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The response of coastal stratocumulus clouds to agricultural irrigation in California

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[1] Stratocumulus clouds (SC) often exist over the eastern subtropical oceans during the summer and have significant impacts on the surface radiation budget. Both atmospheric subsidence and lower troposphere stability (LTS) have been found to play important roles in maintaining SC. Using global climate model simulations, we find that irrigation in California’s Central Valley results in a decrease of land surface temperature, leading to a smaller land-sea heat contrast, and a corresponding reduction in sea breeze, subsidence, and LTS over the near-coastal region. The decrease in LTS directly drives a reduction in modeled SC coverage, and it would arguably do so in reality because of the well-known link between LTS and SC coverage. Consequently, simulated absorbed surface solar radiation over this region increases by 8 W/m² (3.7%) due to the reduction in SC cover, resulting in the warming at the Earth’s surface. This study has important implications for how SC can change with regard to future climate. In contrast to the general effects of climate change on the formation of SC, our results suggest that irrigation practices in the Central Valley may drive a decrease in nearby SC coverage.


1. Introduction

[2] Stratocumulus clouds (SC) cover a large area of the world’s oceans, typically extending over hundreds to thousands of kilometers. With a long cloud lifetime of several days to weeks, SC have a significant impact on the global radiation budget [e.g., Slingo, 1990; Hartmann et al., 1992; Klein and Hartmann, 1993; Wood, 2012]. SC have high albedos (0.6–0.8) that reflect most of the shortwave radiation. Due to their lower elevation, outgoing longwave radiation at the top of SC is similar to that of the ocean surface. Overall, SC have a net radiative cooling effect on Earth’s climate [Ramanathan et al., 1989; Klein and Hartmann, 1993].

[3] There have been many mechanistic studies of SC formation and maintenance, including cloud top entrainment instability, cloud base decoupling, large-scale atmospheric subsidence, cloud top longwave radiative cooling, aerosol, and cloud microphysics effects [e.g., Lilly, 1968; Randall, 1980; Deardorff, 1980; Kuo and Schubert, 1988; Ackerman et al., 1993; Feingold et al., 1996; Stevens et al., 1998; Caldwell and Bretherton, 2009; Xiao et al., 2010, 2012]. However, relatively few studies have examined changes in SC due to climate change, and more importantly, the future changes in SC are highly uncertain in a warmer climate [Miller, 1997; Laufer et al., 2010]. In addition, Clement et al. [2009] show that the changes in cloud cover over the Northeast Pacific are affected by both local vertical temperature structure (changes in lapse rate) and large-scale circulation from both observational data and model simulations. All of these studies have focused on large-scale forcing of SC; none have examined how regional climate change might affect nearby SC coverage.

[4] Lower tropospheric stability (LTS) has been found to be closely linked to SC coverage [Klein and Hartmann, 1993]. Stevens [2005] and Richter and Mechoso [2006] showed further that atmospheric subsidence, which can be affected by large-scale Hadley circulation and local-scale circulation from adjacent continents, contributes to changes in LTS. Changes in adjacent land radiative heating may therefore also affect atmospheric LTS and SC due to variations in land-sea heat contrast, as well as local circulation changes. Moreover, Xu et al. [2004] and Richter and Mechoso [2006] found a significant impact of the orography of the adjacent continents on Namibian and Peruvian SC. The major cause of these changes was a decrease in LTS, which allows more cloud top entrainment, causing SC dissipation [Lilly, 1968; Kuo and Schubert, 1988].

[5] It is well known that California’s Central Valley (hereafter Central Valley) irrigation has a profound impact on the local land surface energy and water budget partitioning [Faunt, 2009] as well as on groundwater depletion [Famiglietti et al., 2011]. The Central Valley is a vast agricultural region that extends over 650 km in length and 40–150 km in width, and accounts for one sixth of irrigated land in the United States [Faunt, 2009].
Faunt [2009] showed that amount of annual evapotranspiration in the Central Valley exceeds that of precipitation by nearly 60%. This excess of evapotranspiration over precipitation results from irrigation having substantial effects on local climate and the regional hydrological cycle [e.g., Bonfils and Lobell, 2007; Kueppers et al., 2008; Lobell et al., 2009; Ozogán et al., 2006, 2010; Kustu et al., 2010, 2011; Sorooshian et al., 2011; Kueppers and Snyder, 2012] and has the potential to increase precipitation in downwind regions [DeAngelis et al., 2010; Puma and Cook, 2010; Lo and Famiglietti, 2013].

Irrigation can also affect large-scale atmospheric circulation. Results from Douglas et al. [2009] indicated that simulated water vapor fluxes over the Indian monsoon region are indeed sensitive to irrigation intensity; coupled with the decrease of the land-sea heat contrast, irrigation may reduce Indian summer monsoon rainfall [Niyogi et al., 2010]. In addition, Gordon et al. [2005] and Douglas et al. [2006] indicated that agricultural irrigation has the potential to alter regional climate by modifying water vapor fluxes. The increased water vapor flux due to irrigation can modify convective available potential energy, which causes changes in the intensity of convection and precipitation. This raises the question of whether Central Valley irrigation affects SC on California’s west coast via modifying local circulation and land surface energy budgets. This study focuses on the response of SC to irrigation practices in the Central Valley region of California and explores which mechanisms can cause changes in SC cover using a coupled land-atmosphere climate model.

2. Model and Experiment Setup

Configurations for the models used in this study follow those of Lo and Famiglietti [2013]. We utilize the National Center for Atmospheric Research Community Atmosphere Model, version 3.5 (CAM3.5) and Community Land Model, version 3.5 (CLM3.5), to conduct two simulations: a
control run (CTR) and an irrigation run (IRRI). Simulations are performed at T85 resolution with 26 vertical hybrid coordinate levels, and climatological sea surface temperatures (SSTs) and sea ice concentrations are applied [Hurrell et al., 2008]. In CAM3.5, SC occurrence is diagnosed as a linear function of LTS [Collins et al., 2004] for better representation of SC. Also, an adaptation of Lo and Famiglietti’s [2010] fitting approach is also employed to estimate the initial conditions of the water table depth and soil moisture profile.

The simulation produces global monthly outputs over a 90 year period. The 90 year time series of Central Valley averaged water table depth had little drift, and the global average (longitude: 0°–360° and latitude: 90°S–90°N) in monthly variations in groundwater table depths approaches an equilibrium depth after several decades. Hence, in this study, we use half of the simulation time period (45 years) as the spin-up time, and the latter 45 years are used for the analysis. In the IRRI run, surface water deliveries and groundwater withdrawal are prescribed in the CLM3.5 within the Central Valley. The impact of irrigation in the Central Valley on coastal SC can therefore be identified via differences between the two experiments. Note that the two-tailed Student’s t test is used to evaluate the statistical significance of the difference. We used a 5% significance level to test whether the null hypothesis, which says that the difference is zero, can be rejected. Two-tailed tests were used since we do not know whether the effect of irrigation is negative or positive.

Figure 2. (a) Annual cycles of LTS [K] and cloud liquid water [g/kg]; (b) vertical changes due to irrigation in potential temperature (θ) [K] from 1000 mb to 500 mb. Both figures are spatial averages for the area of large cloud fraction differences over the Pacific near California as seen in Figure 1.

3. Results

3.1. General Features

The response of coastal SC to irrigation is evidenced by the spatial distribution of the changes between the IRRI and CTR runs shown in Figure 1. The results are for the 45 year average for the period from June to August. The green-shaded cells in Figure 1a show the irrigated area in the Central Valley with T85 spatial resolution and do not overlap with other shaded cells. The contour lines in Figure 1 indicate the climatology (45 year average in the CTR run) during the summer. Major impacts of irrigation are visible in the precipitation over the coastal SC region (the red to blue shading in the color scale). Negative anomalies west of California are apparent, indicating a decrease in precipitation of 0.5 to 2 mm/month, corresponding to a decline of 3% to 14%. Note that only locations with significant differences (α = 0.05) are shown in Figure 1.

In order to understand the cause of the difference in precipitation from irrigation practices, changes in the low-level cloud fraction and cloud liquid water are shown in Figures 1b and 1c. The decreased cloud liquid water in the SC layer shown in Figure 1c is consistent with the decrease in precipitation. More importantly, the cloud fraction decreases by about 2–4% (Figure 1b), which results in a roughly 4% increase of solar radiation (8 W/m²) averaged over the area where the significant decline in cloud fraction occurs. Note that we define the first and second layer (roughly below 950 mb) in the CAM3.5 as the SC layer since they have the largest cloud fractions in the summer climatology in coastal California. Moreover, the cloud fractions in these two layers also show the greatest reduction in the IRRI run.

An interesting puzzle that was considered in the irrigation experiment concerns water vapor in the lower troposphere. A recent study by Lo and Famiglietti [2013] showed that irrigation in the Central Valley had the potential to enhance the precipitation over the southwestern U.S. due to the excess water vapor resulting from irrigation. The near-surface water vapor (second atmospheric model layer, Figure 1d) also increases over the coastal SC regions resulting from irrigation. However, since SC coverage is proportional to LTS, SC coverage in the model will not be affected directly by changes in water vapor.

We calculate the LTS (difference of θ between 700 mb and 1000 mb) averaged over the area of large cloud fraction
differences over the ocean as seen in Figure 1b. Figure 2a shows a comparison of the climatology of LTS and cloud liquid water from the CTR run. LTS is highly correlated with cloud liquid water and cloud fraction (not shown), which is consistent with the results from Zhang et al. [2009]. Figure 2b shows the changes (between the IRRI and CTR runs) in $y$ from 1000 mb to 500 mb, which shows a tilt to the left in the vertical profile, signifying that the atmosphere is less stable. Because of the way that SC are parameterized in CAM3.5, smaller LTS values result in a reduction of SC coverage, which results in a reduction of precipitation. Such an association between LTS and SC coverage and precipitation is known to exist in reality [Klein and Hartmann, 1993; Stevens, 2005]. We also computed the estimated inversion strength (EIS), which is known to correlate more strongly with SC coverage than LTS [Wood and Bretherton, 2006], and found that the monthly variations of EIS over coast of California are very similar to that of LTS.

Our analyses show that irrigation modifies the Central Valley surface energy budget by increasing the latent heat flux (Figure 3b) through an increase in soil water content. The sensible heat flux (Figure 3c) and land surface temperature (Figure 3a) over the Central Valley, however, are decreased. The largest decline in surface temperature is over Central Valley irrigation regions. Since we use prescribed SST in the model, surface temperature over the ocean does not change significantly, resulting in a smaller land-sea heat contrast with Central Valley irrigation. Figure 4 shows the changes in near-surface wind and subsidence at 850 mb and 700 mb. It clearly shows the reduced sea breeze due to the decreased land-sea heat contrast, and the corresponding subsidence decreases over the coastal regions indicating local circulation changes. Therefore, the lower LTS is due to the weakening of the local circulation (sea breeze) and a decrease in subsidence over the SC regions outside of California.

The major mechanism causing the smaller land-sea thermal contrast is irrigation in the Central Valley (colder land surface resulting from irrigation), lowering the sea breeze, together with the smaller subsidence. In this model (CAM3.5), therefore, the dominant impact of irrigation in the Central Valley is the alteration of the local circulation (or sea breeze as shown in Figure 4), which makes the subsidence smaller over the near coastal region, which lowers the LTS.
3.2. Sensitivity Experiments

[16] To test sensitivities of the results of this study to the initial and boundary conditions, we conducted another three sets of simulations, with different initial conditions and SST datasets, but with the same irrigation water values applied. The ensemble simulations show consistent results (not shown), indicating that the results of declining SC fraction, cloud liquid water, and precipitation resulting from irrigation in the Central Valley are robust.

[17] We also explore the effects of irrigation intensity in the Central Valley by conducting two more simulations, (1) using half of the irrigation water amount (175 mm/yr) in EXP1 and (2) doubling the irrigation water amount (700 mm/yr) in EXP2. We hypothesize that as the amount of applied irrigation water increases, the land-sea heat contrast and sea breeze will further decrease resulting in lower LTS and SC cover. Therefore, SC precipitation will further be inhibited as Central Valley irrigation water increases. Comparisons among the sensitivity experiments of irrigation intensity are shown in Figure 5. The results show consistent decreases in land surface temperature in the Central Valley as the irrigation intensity increases. Decreases in sea breeze (defined as the magnitude of the near-surface horizontal wind), cloud liquid water, LTS, and precipitation correspond with higher irrigation intensity. Therefore, it can be concluded that Central Valley irrigation can induce a weakening of the sea breeze and subsequently, a decrease in the fraction of SC cover and an increase in absorbed solar radiation (Figure 5f). Overall, the systematic dependence on the total amount of irrigation suggests that the mechanism (reduced sea breeze with Central Valley irrigation) is robust.

Figure 4. The changes in (a) near-surface wind [m/s], (b) subsidence [0.01pa/s] at 850 mb, and (c) subsidence [0.01pa/s] at 750 mb. Gray shading indicates the 95% significance level. The contour in Figure 4a is for the horizontal wind (u), and its significance test is based on the magnitude of the horizontal wind.
Variations in the response to irrigation practices in the Central Valley were evaluated with coupled land-atmosphere model simulations. In our simulations, irrigation in the Central Valley tends to decrease SC coverage over the eastern Pacific Ocean in the vicinity of California. We find that irrigation modifies the surface energy budget by increasing latent heat flux and decreasing the sensible heat flux and surface temperature over the irrigated area. Consequently, the land-sea heat contrast is reduced, resulting in a weakening of the local circulation (sea breeze) as well as subsidence.

Figure 5. Scatterplots of the annual amount of applied irrigation water [mm] versus the June–August mean (a) surface temperature [K], (b) LTS [K], (c) cloud liquid water [g/kg], (d) precipitation [mm/mon], (e) horizontal wind [m/s], and (f) downward solar radiation [W/m²], respectively. The surface temperature is averaged for the Central Valley, and the horizontal wind is averaged for the regions near the coast that change the most (longitude: 123°W–120°W and latitude: 35°N–38°N). LTS, cloud liquid water, precipitation, and radiation are averaged over the Pacific near California where the cloud fraction has significantly decreased over the ocean as shown in Figure 1b. The total amounts of irrigation water applied are 0 mm/yr, 175 mm/yr, 350 mm/yr, and 700 mm/yr. The error bars are uncertainties estimated based on the standard error of the mean from the simulations of the 45 summers.
over the SC regions near California, reducing the LTS. In CAM3.5, this causes a reduction in both SC coverage and precipitation. Absorbed solar radiation over the SC regions increased by 8 W/m² (3.7%). As indicated by Douglas et al. [2009], after irrigation, the land-sea heat contrast is also reduced, which results in a weakening of the Asian summer monsoon. This is consistent with our result showing that the reduced land-sea heat contrast results in a weakening of the local circulation and decreases low-level atmosphere stability over the Pacific Ocean in the vicinity of California.

[19] Because SC are typically either nonprecipitating or drizzling clouds, the climatological impact of SC tends to come from their long lifetimes and high albedos, which have great impacts on the Earth’s radiation budget. While this research focuses on irrigation in California, there are several large regions with intensive irrigation around the world, such as Peru and China, which may have significant impacts on nearby SC and the radiation budget. This research indicates that irrigation causes reductions of the SC; thus, more solar radiation can penetrate the atmosphere and reach Earth’s surface, having a net warming effect. Analyses of Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) model simulations have shown that atmospheric temperature is expected to increase due to increased greenhouse gas concentrations. Most of the IPCC AR4 models [Solomon et al., 2007], however, lack any representation of irrigation practices. The findings of this study suggest that after incorporating the irrigation water fluxes into the global climate models, the absorbed solar radiation may further increase over the SC regions affected by the irrigation.

[20] Our simulations suggest that standard irrigation practice in the Central Valley reduces LTS by several tenths of a degree, which corresponds to reduction in atmospheric stability. As previously mentioned, lower LTS is due to the weakening of the local circulation and a decrease in subsidence over the SC regions outside of California. While we find a significant decrease in the monthly mean near-surface sea breeze due to irrigation in the Central Valley, the decreases in the monthly mean subsidence are not significant as shown in Figure 4. We believe that this is due to sampling issues as suggested by Zhang et al. [2009]. They showed that the distribution of cloud fraction conditioned on divergence (subsidence) in a mixed layer model is rather different when sampled at daily versus seasonal time scales. Therefore, to study the impacts of the local circulation changes (especially the subsidence) due to irrigation requires higher temporal output. This will be the primary goal in our future work. In addition, as shown by Myers and Norris [2012], impacts of subsidence and EIS may not be consistent with varied responses of SC cover, depending on the relative changes of subsidence and EIS at different climate states. Higher frequency outputs with improved boundary layer cloud parameterization may lead to the better understanding of relative effects of the subsidence, inversion stability, and LTS on the SC cover.

[21] Moreover, in the IRRI run, irrigation water is evenly distributed in each time step over the simulation time period, as in other studies [Puma and Cook, 2010]. However, the timing of irrigation could alter the impacts of Central Valley irrigation on SC because nocturnal precipitation is dominant over the SC regions. To what extent the differences are due to the timing of irrigation will require further research, including more details on realistic farmers’ irrigation practices, which can be prescribed in the CLM. In addition, in this study, our main hypothesis is that Central Valley irrigation decreases temperature over land, reducing the sea-breeze effect and hence reducing subsidence, which decreases cloud fraction directly by reducing LTS. However, the increased water vapor from irrigation has the potential to increase the cloud fraction; therefore, we use the two-tailed statistical significance test to account for both effects.

[22] Finally, the changes in SC cover resulting from irrigation in the Central Valley are based on the assumption that changes in cloud fraction are proportional to changes in LTS in CAM3.5. In this study, we want to demonstrate that changes in regional land use can potentially have significant impact on SC cover. Since SC simulations are sensitive to different cloud parameterizations used in atmospheric models, other global or regional climate models or even large eddy simulations are needed to confirm the results from this study. For example, it will be interesting to explore whether CAM5, which has a sophisticated representation of SC dynamics, produces the same decrease in SC coverage. We anticipate testing the newest cloud parameterization and high spatial resolution simulations in CAM5 in our future work and focusing on the diurnal scales of the land-sea breeze as well as subsidence variations.

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References


Kueppers, L., and M. Snyder (2012), In


Lobell, D., G. Bala, A. Mirin, T. Philips, R. Maxwell, and D. Rotman (2009), Radiation and land use change may be reducing the Indian summer monsoon rainfall, J. Atmos. Sci., 66, 3503–3522.


