air Quality and Meteorological Information System (AQMIS) of the California Air Resources Board (www.arb.ca.gov/aqmis2/aqmis2.php). We use hourly observations of ozone, carbon monoxide (CO), nitrogen oxides (NO_x), and VOC concentrations from 35, 18, 19, and 7 stations, respectively, in the Central Valley (downloaded from www.arb.ca.gov/aqmis2/aqdselect.php?tab=hourly). The MODIS ET (Tang et al. 2009) and surface skin temperatures (Jin and Dickinson, 2010) are employed to evaluate the model's performance on meteorological fields.

2.4 Model evaluation

To examine the effects of irrigation on air quality, two simulations are conducted. One is called the “control run (CTRL)”: running WRF-Chem as usual. The other is called the “irrigation run” or “Test run (Test)”: running WRF-Chem the same as for the control run but including irrigation in the irrigated lands. The summer of 2005 is selected as the test year since the anthropogenic emissions inventory is for this year. Since MEGAN data are monthly, the run is reinitialized for each of the two months. For example, the run for July is started, from 00 Z, June 23, 2005, to 12 Z, August 1, 2005, with the first few days as spin-up.

2.4.1 Evaluations of meteorological fields

The effects of irrigation on meteorological fields are thoroughly examined in previous studies. For example, in the study of Sorooshian et al (2011), the model simulations are validated against soil temperature, surface temperature, humidity, and winds measured at the sites of the

California Irrigation Management Information System (CIMIS, <http://www.cimis.water.ca.gov/>) (see their Table 1 and 4); additionally in Nebraska, the model results are validated against surface sensible heat and latent heat fluxes at Ameriflux irrigation sites(see their Table 2). With irrigation being added, the warm and dry biases are dramatically removed (see their Figures 2a, 3, and 4 also). Sorooshian et al. (2012) found that the model ETs with an irrigation scheme are consistent with the ETs from remote-sensing retrievals by Tang et al. (2008) in annual and interannual variability. Furthermore, Sorooshian et al. (2014) have compared soil moisture, ET, and precipitation from the model with an irrigation scheme against available observations and other model results. In all three studies, simulations with different irrigation schemes are compared with each other and against observations. The simulations with the realistic irrigation scheme based on Hanson et al. (2004) are the most consistent with the observations.

Figure 2 shows the comparisons of daytime mean surface skin temperature (top) and mean monthly ET between MODIS retrievals and model simulations from the control and irrigation runs. In Figure 2, MODIS surface skin temperatures are retrieved at 13:30 solar time based on by Jin and Dickinson (2010); model data are from 21UTC (13:00 Pacific Standard Time or PST). Clearly, the model well captures the patterns shown from satellite data. Without considering irrigation in WRF_Chem, the model overestimates skin surface temperature and underestimates ET in the Central Valley. At the basin-scale, MODIS ET is 145 mm per month. WRF-Chem ET is 41 mm per month for the control run and 174 mm per month with the irrigation run. The skin temperature is 37°C for MODIS data, 45.4°C for WRF-Chem control run and 34.3°C for WRF-Chem irrigation run. Ozdogan et al (2010) reported the ET field measurements at the Five Points Station (36.34°, -120.11°) in a cotton field. The monthly ET was 221 mm and 201 mm in July and August, 2005, respectively. The ET from the model's closest

grid for July and August is 190 mm and 168 mm with the irrigation scheme, and is 42 mm and 21 mm without it, respectively. The model simulations with the irrigation scheme are between MODIS ET and field observations, and again irrigation improved the results in comparison with control runs.

The authors have not found vertical measurements of meteorological fields to validate the model's performance in the Central Valley: the available routine meteorological soundings at 0600 PST and 1800 PST are conducted in the San Francisco Bay area (<http://esrl.noaa.gov/raobs/>).

2.4.2 Evaluation of air pollutant concentrations

The model simulations are validated using the hourly observations collected in the Central Valley. The statistics include mean bias (MB), the normalized mean bias (NMB), the mean normalized bias (MNB), the root mean square error (RMSE), the normalized mean error (NME), the mean normalized gross error (MNGE), the correction coefficient (R), and the index of agreement, all of which have been used in this region (e.g., Shi et al., 2010). The metrics of MB, NMB, and NME and R are the most commonly used (Simon et al., 2012). Table 2 shows the statistics at the non-irrigation sites (mostly in urban areas) for July and August; Table 3 presents the statistics at the irrigation sites for the two months. The irrigated sites in Table 3 represent the model irrigation sites at 4 km resolution (the air quality observation sites are not really located in the irrigated crop fields as the sites of CIMIS are). In general, the model underestimates the observations of O₃, CO and VOC (negative MB). Based on most of the metrics shown in Tables 2 and 3, the model performs slightly better for the irrigation run than that for the control run, especially at sites over the irrigation areas (Table 3). In comparison with

previous studies (e.g., Shi et al., 2010) in this region, our results shown in Table 2 are not as good as theirs; however, the results from Table 3 are comparable with Shi et al's results for NME, NMB and R. Note that in Shi et al's simulations, the integration time periods were short-term (72 hours) for each run. It is widely recognized that meteorological fields for long-term runs (>240 hours) are biased (e.g., Zhang et al., 2007); nevertheless, the common metrics for ozone shown in Tables 2 and 3 fall in the ranges discussed by Simon et al. (2012).

The reason that the model performs better over the irrigation areas than in urban areas could be attributed to model resolution. A previous study indicates that for urban scales on the order of Mexico City, the resolution of WRF-Chem needs to be at least 6 km or higher resolution (Tie, et al., 2010). Misenis and Zhang (2010) show that WRF-Chem simulations at 4 km are superior to simulations at 12 km in Houston. Li et al. (2015) indicate that model results at 1.33 km resolution are better than at 4 km resolution in simulating air quality in Phoenix and Los Angeles. In California's Central Valley, there are many small towns with air quality sites; models with 4 km resolution are insufficient to resolve these smaller urban settings.

Table 4 presents the statistical results under cloudless and cloudy/rainy conditions based on the simulations from the control run. Table 4 indicates that the model performed better for ozone and NO_x under clear skies than under cloudy skies for metrics of MB, NMB, NME, MNB and MNGE. The model performance of O₃ and NO_x on R, IA and RMSE does not exhibit significant differences under the two weather conditions. Finally, the model's performance of CO and VOCs displays no significant differences between clear and cloudy skies for all metrics.

The model simulations with irrigation produced results similar to those of the control run (Table 4).

Although there are many observation sites for each pollutant, only the two sites with complete observations are shown in Figure 3. Figure 3 presents the daily 1 hr maximum (DMA1) concentrations of NO_x ([NO_x]), CO ([CO]), and VOC ([VOC]), and daily 8 hr maximum average (DMA8) ozone concentrations ([O₃]) at Clovis (36.8193°N, 119.7164°W) in the San Joaquin Valley and Sacramento (38.6137°N, 121.2680°W) in the Sacramento Valley. The model highly underestimates [VOC] at the Clovis site, and it also highly underestimates CO and overestimates NO_x at the Sacramento site. Nonetheless, the model simulations capture the variability of pollutant concentrations in general. Furthermore, the model's primary pollutant concentrations such as DMA1 [CO], [NO_x] and [VOC] from the test run are slightly higher than those from control run, while DMA8 [O₃] from test runs are slightly lower than that from the control run.

Figure 4 shows the comparison of DMA1 [NO_x], DMA1 [CO] and DMA8 [O₃] between observations and simulations with and without irrigation at Davis (38.53455N, 121.7734°W), a site of genuine irrigated land in the real world and within the model. At this site, the model generally captures the variations shown from observations; modeled [CO] and [NO_x] from irrigation runs are slightly higher than that from control runs.

Figure 5 shows the DMA8 [O₃] comparisons between observations and models at the Lower Kaweah Campground Camping ground (36.5661N, 118.7777W) and Sequoia National Park (36.48941N, 118.82914W), located on the western slope of the southern Sierra Nevada Mountains (See Figure 1). Again, the model underestimates [O₃] by 10-20 ppb while it captures the variability. Interestingly, DMA8 [O₃] from irrigation runs are consistently higher than that from control runs by about 1-5 ppb. In addition to the model deficiencies, terrain elevation differences between the model and the actual elevation at observation sites could also contribute

to ozone concentration differences. At the camping ground, the site's elevation is 1926 m while model grid's elevation closest to the site is 1505 m, At Sequoia National Park, the observation site's elevation is 515 m while the model grid's elevation closest to the observation site is 833m. It's obvious that a model with 4-km resolution cannot resolve the complex terrain in this mountainous area.

We checked DMA8 [O₃] site by site throughout the Central Valley: in general, model simulations captured observations very well. The exceptions, as noted above, are the underestimations on high DMA8 [O₃] events at some sites. Note that this is a monthly-scale run, so the model results will be impacted by meteorological forcing from the lateral boundaries (e.g., Zhang et al., 2007), by uncertainties within the physical parameterization schemes (e.g., Misenis and Zhang, 2010; Tao, et al., 2008; Cuchiara et al., 2014), and by nonlinear meteorological-chemical processes (e.g., Kwok et al., 2015; Steiner et al., 2008).

The hourly statistics shown in Tables 2, 3 and 4, and Figures 2, 3, 4, and 5 indicate that this model's particular configuration has adequately captured the ozone spatial distribution and temporal variability, enhancing our confidence that it would be suitable for further investigations of irrigation effects.

3. Impact of irrigation on meteorology and air quality

3.1 Impacts of irrigation on meteorological fields in the Central Valley of California

Given a set of consistent emissions, the spatial and temporal distribution of ozone and other photochemical pollutants is determined by both meteorological conditions and

photochemical reactions. In this section, we discuss the irrigation-induced changes to those meteorological fields relevant to air quality.

Figure 6 shows the differences of meteorological fields between the irrigation and control runs (irrigation minus control, the same for all other figures). These data are averaged from 11:00 am to 06:00 pm local time. The differences with statistical insignificance at the 95% confidence level ($\alpha=0.05$) are masked for all variables except cloud fraction, whose differences with statistical insignificance at the 60% level ($\alpha=0.4$) are masked. Figure 6 indicates that agricultural irrigation mainly results in soil moisture and near-surface humidity increases of about 0.1-0.3 m^3/m^3 with an average of 0.23 $\text{m}^3 \text{ m}^{-3}$ (Figure 6a) and 4-8 g/kg with average of 4.95 g/kg (Figure 6b), respectively, and that it produces 2-m air temperature decreases of about 1-5 K with an average of -3.1 K for the two-month means during daytime (Figure 6c). At the same time, irrigation generates near-surface local winds (Figure 6d), which flow from the irrigated areas to surrounding unirrigated areas with magnitudes of 1-3 m/s. Within irrigation grids, the U-component is -0.37 m/s. The impact of irrigation on meteorological fields in surrounding unirrigated areas is marginal except for winds, consistent with the previous studies of Sorooshian et al., (2011 and 2014), since the same irrigation scheme is used. Figure 6e shows the daytime changes of PBL height due to irrigation: within irrigation areas, the PBL heights decrease 300 m to 1000 m (average of 610 m or -30%). Irrigation also reduces the PBL height downwind of irrigated areas by 100-300 m.

The changes of cloud fractions due to irrigation are shown in Figure 6f. No cloud changes occurred in the irrigated area during the daytime. Increased cloud fractions occur in the surrounding non-irrigation areas (Figure 6f) with magnitudes less than 15%. This distribution of cloud changes is consistent with the changes of local circulation shown in Figure 6d. Note that

summer in the Central Valley is the dry season and is dominated by the Pacific anticyclone and local mountain-valley circulations, with downward vertical motions in the valley during daytime in the absence of a strong synoptic weather system. Irrigation-cooling enhances downward vertical motion in the Valley (induced by mountain-valley circulations) and therefore prevents cloud formation in the Valley during daytime. Irrigation-enhanced surface winds (Figure 6d) transport the air parcels with increased water vapor (Figure 6b) to the surrounding non-irrigation areas and mountains, where there is upward motion that favors cloud formation (Figure 6f).

The downward solar radiation is also examined (not shown). The results indicate that irrigation-induced solar radiation variation is consistent with the variation of cloud cover. In other words, solar radiation is not affected by irrigation in the Central Valley even at the same statistical significance as applied in Figure 6f.

Figure 7 shows the mean vertical profiles of turbulent kinetic energy (TKE) (Figure 7a), potential temperature (Figure 7b), mixing ratio (Figure 4c), and westerly winds (Figure 4d) with and without irrigation. The data are averaged over all of the irrigation grid cells in the San Joaquin Valley (Figure 1). Irrigation not only cools the ground surface but also cools the lower troposphere up to 1500 m (Figure 7b). In the control run, the mixing layer is clearly seen (the blue line in Figure 7b) while in the irrigation run this feature disappeared, indicating that irrigation induces weak instability vertically. Irrigation reduces surface potential temperatures up to 3 K averaged over all grid cells.

Irrigation reduces the TKE significantly during daytime. As shown in Figure 7a, with irrigation, the TKE decreases rapidly with height and disappears about 500-1000 m a.g.l., while turbulent mixing may occur up to 3000 m a.g.l. in the control run. Note that in the control run, the maximum TKE appears about 500 m a.g.l. Therefore, irrigation can reduce turbulent

intensity and decrease the vertical mixing and diffusion of pollutants, especially for the primary pollutants, such as precursors of ozone (i.e., NO_x, VOCs).

Irrigation increases the humidity over near-surface layers. As shown in Figure 7c, irrigation increases mixing ratios from 1 to 4 g/kg in the lower 1000 m a.g.l. of the atmosphere. The maximum mixing ratio differences mainly occur in the surface layer with a magnitude of 3-4 g/kg. This difference decreases quickly with increasing altitude.

Figure 7d is the westerly wind profile averaged over the irrigation cells. The vertical variation of winds is much more complex than the other meteorological fields as shown in Figure 7. Both control run and irrigation run exhibit two wind peaks vertically: one occurs below 500 m a.g.l. and the other occurs about 1500 m a.g.l., which may be related to the heights of the mountains located to the west and east of the San Joaquin Valley. Irrigation results in the wind peak below 500 m a.g.l. weakening and that near the 1500 m a.g.l. enhancing, since the model generates relatively stronger local circulation in the west irrigation boundary than that in east irrigation boundary (shown in Figure 6d for the lower branch of the circulation).

In summary, irrigation increases soil moisture (Figure 6a) and latent heat fluxes or ET (Figure 2), and hence reduces Bowen Ratios and surface temperatures (Figure 6c), which decreases PBL height (Figure 6e) and PBL instability (Figure 7a and b). Irrigation cools the ground surface and thereby generates local circulations (Figure 6d) due to the changes of local thermal differences. This is an example of so-called “irrigation-induced first order changes” (Lo and Famiglietti, 2013) and these changes are statistically important (at the 95% significant-level). The second order changes include cloud variations. Our results indicate that irrigation enhances cloud formation in the downwind directions at a 60% significant level. In other words, irrigation-

induced cloud and rainfall changes in the Central Valley are negligible, consistent with previous studies (e.g., Sorooshian et al., 2014).

3.2 Impacts of irrigation on pollutants in the Central Valley

Figure 8 is the same as Figure 7 but for the profile of pollutants. Overall, irrigation increases primary pollutant concentrations at ground surface but decreases them above the surface (above 500 m because irrigation weakens vertical mixing). Specifically, irrigation increases surface [CO] by 15 ppb, [VOC] by 6 ppb and [NO_x] by 0.9 ppb, averaged over the irrigation areas in the San Joaquin Valley. The differences of the pollutant concentrations with/without irrigation may reach up to 2000 m a.g.l., relevant to the changes of TKE and winds with heights as shown Figure 7a and d.

The ozone vertical variation (Figure 8d) is different from the primary pollutants (Figure 8a, b and c). Within the first model layer (about 14 m a.g.l.), ozone concentrations from the control run are slightly greater (about 1 ppb) than those from the irrigation run. In other words, irrigation results in ground surface ozone decreases of about 1 ppb for an irrigation area average. The maximum concentrations of ozone do not appear near the ground surface due to titration and dry deposition. For the control run, the maximum occurs at about 600-700 m a.g.l. while it occurs at about 200-300 m a.g.l. for the irrigation run. In other words, irrigation results in the altitude of the ozone maximum decreasing, compared with the control run. Above 500 m a.g.l., ozone concentrations from the irrigation run are less than that from the control run by 5 ppb, mostly because of lower precursor concentrations as shown in Figure 8a and b, and lower

temperatures in the irrigation run (Figure 7b), since ozone is somewhat sensitive to temperature changes in this region (Steiner et al. 2010).

Figure 9 displays the changes of hourly surface [CO], [NO_x], [VOC], and [O₃] due to irrigation under cloudy and clear sky conditions between irrigation runs and control runs. Figure 9 shows that irrigation increases [CO] up to 10-40 ppb (Figure 9a) with an irrigated grid average of 16 ppb or 8.53%, [NO_x] up to 1-4 ppb (Figure 9b) with an irrigated grid average of 0.72 ppb or 12.6%, and [VOC] up to 6-10 ppb (Figure 9c) with an irrigated grid average of 4.6 ppb or 21.4%, highly dependent on location. These increases occur mainly in the irrigation zone, especially near its urban areas, because of the decreases in the vertical turbulent intensity and turbulent mixing as shown in Figure 7. In other words, irrigation causes concentrations of primary pollutants to increase near the surface, compared to the test run and control run. Figures 9a and c also indicate that irrigation increases [CO] by 5 to 20 ppb and [VOC] by 1-2 ppb in surrounding non-irrigation areas, which is caused by transport of irrigation-induced local circulations, whose winds flow toward the surrounding non-irrigation areas (Figure 6d). NO_x exhibits little evidence of transport because of its shorter atmospheric residence time. Our results on irrigation-induced increases in surface primary pollutant concentrations under clear skies are consistent with a previous study in this region (e.g., Jacobson, 2008). On the other hand, Figure 9d indicates that irrigation results in small hourly ozone changes in irrigated land; but that it causes hourly ozone changes up to 2-7 ppb in the surrounding non-irrigation areas, depending on location. The differences shown in Figure 9 are statistically significant at a confidence level of 95%.

The hourly data in cloudy conditions (defined as cloud cover is greater than 10% in an hour from both CTRL run and Test run) are also examined as shown in Figure 10 at the same

confidence level (95%). Over all, with clouds or rain, irrigation results in no differences of surface primary pollutant concentrations. The exception to this pattern occurs in the southern San Joaquin Valley, where irrigation increases the surface concentrations of primary pollutants, which is inconsistent with a previous study (e.g., Jacobson, 2008). The reason could be fundamental differences between the two physical/chemical models and/or the different integration time periods, since irrigation-induced weather and climate exhibits interannual variability (Kueppers et al., 2007; Sorooshian, et al., 2012). Irrigation also results in little $[O_3]$ changes under cloudy or rainy conditions.

Figure 11 shows the surface $[O_3]$ differences during daytime (Figure 11a; 9am-6pm PST) and nighttime (Figure 11b; 8pm-5am PST) under cloudless skies for the two months. Clearly, irrigation increases $[O_3]$ in the surrounding non-irrigation areas both daytime and nighttime with a magnitude of up to 1-6 ppb, especially around the San Joaquin Valley. Irrigation slightly decreases $[O_3]$ in irrigation areas during daytime. The differences shown in Figure 11 are statistically significant at the 95% confidence level. The differences of $[O_3]$ under cloudy conditions are also examined separately both for daytime and for nighttime, and no significant differences are found at the same confidence level.

The differences of $[CO]$, $[NO_x]$ and $[VOC]$ are also examined during daytime and nighttime under both clear sky and cloudy conditions (figures not shown). The results indicate that the concentrations increase in the irrigated areas both daytime and nighttime with magnitudes depending on time and location under the same confidence level shown in Figure 11. The examination of hydroxyl ($[HO]$) shows the differences due to irrigation cannot pass the statistical test at the same confidence level.

The distribution of $[O_3]$ differences may be caused by different physical-chemistry processes, as follows. (1) The increases of ozone precursors (such as NO_x , VOC) (Figures 8, 9 and 10) due to irrigation cooling (Figures 7 and 8) would consequently enhance the increase of surface $[O_3]$; (2) The greatly reduced PBL height (Figure 6e) would suggest higher $[O_3]$ because of a reduced mixing zone (Figure 7a); (3) the reduced temperatures (Figure 6c and Figure 7b) will decrease the $[O_3]$ photochemical reaction rates (Pusede and Cohen, 2012; Steiner et al., 2010); (4) irrigation-induced local circulations enhance the valley-mountain upslope winds during daytime (Figure 6d), which will transport ozone and other pollutants towards non-irrigation areas; (5) previous studies indicate that wetter soil surfaces increase ozone dry deposition, which would decrease surface $[O_3]$ (e.g., Altimir et al., 2006), and (6) a wetter lower troposphere enhances $[HO\bullet]$ generation, which would decrease $[O_3]$ (Jacob and Winner, 2009; Wu et al., 2008). Although all of these physical/chemical processes are implemented into WRF-Chem, standard WRF-Chem does not output these ozone generation rates or reaction rates, separately. Therefore, it becomes difficult to quantitatively determine the relative contributions of each component to the final $[O_3]$ distributions as shown in Figures 9d, and 11 and the figures discussed later.

Figure 12a shows the mean differences of DMA8 $[O_3]$ for all weather conditions: it shows that irrigation reduces $[O_3]$ up to 5 ppb within irrigation areas (irrigated area average is -0.40 ppb or -0.76%) but increases $[O_3]$ up to 2-7 ppb in surrounding non-irrigation areas. The $[O_3]$ changes are highly dependent on location. The greatest decrease occurs in the San Joaquin Valley and the greatest increase occurs on the western slope of the southern Sierra Nevada Mountains, east of San Joaquin Valley (locations labeled in Figure 1), mostly relevant to irrigation intensity as shown in Figures 2 and 6. Figure 12a demonstrates that irrigation

decreases $[O_3]$ in irrigation areas but increases it in surrounding non-irrigation areas with a statistical significance of $p < 0.10$ level in most of the areas.

To further explore $[O_3]$ variations, we present the frequencies of dates with $[O_3]$ changes. Figure 12b shows the distribution of the frequencies of dates when DMA8 $[O_3]$ differences (Irrigation run – CTRL run) are less than -2 ppb for July and August, 2005, indicating that the frequencies of dates are more than 0.3 over the irrigation areas (with values depending on location), especially in the San Joaquin Valley, where the frequencies reach up to 0.5-0.7. Figure 12c shows the distributions of the frequencies of dates when DMA8 $[O_3]$ differences are greater than 2 ppb, indicating that frequencies of dates are more than 0.3 over some of the surrounding non-irrigation areas with the magnitude depending on location, especially in the San Joaquin Valley, where the frequencies are greater than 0.7.

In summary, model simulations indicate that irrigation in the Central Valley increases primary pollutants in clear skies, consistent with previous studies. Our model simulations also show that irrigation with cloud cover or rainfall does not alter primary pollutant concentrations throughout the Valley except in its southern part, where irrigation also increases surface primary pollutant concentrations, inconsistent with previous studies. Irrigation slightly decreases ozone concentrations at ground-level over the irrigated area. In contrast, irrigation increases ozone concentrations over the surrounding non-irrigation areas under clear skies, daytime and nighttime. As for other aspects of spatial distribution already discussed, these changes are highly dependent upon location. These pollutant variations result from changes of irrigation-induced local circulations and of vertical turbulent mixing.

3.3 Impacts of irrigation on pollutants in the contiguous United States

Finally, we extend our study area to the contiguous United States (CONUS) for estimating the ozone variations induced by agricultural irrigation (locations shown in Figure 13a as masked by gray). The agricultural irrigation crop land, based on USGS data, is found in the Central and Imperial Valleys of California, southern Idaho, the central U.S., and in the southeast U.S. Throughout these regions, the same irrigation scheme as in California is used. WRF-Chem is configured with a single domain at 12 km resolution (consisting of 405 by 252 grid cells), due to computation-cost constraints, while the remaining model components are exactly the same as the Central Valley runs. The model is run from 00Z, June 23, 2005 to 12Z, August 31, 2005 (no lateral boundary nudging is used).

Figure 13b displays the differences of DMA8 [O₃] over the CONUS at 90% confidence level. Strikingly, distributions of DMA8 [O₃] differences at 12 km resolution runs shown in Figure 13b are quite similar to those at 4 km resolution runs shown in Figure 12a in the Central Valley of California. Over the irrigation areas, DMA8 [O₃] decreases while DMA8 [O₃] increases over the surrounding non-irrigation areas in the irrigation run, compared with the control run.

As shown in Figures 13a and b, irrigation-induced DMA8 [O₃] reductions are seen in other irrigation areas for the 12 km run. These areas include the Imperial Valley of California, western Arizona, southern Great Plains, and the southeastern US with different magnitudes. Figure 13b also shows that irrigation-induced DMA8 [O₃] increases occur mostly along the southeastern coasts with 0.5 to 2 ppb, in addition to the non-irrigation areas in the Central Valley of California. However, in the Pacific Northwest, irrigation-induced DMA8 [O₃] changes are not clear.

Our sensitivity studies indicate that large-scale irrigation results in surface DMA8 [O₃] changes up to 2-5 ppb at local to area scales, which is about 3% to 6% of typical ambient ozone concentrations at some locations. The results discussed in this paper come from one summer season and are based on emissions from the NEI 2005. The results could vary with different emission inventories and in different years, since irrigation-induced temperatures and ETs exhibit interannual variability (Kueppers et al., 2007; Sorooshian et al. 2012). On the other hand, in California, recent exceptional droughts mean less water for agriculture irrigation, which may result in air quality changes in the opposite direction. i.e., under the same emission inventories, reducing irrigation could result in surface ozone increases and primary pollutant decreases over the irrigation region, compared to those years with normal irrigation. Therefore, irrigation-induced changes of ambient pollutant concentrations (both primary and secondary pollutants) should be taken into consideration in the State Implementation Plans. Irrigation mainly reduces surface temperatures, PBL heights, and TKE; therefore, the irrigation method can be used to investigate the effects of urban vegetated-irrigation and of green-roof programs on air quality in urban areas.

Our results are based on fixed model configurations including model domain size, resolution, meteorological forcing, physics, and chemistry parameterizations. Previous studies indicate that model results may vary if any of the model parameters or set up changes. For example, Milovac et. al.(2014), by comparing the measurement from six eddy covariance stations and Lidar data in Germany for about 25 days, found that the model exhibits significantly higher sensitivity to land surface processes than to PBL schemes, and that the MYNN PBL scheme outperforms the YSU PBL in representing the convective PBL structure. Misenis and Zhang (2010), using different PBL schemes (including YSU) and land surface models, have

conducted simulations over the Houston-Galveston area for a 5-day summer episode from the 2000 Texas Air Quality Study. They found that both meteorological and chemical predications at the surface and aloft showed stronger sensitivity to land surface processes than to the PBL schemes. On the other hand, Cuchiara et al. (2014), using different PBL schemes and the Second Texas Air Quality Study measurements in 2006, found that “the overall results did not indicate any preferred PBL scheme for the Houston case. However, for ozone predictions, the YSU scheme showed greatest agreements with observation values”. In the southwestern U.S., we investigated PBL schemes using WRF-Chem v3.5.1 and noticed that, using the YSU PBL scheme, the PBL height could reach up to 4000-5000 m a.g.l. and sometimes the PBL height could reach over 5000 m a.g.l.. After consulting with WRF-Chem developers (S. Peckham, Jan. 2014, personnel communication), we use MYNN PBL. Based on the studies mentioned here, the model performance related to different PBL schemes depends on events, location, and even the overall model configuration.

4 Conclusions

In this research, using WRF-Chem, we have examined whether and to what degree agricultural irrigation affects air quality in the Central Valley for July and August 2005. A WRF-Chem control run (running it as usual) and a WRF-Chem irrigation run (running the model with a realistic irrigation scheme to represent the real world irrigation occurring in the Central Valley) are conducted, separately. First we compared model simulations (both control run and irrigation run) with available observations. The results from the two runs show that the model captures the basic features of hourly ozone variation at numerous observation sites ($r=0.64$, and

596 IA=0.81) at current setup. Although the model underestimates ozone and VOC surface
597 concentrations, its overall results are comparable with those from previous model studies and
598 match observations quite well at most of the sites most of the time, especially at the irrigation
599 sites. Furthermore, in comparison with 8 hr daily maximum average (DMA8) ozone
600 concentrations ($[O_3]$), the model captures their daily variation except for some pronounced
601 elevated ozone episodes at some sites. Finally, in comparison with observations, the model with
602 the irrigation run performed better than the control run for both meteorological fields and
603 ground-level pollutant concentrations.

604 Next, the effects of agricultural irrigation in the Central Valley of California are
605 investigated based on the control and irrigation runs. Our results indicate that irrigation increases
606 soil moisture and near-surface humidity, but decreases near-surface temperatures, PBL heights
607 and TKEs, consistent with the known atmospheric physics and with previous studies. Irrigation
608 increases primary pollutant concentrations at ground-level under clear skies, consistent with
609 previous studies (e.g., Jacobson 2008). In 2005, for example, $[CO]$ increases up to 40 ppb,
610 especially near urban areas, $[NO_x]$ increases up to 5 ppb, and $[VOC]$ increases up to 6-10 ppb in
611 the same region. During cloud cover or rainfall, our results indicate that irrigation does not affect
612 primary pollutant concentrations, except in the southern San Joaquin Valley, where irrigation
613 increases pollutant concentrations, inconsistent with previous studies, probably because of case
614 and/or model differences. On the other hand, irrigation decreases surface $[O_3]$ by 0-5 ppb in
615 irrigated areas but increases them 2-7 ppb over the surrounding non-irrigation areas. These
616 statistically significant pollutant concentration changes can be explained by the fact that
617 irrigation cools and wets the surface, which reduces TKE and therefore constrains the vertical

618 **mixing of the primary pollutants.** Irrigation-induced local circulations transport precursors and
619 ozone to the surrounding non-irrigation areas.

620 Finally, the investigation is extended to the CONUS domain using the same irrigation
621 scheme practiced in California. The results indicate that the conclusions over the Central Valley
622 can apply to most other areas of the CONUS, except in the northwestern U.S.: i.e., irrigation
623 causes surface ozone decreases above the irrigation areas.

624 Our results are based on the NEI 2005 and one summer season. Since irrigation-induced
625 surface temperatures and other meteorological fields exhibit interannual variation, irrigation-
626 induced [O₃] variation should have interannual variation as well, a future research topic.

627
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844 Table 1: Physical-chemistry parameterization schemes

Microphysics scheme	Morrison double-moment (Morrison et al., 2009)
Short-wave radiation	RRTMG (Mlawer et al., 1997)
Land surface model	Noah (Chen and Dudhia, 2001)
Urban physics	urban canopy model (Chen et al., 2011)
Convective scheme	Grell-Devenyi ensemble (Grell and Devenyi, 2002)
PBL and surface layer scheme	MYNN (Nakanishi and Niino, 2004)
Sea surface update	yes
Advection scheme	5 ^a horizontal/3 ^a vertical
Chemistry mechanism	RAMD2+aqueous chemistry
Aerosol option	MADE/SORGAN
Anthropogenic emissions	NEI05
Biogenic emissions	MEGAN
Photolysis	Madronich, 1987
Dry deposition	Wesley, 1989
Biomass emissions and parameterization	MODIS (Freitas et al. 2011).
Aerosol radiation feedback	yes
Subgrid convective aqueous chemistry	yes
Subgrid convective wet scavenging	yes

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Table 2: Statistics of air pollutant concentrations at observation sites in non-irrigation

areas

		Ozone	NOx	CO	VOC
MB (ppb)	CTRL	-6.4	0.75	-16.8	-30.2
	TEST	-6.1	1.6	-9.1	-28.7
NMB (%)	CTRL	-28.0	11.9	-11.1	-70.5
	TEST	-26.0	-6.1	-14.8	-67.1
NME (%)	CTRL	57.9	74.6	48.5	72.9
	TEST	57.0	49.7	47.2	70.5
MNB (%)	CTRL	3.1	44.7	14.6	-53.9
	TEST	4.2	20.8	4.9	-49.2
MNGE (%)	CTRL	56.3	95.7	54.2	61.9
	TEST	55.6	57.0	47.1	60.0
R	CTRL	0.33	0.49	0.48	0.39
	TEST	0.34	0.43	0.46	0.39
IA	CTRL	0.20	0.29	0.15	0.22
	TEST	0.12	0.26	0.16	0.26
RMSE (ppb)	CTRL	37.5	18.7	210.7	96.6
	TEST	37.1	23.0	212.5	94.6

859 Table 3: Statistics of air pollutant concentrations at observation sites in the irrigation
860 areas

		Ozone	NOx	CO	VOC
MB(ppb)	CTRL	-6.1	-1.8	28.9	-25.9
	TEST	-5.4	-1.3	22.2	-23.9
NMB(%)	CTRL	-24.6	-31.7	31.0	-70.1
	TEST	-21.1	-24.1	23.8	-65.0
NME (%)	CTRL	28.9	57.1	52.1	70.4
	TEST	26.0	57.5	48.9	65.8
MNB (%)	CTRL	-23.9	-20.9	48.1	-61.7
	TEST	-21.5	-12.6	39.7	-55.9
MNGE (%)	CTRL	28.3	60.8	64.8	62.1
	TEST	26.1	61.1	59.7	57.4
R	CTRL	0.63	0.62	0.36	0.46
	TEST	0.70	0.64	0.33	0.47
IA	CTRL	0.81	0.44	0.20	0.47
	TEST	0.83	0.45	0.11	0.50
RMSE(ppb)	CTRL	18.0	9.7	120.5	77.0
	TEST	17.6	9.8	129.3	73.0

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Table 4: Statistics of air pollutants at the observation sites under cloudy and cloudless conditions. Data are from the control run.

		ozone	NOx	CO	VOC
MB(ppb)	cloudless	-5.0	0.6	-31.6	-28,6
	cloudy	-5.0	3.4	-13.6	-23.2
NMB(%)	cloudless	-21.1	9.9	-19.3	-70.5
	cloudy	-27.9	58.6	-9.1	-67.9
NME (%)	cloudless	35.2	73.2	47.7	71.9
	cloudy	41.2	90.5	49.1	70.0
MNB (%)	cloudless	-3.4	39.9	3.8	-57.4
	cloudy	-13.6	132.8	20.4	-55.2
MNGE (%)	cloudless	46.7	93.1	50.5	62.1
	cloudy	53.3	149.2	56.2	61.3
R	cloudless	0.79	0.53	0.46	0.42
	cloudy	0.80	0.52	0.47	0.37
IA	cloudless	0.69	0.32	0.20	0.31
	cloudy	0.72	0.33	0.17	0.21
RMSE(ppb)	cloudless	21.2	16.0	222.3	89.8
	cloudy	19.3	16.4	205.1	87.3

Figure Captions

Figure 1: Model Domain 3 (4 km resolution) terrain elevations (m) in California's Central Valley. Dots represents observations sites for O₃, NO_x, CO, and/or nonmethane hydrocarbons. The blue-filled areas indicate the urban grids while the gray-filled areas represent the irrigation grids.

Figure 2: Comparisons of surface skin temperature (top) and ET (bottom) between MODIS retrievals and model simulations with and without irrigation. The irrigated areas are indicated by a heavy outline, as shown in Figure 1.

Figure 3: Comparisons of daily 8 hr maximum average (DMA8) ozone concentrations ([O₃]), daily 1 hr maximum (DMA1) CO, DMA1 NO_x, and DMA1 VOC concentrations between observations (black) and model with irrigation (red) and without irrigation (green) at Clovis (36.8193°N, 119.7164°W) and Sacramento (38.6137°N, 121.3680°W).

Figure 4: Same as Figure 3 but for the Davis site (38.53455°N, 121.7734°W).

Figure 5: DMA8 [O₃] comparison between observations (black) and model simulations with irrigation (red) and without irrigation (green) at Sequoia National Park Camping ground (36.5661N, 118.7777W) and Sequoia National Park (36.48941N, 118.82914W).

Figure 6: Differences of meteorological fields due to irrigation during daytime (11am to 5 pm local time). (a) top-layer soil moisture differences, (b) 2-m specific humidity differences, (c) 2-m air temperature differences, (d) 10-m U-component differences, (e) PBL height differences, and (f) cloud fraction differences. Data are averaged from July and August 2005. The enclosed inner area in each panel represents the irrigated areas of the Central Valley. The differences are statistically significant at the 95% confidence level except cloud fraction, which is at 60%-level.

Figure 7: Vertical profiles of (a) TKE, (b) potential temperatures, (c) mixing ratios, and (d) westerly winds with and without irrigation. The data are averaged over the irrigation grid cells shown in Figure 1b during daytime.

Figure 8: Same as Figure 4 but for pollutants. (a) CO concentrations, (b) NO_x concentrations, (c) VOC concentrations and (d) ozone concentrations.

Figure 9: Differences of hourly pollutant concentrations at ground-level during clear skies (a): CO, (b), NO_x, (c), VOC, and (d) O₃. The differences are statistically significant at the 95% confidence level.

Figure 10: Same as Figure 9 but for periods of cloud cover and/or rainfall.

Figure 11: Ground-level ozone concentration differences (Test – CTRL) during (a) daytime (9 am-6pm PST) and (b) nighttime (8 pm-5 am PST) in July and August 2005. The differences are statistically significant at the 95% confidence level. Irrigation areas are indicated by the bold outline.

Figure 12: Ground-level ozone variation due to irrigation in July and August, 2005. (a) Two month DMA8 ozone concentration ([O₃]) differences (ppb) between Irrigation and CTRL runs; (b) Frequencies of the days when the differences of daytime [O₃] between irrigation and control runs are less than -2 ppb; and (c) the same as (b) but greater than 2 ppb. The enclosed inner area in each panel represents the irrigated areas.

Figure 13: Ozone variation in the contiguous U.S. due to irrigation. (a): Terrain elevation at 12 km resolution; irrigated crop lands are masked as gray while urban areas are masked as blue; (b) The DMA8 [O₃] differences (irrigation-control).

Figure

Figure 1: Model Domain 3 (4-km resolution) terrain elevations (m) in California’s Central Valley. Dots represents observations sites for O3, NOx, CO, and/or nonmethane hydrocarbon. The blue-filled areas indicate urban grids while the gray-filled areas represent irrigation grids. The bold outline indicates the irrigated areas in the Central Valley.

Figure 2: Comparisons of surface skin temperature (top) and ET (bottom) between MODIS retrievals and model simulations with and without irrigation. The bold outline indicates the irrigated areas shown in Figure 1.

Figure 3: Comparisons of daily 8 hr maximum average (DMA8) ozone concentrations, daily 1 hr maximum (DMA1) CO, DMA1 NO_x, and VOC concentrations between observations (black) and model simulations with irrigation (red) and without irrigation (green) at Clovis (36.8193, -119.7164) and Sacramento (38.6137, -121.3680). The time periods are from Jun. 24, to Aug.31, 2005.

Figure4

Figure 4: Same as Figure 3 but for the Davis site (38.53455°N, 121.7734°W).

Figure 5: DMA8 [O3] comparison between observations (black) and model simulations with irrigation (red) and without irrigation (green) at Sequoia National Park Camping ground (36.5661N, 118.7777W) and Sequoia National Park (36.48941N, 118.82914W). The time periods are from Jun. 23, to Aug., 31, 2005.

Figure 6: Differences of meteorological fields due to irrigation during daytime (11am to 4 pm local time). (a) top-layer soil moisture differences, (b) 2-m specific humidity differences, (c) 2-m air temperature differences, (d) 10-m U-component differences, (e) PBL height differences, and (f) cloud fraction differences. Data are averaged from July and August 2005. The enclosed inner area in each panel represents irrigated areas. The differences are statistically significant at the 95% confidence level, except for cloud fractions, which is at the 60% level.

Figure 7: Vertical profiles of (a) TKE, (b) potential temperatures, (c) mixing ratios, and (d) westerly winds with and without irrigation. The data are averaged over the irrigation grid cells shown in Figure 1 during the daytime.

Figure 8: The same as Figure 4 but for pollutants. (a) CO concentrations, (b) NOx concentrations, (c) VOC concentrations and (d) ozone concentrations.

Figure 9: The differences of air pollutant concentrations at ground-level with and without irrigation (Irrigation minus CTRL) during clear sky periods. (a) CO concentration differences ($[CO]$), (b) NO_x concentration differences ($[NO_x]$), (c) VOC concentration differences ($[VOC]$), and (d) ozone concentration differences ($[O_3]$). The data are averaged for daytime over two months. The enclosed inner area represents the irrigation areas. The differences are statistically significant at the 95% confidence level.

Figure 10: The Same As Figure 9 but for the periods of cloud cover and/or rainfall.

Figure 11: Ground-level ozone concentration differences (Test – CTRL) during (a) daytime (9 am-6pm PST) and (b) nighttime (8 pm-5 am PST) in July and August 2005. The differences are statistically significant at the 95% confidence level. Irrigation areas are shown by the bold outline.

Figure 12: Ground-level ozone variation due to irrigation in July and August, 2005. (a) Two month daytime ozone concentration ($[O_3]$) differences (ppb) between Irrigation and CTRL runs; (b) Frequencies of the days when the differences of daytime $[O_3]$ between irrigation and control runs are less than -2 ppb; and (c) the same as (b) but greater than 2 ppb. The enclosed inner area represents the irrigation areas.

Figure 13: Ozone variation in the contiguous U.S. due to irrigation. (a): Terrain elevations at 12 km; irrigated crop lands are masked as gray while urban areas are masked as blue; (b) The DMA8 [O₃] differences (irrigation-control) due to irrigation.