Direct impact of solar farm deployment on surface longwave radiation

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Abstract
Motivated by a previous study of using the Moderate Resolution Imaging Spectroradiometers (MODIS) observations to quantify changes in surface shortwave spectral reflectances caused by six solar farms in the southwest United States, here we used a similar method to study the longwave effects of the same six solar farms, with emphases on surface emissivities and land surface temperature (LST). Two MODIS surface products were examined: one relying on generalized split-window algorithm while assuming emissivities from land cover classifications (MYD11A2), the other based on Temperature Emissivity Separation algorithm capable of dynamically retrieving emissivities (MYD21A2). Both products suggest that, compared to adjacent regions without changes before and after solar farm constructions, the solar farm sites have reduced outgoing radiances in three MODIS infrared window channels. Such reduction in upward longwave radiation is consistent with previous in situ measurements. The MYD11A2 results show constant emissivities before and after solar farm constructions because its land type classification algorithm is not aware of the presence of solar farms. The estimated daytime and nighttime LST reduction due to solar farm deployment are $\sim 1–4K$ and $\sim 0.2–0.9K$, respectively. The MYD21A2 results indicate a decrease in Band 31 ($10.78–11.28 \mu m$) emissivity up to $-0.01$ and little change in Band 32 ($11.77–12.27 \mu m$) emissivity. The LST decreases in the MYD21A2 is slightly smaller than its counterpart in the MYD11A2. Laboratory and in situ measurements indicate the longwave emissivity of solar panels can be as low as 0.83, considerably smaller than MODIS retrieved surface emissivity over the solar farm sites. The contribution of exposed and shaded ground within the solar farm to the upward longwave radiation needs to be considered to fully explain the results. A synthesis of MODIS observations and published in situ measurements is presented. Implication for parameterizing such solar farm longwave effect in the climate models is also discussed.

1. Introduction

Given the imminent threats of climate changes caused by the increases of greenhouse gas emissions, it becomes increasingly urgent to reduce carbon emission and slow down the warming trend (IPCC 2013). Increasing the proportion of renewable energy, including solar energy, in electricity production is widely considered as an effective remedy to the issue. Solar farming refers to building solar facilities and installing solar panels to harvest incident solar energy and generate electricity. While solar farms can produce renewable energy for our demands and reduce carbon emission from electricity production (Ito et al 2003, Akella et al 2009), solar panels can, as visually black surfaces, alter the surface radiative properties (Hu et al 2016, Li et al 2018, Fan and Huang 2020, Zhang and Xu 2020) and, as elevated and tilted surfaces, affect boundary layer dynamics (Fthenakis and Yu 2013).

The most apparent and visible effect of solar farming is the reduction of surface reflectance. Solar panels are designed to absorb as much solar energy as possible for maximum energy generation. Unlike other land cover changes where all absorbed solar energy is converted to thermal energy, a portion of solar energy absorbed by
solar panels is converted to electricity. The current conversion efficiency (fraction of incoming solar energy converted to electricity) ranges from 10.5% to 26.7% (Green et al 2020). Thus, still a considerable amount of absorbed solar energy is converted to the thermal energy by the solar panels. By doing so, the solar farming could affect the surface energy balance. Several climate modeling studies simulated the potential climate effects of large-scale solar farming due to such perturbation on the surface net downward solar radiation. These studies replaced the surface albedo of the original surface by the assigned effective surface albedo of a typical solar farm (Hu et al 2016, Millstein and Menon 2011, Li et al 2018, Lu et al 2020). They suggested that, if solar farms were to be built in a large scale in the future, the reduction of reflected solar radiation and the energy conversion to electricity could at least result in a significant regional climate effect. These studies, however, disagreed with the sign and magnitude of the effect, which is primarily due to different assumptions on the solar panels, the scale of deployment, and the models used for the simulations.

Both in situ measurements (Barron-Gafford et al 2016, Chang et al 2018, Broadbent et al 2019) and satellite retrievals (Fan and Huang 2020, Zhang and Xu 2020) have consistently supported this shortwave effect of solar farms and provided observational constraints for modeling studies. Specifically, they quantified the magnitude of the changes in surface spectral reflectances, which depends on radiative properties of solar panels and underlying surfaces. Compared to in situ measurements, long records of high-quality satellite global observations enable us to contrast not only between solar farms and adjacent background surfaces but also before and after the construction of solar farms. Using the Moderate Resolution Imaging Spectroradiometers (MODIS) aboard the NASA Aqua satellite, our prior study (Fan and Huang 2020) analyzed the observations above six solar farms in the southwestern U.S. and showed an up to 25% reduction in surface reflectance over seven visible and near-infrared MODIS bands, which led to a ~23% decrease in upward shortwave radiative flux at the surface and ~14%–18% decrease at the top of the atmosphere.

Fan and Huang (2020) demonstrated feasibility of using long-term satellite retrievals to quantify the surface reflectance changes caused by solar farm deployments in the past decade. Its success motivates us to use the similar approach to investigate the impact of solar farming on surface longwave radiation budgets, i.e., the impact on surface spectral emissivities and land skin temperature (LST). Such impacts on longwave radiation have not been incorporated into any aforementioned large-scale modeling studies. Intuitively, the net energy gain from the shortwave effect should warm the solar panels during the day. If everything is equal, the temperature of the solar panels should be expected to be higher than the background surface. However, in reality, multiple factors have to be considered. For example, the solar panel is usually placed ~1–2 meters above the surface and it is well known that desert daytime LST is much warmer than the surface air temperature due to strong surface solar absorption. Zhang and Xu (2020) used the MODIS Land Surface Temperature and Emissivity Product Collection-6 to analyze 23 solar farms over the globe. They concluded that both daytime and nighttime LST over the solar farm had decreased because of the energy conversion to electricity and enhanced convective heating. Such notion of cooler surfaces over solar farms, however, is not consistent with evidence from in situ measurements. Using in situ measurements obtained from a variety of positions ranging from inside the soil to 6.3 m above the surface, Broadbent et al (2019) showed that, during the daytime, the solar module is significantly hotter than the ground of the reference site without solar panels except at noon when the temperatures of both surfaces are similar. The upward longwave radiative flux measured at 5.7 meters above the surface is indeed smaller over the solar farm than over the reference site, suggesting that the longwave emissivity, not, LST, of the solar farm is smaller than its counterpart of the original barren surface (i.e., the surface at the reference site). Broadbent et al (2019) further estimated the broadband longwave emissivity of the solar panel to be 0.83, in contrast to the broadband emissivity of reference barren sand surface of 0.92.

As a continuation of our previous study and an attempt to understand the aforementioned two studies about the effect of solar farms on the longwave surface radiation budget, this study analyzes the same six solar farms studied in Fan and Huang (2020). Section 2 summarizes the data and modeling tool used in this study, including two MODIS surface retrieval products and a forward radiative transfer model. Section 3 presents a case study of the Desert sunlight Solar Farm (DSSF) to ensure that the differences as seen in the MODIS products before and after the construction of the solar farm are indeed due to the deployment of solar panels instead of other meteorological factors. The changes of surface emissivities and LSTs in six solar farms are then summarized in section 4, with a highlight on the distinction of different retrieval products and an emphasis on the importance of emissivity retrievals in determining the LSTs. Bringing all available evidence together including previous studies of lab measurements and in situ measurements, and our satellite retrievals from two products, section 5 discusses how to interpret all the results. A final summary and further discussion about the implication for climate modeling studies are then given in section 6.
2. Data and methods

Observations made by MODIS on NASA Aqua satellite are used in this study. MODIS is a 36-band imaging spectroradiometer that can measure spectral radiances ranging from visible to infrared bands. The Aqua satellite was launched in May 2002. Further details about the instrument and the satellite can be found in King et al (1992, 2003). Here, we used level-3 gridded and averaged products of LSTs and surface spectral emissivities of MODIS infrared window channels in the analysis.

Specifically, we analyzed two MODIS Level-3 LST and Emissivity Products. The product ID of the first is MxD11. This product uses a generalized split-window algorithm to estimate LST after performing atmospheric correction. Surface emissivities of two MODIS thermal infrared window bands (bands 31 and 32) are assigned from a look-up table based on different land cover types, atmospheric column water vapor, and surface air temperature. Validation showed that the retrieved LST has an uncertainty of less than 1 K if the emissivities are known and accurate (Wan et al 2015). MxD11 has been used in Zhang and Xu (2020) to study the LST changes in multiple solar farms in China. The other product is referred to as MxD21. It uses Temperature Emissivity Separation (TES) algorithm to dynamically retrieve surface emissivities in three MODIS thermal infrared window bands (bands 29, 31, and 32) and the LST at the same time. This product aims to address several biases in the MxD11 product, especially improving the retrieval quality over the barren area (Hulley and Hook 2017). In addition, the ability to directly estimate the surface emissivities rather than inferring from the lookup table shows the potential to depict the emissivity effect of solar farms, considering that the look-up table used by MxD11 does not consider the presence of solar panels on the ground. Validation of the MxD21 retrieval products showed consistent accuracies in LST retrieval at the 1 K level and an emissivity error of up to 2% over all land surface types including vegetation, water, and deserts (Hulley and Hook 2017). For both products, several versions with different spatial and temporal resolutions of both products are available for use. Here, to be consistent with our previous study (Fan and Huang 2020), the version with 8-day temporal and 1-km spatial resolutions was chosen, despite the availability of daily products. An advantage of using the 8-day product is that each data point in an 8-day period is the optimal estimate of the respective band emissivity or LST within the period (i.e., from only clear-sky observations within an 8-day period) so that the adversarial effects on surface retrievals from clouds and solar zenith angle can be minimized. The full product IDs analyzed in our study are MYD11A2 and MYD21A2, respectively.

Statistical analyses were carried out in six operating solar farms in the southwestern U.S, which is consistent with our previous study (Fan and Huang 2020). Basic information about these solar farms is shown in table 1. Each solar farm site and the corresponding four control sites are the same as in our previous study. The control sites were chosen carefully based on true-color satellite imageries to ensure retrieval quality and avoid involving other land cover changes as much as possible throughout the years of interest. Surface properties before and after the construction of a solar farm were compared to each other to derive the changes due to solar farm deployments. Large-scale meteorological variables could be potential confounders that deviate our quantity estimation. The local meteorological effects should affect both the solar farms and the corresponding control fields in a similar way because of the close proximity (<20 km between a solar farm and any respective control site). By removing the differences between solar farms and surrounding bare grounds, the effects from large-scale meteorological factors are removed and the effects from solar panels are reflected in the anomalies.

MODTRAN5 (Moderate Transmission Code, version 5) is used as the forward radiative transfer model to evaluate the impacts of surface emissivity and LST change on the surface and TOA radiation fluxes. MODTRAN5 was collaboratively developed by Spectral Sciences Inc. and Air Force Research Laboratory (Berk et al 2005) and has been widely applied in remote sensing studies and applications. Comparisons between MODTRAN5 and LBLRTM, a line-by-line radiative transfer model (Clough and Iacono 1995, Clough et al 2005), showed agreement up to a few percent or better (Anderson et al 2006). Surface emissivities before and after the construction of this solar farm were directly fed into the radiative transfer calculation. Climatological LST, temperature and humidity profiles of the solar farm site were obtained from hourly output of the ECMWF Reanalysis v5 (ERA5) with a spatial resolution of 0.25° by 0.25° (Hersbach et al 2018a, 2018b, 2020).

3. Retrieved emissivity and LST changes in DSSF

As a case study, the MODIS observations over the Desert sunlight Solar Farm (DSSF) are first analyzed. The DSSF site is located in Riverside County, California. It occupies a total area of 16 km² with a power capacity of 550 MW. It was constructed between 2012 and 2015. More information, including the aerial snapshot of the solar farm, can be found in Fan and Huang (2020). For the case study, here we only show the results from MYD21A2. Results from MYD11A2 will be extensively discussed in section 4.
### Table 1. Basic information about the six solar farm sites examined in this study. The unit for power generation is megawatts in alternative current (MW\textsubscript{AC}).

| Full name and acronym   | Location                 | Starting year of construction | Year of commission | Site area | Power (nominal capacity) |
|-------------------------|--------------------------|-------------------------------|--------------------|-----------|--------------------------|
| Solar Star (SSSF)       | Rosamond, California     | 2011                          | 2015               | 13 km\textsuperscript{2} | 579 MW\textsubscript{AC} |
| Topaz Solar Farm (TSF)  | Carrizo Plain, California| 2011                          | 2014               | 19 km\textsuperscript{2} | 550 MW\textsubscript{AC} |
| Desert sunlight Solar Farm (DSSF) | Riverside County, California | 2012                          | 2015               | 16 km\textsuperscript{2} | 550 MW\textsubscript{AC} |
| Copper Mountain Solar Facility (CMSF) | Boulder City, Nevada | 2010                          | 2016               | 16 km\textsuperscript{2} | 552 MW\textsubscript{AC} |
| California Valley Solar Ranch (CVSR) | Carrizo Plain, California | 2011                          | 2013               | 8 km\textsuperscript{2}   | 250 MW\textsubscript{AC} |
| Agua Caliente Solar Project (ACSP) | Yuma County, Arizona    | 2011                          | 2014               | 10 km\textsuperscript{2} | 290 MW\textsubscript{AC} |
The left column in figure 1 shows the one-year mean surface emissivity difference between 2018 and 2009 (i.e., three years before and after the DSSF construction) over the solar farm and surrounding area, with four selected control sites labeled as C1, C2, C3, and C4, respectively. Within the area covered by solar panels (green rectangles), distinct changes in surface emissivities can be seen in all three MODIS bands. The differences between 2018 and 2009 are $+0.02$ for Band 29, $-0.006$ for Band 31, and $+0.001$ for Band 32. The differences in for Band 31 and Band 32 surface emissivities are small, likely comparable to or even smaller than the uncertainties in each individual retrieval caused by other factors (e.g., atmospheric correction, degraded instrument performance over the years). This also explains why the maps of emissivity changes are noisy for Bands 31 and 32. The four control fields are the same as those chosen in Fan and Huang (2020), which were selected by choosing regions with minimal land cover changes such as vegetation removal, avoiding complicated terrains, and having the same area as the corresponding solar farm. It turns out that the emissivity changes over the four control fields are indeed close to zero. The middle column shows the raw MODIS time series of the surface spectral emissivities for the three bands, respectively. A 13-step (104-day) moving average has been applied to suppress the intra-seasonal variation and produce the low-pass filtered time series for each band, as shown in the right column. Before the construction of the solar farm (i.e., prior to 2012), surface emissivities of the solar farm site closely tracked those of the control fields. It is during the construction period of the solar farm...

Figure 1. Spatial pattern and temporal trend of the MYD21A2 surface spectral emissivities at the DSSF. Three rows show surface emissivity in the MODIS Band 29, 31, and 32, respectively. Left column shows the annual-mean emissivity difference between 2018 and 2009. Green box encloses the solar farm site, while four gray boxes enclose the control sites where there has been no land use change. Raw and smoothed time series of the emissivity the solar farm site and four control sites are plotted in the middle and right columns, respectively. The smoothing is done by a 13-point moving average to suppress the intra-seasonal variation. Purple dashed vertical lines indicate the start and end of the solar farm construction (i.e., 2012 and 2015).
(i.e., 2012–2015, indicated by two vertical purple dashed lines in figure 1) that a clear change of surface emissivities in the solar farm happened and started to distinguish from the time series of the four control sites. After the commission of the solar farm, the time series of the surface emissivity of the solar farm is consistently separated from those of the control sites for all three bands. The time series shown in the middle and right columns can clearly attribute the changes of surface emissivity to the installation of solar panels rather than other factors.

Figure 2 shows the daytime (top row) and nighttime LST (bottom row) anomalies at the DSSF as retrieved from the MYD21A2 product. DAYtime and nighttime here refer to ∼1:30 pm and ∼1:30 am local time when the MODIS makes the measurements. In contrast to surface emissivities, LST has a significant seasonal cycle that masks the small signal from solar panel deployment. Besides, surface temperature is subject to effects by large-scale meteorological influences, which exerts equally on the solar farm and control sites due to their close proximity. Therefore, all time series are thus subtracted by the averaged LST over the respective chosen control fields in figure 2 in order to remove both the seasonal cycle and other large-scale meteorological influences, assuming that such meteorological influences affect both solar farm and control sites in the same manner. The time series without deseasonalizing or subtracted by the seasonal mean are likewise presented in figures S1 and S2 (available online at stacks.iop.org/ERC/3/125006/mmedia) in the supplementary materials. Over the control sites and other areas surrounding the solar farm, the annual-mean daytime or nighttime LST difference between 2018 and 2009 is positive and can be as large as ∼1.6 K. But the difference over the DSSF is negative, ∼~2 K for the daytime and ∼~0.5 K for the nighttime LST differences. Defining the anomaly as the deviation from the LST averaged over the four control sites, the original and low-pass filtered LST anomaly time series are plotted in the middle and right columns of figure 2, respectively. Similar to the discussion about figure 1, it is clear that both daytime and nighttime LST anomalies over the DSSF started to decrease when the solar farm construction started. Such tendency is especially obvious for the daytime LST anomalies: for the 104-day smoothed time series, the daytime LST anomaly over the DSSF was ∼~1.2–1.6 K before 2012, dropped almost linearly with time to ∼~0.5 K from 2012 to 2014, and then stayed between 0 and ∼~0.5 K after the DSSF started to operate. The nighttime LST anomalies over the DSSF also drops from 2012 to 2015, but the amplitude is smaller than its nighttime counterpart. In contrast, the time series of LST anomalies over the control sites do not exhibit similar changes during the DSSF construction period. Such time series plots clearly reveal that the solar farm construction, not climate variations, is the reason why such changes are seen over the DSSF site but not over the control sites.
Simulated outgoing longwave radiation (OLR) and its change due to solar farm deployment based on the ERA5 reanalysis profiles of temperature and humidity profiles and the surface emissivities over the DSSF site derived from the MYD21A2 product. The land surface temperature change is also from the same MODIS product. To be representative, the changes for daytime and nighttime and the changes for winter and summer are computed separately. The calculation was done by MODTRAN version 5. More details of the calculation can be found in section 3.

We then used MODTRAN 5 to calculate how much observed changes by the MYD21A2 product can affect the outgoing longwave radiation (OLR) at the top of the atmosphere (TOA). To consider the diurnal and seasonal difference in temperature and humidity profiles, four typical scenarios are considered, i.e., daytime and nighttime in the winter season (DJF) and in the summer season (JJA), respectively. The temperature and humidity profiles, as well as the LST in the control case, were from the ERA5 reanalysis hourly output at 12 pm and 12 am (local time) averaged over DJF and JJA in the year of 2018, respectively. The observed surface emissivities before the construction of DSSF were directly used for the control case calculation. For the perturbed case, the aforementioned changes as in the MODIS MYD21A2 product were added onto the control case scenario. The differences between the perturbed and control cases are shown in Table 2. OLR is reduced by 2.85 W m$^{-2}$ and 0.59 W m$^{-2}$ for the summer daytime and nighttime, respectively. Note such change is smaller by a factor of $\sim$17–84 than the change of TOA reflected shortwave flux caused by the DSSF construction, i.e., $\sim$50 W m$^{-2}$ (Fan and Huang 2020). The OLR changes here are overwhelmingly caused by the changes of LST, as the changes of surface spectral emissivity only ranges from $-0.0006$ to $-0.0107$. The difference between daytime and nighttime difference is dominantly due to the different change of LST during daytime and nighttime. The changes of OLR in DJF are larger than their counterparts in JJA because the atmosphere has smaller total column water vapor in the winter than in the summer, leading to more surface radiation reaching to the TOA (especially over the thermal IR window region) in the winter than in the summer.

In summary, the analysis of the MYD21A2 product shows that solar farm deployment in the DSSF leads to a decrease in the retrieved LST for both daytime and nighttime and such decrease distinguishes the DSSF site from the surrounding control sites on both the spatial map and the time series plot. The surface emissivity changes over the DSSF site can be also seen from the MYD21A2 product, especially from the time series plot, but the changes are small, at least a factor of 10 smaller than the change of shortwave surface reflectance shown in Fan and Huang (2020). Nevertheless, from the changes in LST and surface emissivities and the calculated OLR changes, it is clear that solar farm deployment must have reduced the surface upward longwave radiances. Otherwise, it would not be possible to have such negative changes in LSTs and weak negative changes in surface emissivities. This inference is indeed consistent with the in situ measurements from Broadbent et al. (2019).

### Table 2. Simulated outgoing longwave radiation (OLR) and its change due to solar farm deployment

| Variables                  | Before | After | Change  |
|----------------------------|--------|-------|---------|
| From MYD21A2               |        |       |         |
| Band 29 emissivity         | 0.885  | 0.896 | 0.011   |
| Band 31 emissivity         | 0.954  | 0.947 | -0.007  |
| Band 32 emissivity         | 0.968  | 0.968 | $7 \times 10^{-4}$ |
| From ERA5 Reanalysis & MYD21A2 results | | | |
| LST at 1:30pm (K)          | 329.68 | 302.65 | 2.00    |
| LST at 1:30am (K)          | 300.81 | 280.17 | -0.50   |
| From MODTRAN Calculation   |        |       |         |
| OLR at 1:30pm (W m$^{-2}$) | 321.69 | 278.35 | -2.85   |
| OLR at 1:30am (W m$^{-2}$) | 286.73 | 244.51 | -0.59   |

4. Retrieved emissivity and LST changes in the six solar farms

The analyses described in the previous section have also been applied to other five solar farms listed in Table 1. Specifically, for a given solar farm and its neighboring control sites, four years of data right before the construction and four years of data right after the operation were processed. The differences were then obtained for each season between two four-year eras (i.e., in total 16 differences between two eras). Large-scale climate variations such as ENSO can definitely affect such seasonally averaged LST differences. To suppress such influence of large-scale climate variability, the difference averaged over four control sites is subtracted from the difference over the corresponding solar farm site. The premise here is that the large-scale variability should affect the solar farm in the same way as it affects the nearby control sites (which are no more than a few kilometers away from the solar farm site). Thus, by such spatial differencing, the changes due to solar farm deployment can be
Meanwhile, the MYD11A2 shows a reduction of LST for both day and night across all the six sites and 32 show zero difference before and after the solar farm construction for all the six sites. The MYD11A2 surface emissivity retrieval with zeros changes in the surface emissivity would have not resulted in reduced LST. The differences shown in the MYD21A2 product are less uniform than that in MYD11A2 across the six sites. The difference in the Band 32 surface emissivity can be positive or negative but very small in magnitude, and except the DSSF, the rest sites show no statistically significant differences. For Band 29, only the DSSF site has a positive difference of 0.02 in surface emissivity, while the rest sites all have a negative difference comparable to their changes in the Band 31 surface emissivity. The MYD21A2 daytime LST differences are much smaller in magnitude, and except the DSSF, the rest sites show no statistically significant differences in the LST. The ACSP site, as an outlier, shows positive LST differences over both daytime and nighttime. A close examination of the cloud-free annual mosaics figure 5 shows that the ACSP site used to be cropland, and its vegetation coverage varied from year to year. The vegetation coverage was greatly reduced in the last year before solar farm construction (i.e., 2010), presumably in preparation for the upcoming construction. This contrasts with other sites, where the land cover does not change prior to the solar farm construction (an example of the DSSF annual mosaics is given in figure 5), thus the LST differences of these sites can better reveal the impact due to solar farm deployment.

Figure 3 summarizes the differences obtained from such analyses using either MYD21A2 (black) or MYD11A2 (red) data products. Note that, unlike MYD21A2, MYD11A2 only provides surface emissivity retrievals for MODIS Bands 31 and 32 but not Band 29. As mentioned in section 2, MYD11A2 adopted a look-up table approach for surface emissivity retrievals. As a result, the MYD11A2 surface emissivity over both Bands 31 and 32 show zero difference before and after the solar farm construction for all the six sites (figures 3(b) and (c)). Meanwhile, the MYD11A2 shows a reduction of LST for both day and night across all the six sites (figures 3(d) and (e)), with the daytime reduction larger than nighttime reduction by 1–3 K. Consistent with the discussion in section 3, this also suggests that MODIS observed upward radiance at the TOA must be reduced after the solar farm construction. Otherwise, MYD11A2 retrieval with zeros changes in the surface emissivity would have not resulted in reduced LST. The differences shown in the MYD21A2 product are less uniform than that in MYD11A2 across the six sites. The difference in the Band 32 surface emissivity can be positive or negative but very small in magnitude (within ±0.004) for all the six sites. The difference in Band 31 surface emissivity is small but all negative and statistically significant. For Band 29, only the DSSF site has a positive difference of 0.02 in surface emissivity, while the rest sites all have a negative difference comparable to their changes in the Band 31 surface emissivity. The MYD21A2 daytime LST differences are negative, comparable to the changes in MYD11A2 counterparts, and statistically significant for all sites except the ACSP. The MYD21A2 nighttime LST differences are much smaller in magnitude, and except the DSSF, the rest sites show no statistically significant differences in the LST. The ACSP site, as an outlier, shows positive LST differences over both daytime and nighttime. A close examination of the cloud-free annual mosaics (figure 4) shows that the ACSP site used to be cropland, and its vegetation coverage varied from year to year. The vegetation coverage was greatly reduced in the last year before solar farm construction (i.e., 2010), presumably in preparation for the upcoming construction. This contrasts with other sites, where the land cover does not change prior to the solar farm construction (an example of the DSSF annual mosaics is given in figure 5), thus the LST differences of these sites can better reveal the impact due to solar farm deployment.

Both MYD11A2 and MYD21A2 data products analyzed here are 8-day best estimates. The MODIS radiances used for such estimates were not included in the data products. Even so, the differences shown in figure 3 across all six sites consistently suggest that the overall effect of solar farm deployment on the longwave radiation is to reduce the surface upward radiance, and thus, to reduce the TOA outgoing longwave radiance as well. Such decrease in TOA outgoing longwave radiance is consistent with the in situ measurements of the decrease in upward longwave radiation at around 4.2 meters above the solar panel (Broadbent et al 2019). The LST retrievals show a reduction of daytime LST more than its nighttime counterpart. As far as surface emissivity change is concerned, MYD11A2 shows no change because its retrieval needs a priori surface type information and solar
farm is not one of such predefined surface types; MYD21A2 results indicate little changes of surface emissivity in Band 32, small negative changes up to only $-0.01$ in Band 31, and either positive or negative changes in Band 29.

5. Insights from the in situ measurements and synthesis with MODIS observations

5.1. Insights from the in situ measurements

Analysis in section 4 is based on satellite remote sensing retrieval results. Such retrievals of surface emissivity and LSTs are derived with assumptions, e.g., the surface within a MODIS footprint is flat (i.e., no diffusive radiative transfer caused by topography) and the LST is homogeneous within a MODIS footprint (i.e., no thermal inhomogeneity). These assumptions are also used in the treatment of surface longwave radiation of climate models, especially in the atmospheric component of the climate models. In reality, solar panels are placed $\sim1.5-2$ meters above the ground and tilted from horizontal at an angle approximately equal to the latitude of the site (for maximum exposure to incident solar radiation). The row-to-row spacing usually is determined to ensure that each row does not shade the row of panels behind it. Therefore, within a solar farm, the upward longwave emission from the ‘surface’ as seen by the MODIS retrieval algorithm consists of three components: (1) the longwave emission from the solar panels that are titled and elevated from the ground; (2) the longwave emission from ground shaded by solar panels in the daytime; and (3) the longwave emission from ground not shaded by solar panels day and night (usually referred to as exposed ground). The skin temperatures for solar panels, shaded ground, and exposed ground are also different. Therefore, aforementioned assumptions used in the MODIS retrievals are not strictly applicable to the case of solar farm, in the same way as how they are not strictly applicable to the case of open canopy forest.
Broadbent et al (2019) documented detailed measurements of temperature and surface energy balance at Arizona Public Service Redrock solar power plant, a solar farm site with great similarity to the sites analyzed here in terms of latitude and ground surface type. Below is a synthesis of the relevant results in Broadbent et al (2019).

An accompanying sketch to summarize the results is shown in figure 6:

1. It is well known that, in the daytime, a sharp vertical temperature gradient exists from the desert surface to the near-surface air, which is due to the strong absorption of solar radiation by the surface. At the control fields outside the solar farm site, Broadbent et al (2019) measured a temperature drop of 18.2 K from the surface to 1.5 meters above the surface at 1 pm local time. For the solar farm site, this temperature drop is 16.9 K. Over the night, the temperature gradient is greatly reduced in the absence of surface solar absorption, which is only ∼5 K difference between the surface and the 1.5-meter air.

2. During the daytime, the front size of solar panel is warmer than the surrounding 1.5-meter air because not all absorbed solar energy is converted to electricity and some is converted to heat up the solar panel. Given the large vertical temperature gradient from 1.5 meters to the surface, around 1:30 pm local time, the temperature of front side of solar panel is almost the same as the LST of the control field outside the solar farm site. During nighttime, solar panels do not absorb any solar radiation anymore and its temperature at 1:30 am local time is the same as the ambient air temperature at the same elevation, i.e., 5 K lower than the LST of the control field.

3. During the daytime, shaded ground within solar farm site has a lower skin temperature (∼ 7.5 K) than the exposed ground in the control field. At night, solar panel prevents the shaded ground from directly losing heat through longwave radiation to the space by emitted longwave radiation downward to the surface. As a result, the temperature difference between the shaded ground and the exposed ground is only ∼5 K.
result, the radiative cooling of such shaded ground overnight is not as fast as the exposed ground does. Consequently, it has a higher skin temperature (∼+3.5 K) than the exposed ground in the control field.

4. The exposed ground between solar panel rows, owing to the turbulent heat flux transport within the boundary layer, does not have the same skin temperature as the exposed ground in the control field either. But the temperature difference is not as large as the difference in (3) because of the direct solar absorption by the surface. Broadbent et al (2019) reported a −2.5 K difference at 1.30 pm local time and +2.5 K difference at 1:30 am local time between the exposed ground within the solar farm site and the counterpart at the control field.

Broadbent et al (2019) also measured broadband radiative flux at 5.7 meters above the ground and, together with temperature measurements, estimated the longwave broadband emissivity of solar panel and ground surface as 0.83 and 0.92, respectively. Riverola et al (2018) measured the surface spectral emissivity of crystalline silicon (c-Si) solar cells, a widely commercialized type of solar cells, from 0.35 to 16 μm. They showed that, from 4 μm to 16 μm (i.e., the portion of spectrum most relevant to longwave radiation in the climate sciences), the surface emissivity of solar cells varies from 0.85 to 0.7 (figure 1(d) in Riverola et al 2018). Over the spectral regions overlapped with MODIS Bands 29, 31, and 32, the measured surface emissivity of this type of solar cell is always less than 0.8. Natural ground surface seldom has a broadband longwave emissivity less than 0.9. Over the mid-IR window region, a natural surface emissivity < 0.8 can be only seen over the Sahara Desert; and the natural surface emissivity over Southwestern U.S. is always > 0.9 (Huang et al 2016). These known facts about nature surface emissivity and the two studies suggest that the emissivity of solar panel should be considerably lower than the emissivity of surrounding ground surfaces, including ground surface within the solar farm.

5.2. Understanding the satellite measurements

Based on the in situ measurements discussed in the previous subsection and the MODIS results analyzed in sections 3 and 4, we can depict how the solar farm deployments affect the longwave radiation as follows. During the day, especially around the local noon:

1. The surface temperature of front side of solar panel is about the same to the skin temperature of barren surface outside the solar farm while the solar panel surface emissivity is much smaller than the surface emissivity outside the solar farm. Therefore, the upward longwave emission from solar panel should be smaller than the counterpart from the control sites outside the solar farm.

2. The shaded ground within solar farm has a skin temperature lower than the control site as well. Moreover, the exposed ground within the solar farm is also cooler than the control site, presumably due to turbulent heat transport trying to homogenize the temperature among shaded and exposed ground within the solar farm. Since the shaded and exposed grounds have the same surface emissivities as the control site, the upward longwave emission from shaded and exposed grounds within the solar farm is also smaller than the counterpart from the control sites.

Since (1) and (2) work toward the same direction, the upward longwave emission from the entire solar farm site thus is smaller than the counterpart from the control sites, which is consistent with the inferences from the MODIS measurements.

At night, the solar panel is colder than the control site ground surface, so its upward longwave emission is still less than the control site counterpart. However, the shaded and exposed ground surfaces within the solar farm are warmer than the control site surface; thus, the upward longwave emission from such areas can be more than the upward longwave emission from the control site. Therefore, the changes over the solar panel and the changes over the ground within the solar farm offset each other to some extent. All three parts together, it is not immediately clear whether the upward longwave emission from the entire solar site is more or less than the counterpart from the control site. As indicated by the MODIS observations, the differences in the upward longwave emissions, if any, should be much smaller than the daytime differences.

While no long-term in situ measurements from the six solar farms are available for analysis, the in situ measurements delineated in Broadbent et al (2019) are qualitatively consistent with the MODIS observations over the six solar farms regarding the effects of solar farms on the upward longwave radiation: solar farm deployment reduces upward longwave radiation around noon; the impact on mid–night upward longwave radiation, if any, is much smaller than its daytime counterpart.
5.3. From MODIS measurements to retrieved surface products

What MODIS measures is the upward spectral radiance at different spectral channels. To retrieve surface emissivities over multiple bands and LST from the MODIS measurements is an ill-posed inversion problem: if the number of spectral channels is \( N \), normally \( N + 1 \) quantities in total need to be estimated from \( N \) measurements. Assumptions must be made to solve such ill-posed inversion problem. The MYD11A2 product uses a generalized split-window algorithm to estimate the LST (Wan et al 2015). It assumes that surface emissivities are stable and well known, which can be assigned using a land-cover classification map. Li et al (2013) found that such generalized split-window algorithm fails to deal with the dependence of land surface emissivities on surface soil moisture, vegetation cover changes, and compositional changes. As is apparent in figure 3, such land-cover classification map does not include solar farm as a type of land cover, leading to zero changes in retrieved surface emissivities in the MYD11A2 product.

The MYD21A2 algorithm employs the Temperature Emissivity Separation (TES) algorithm (Hulley and Hook 2017), which was originated from the normalization emissivity method (NEM). The NEM module first assumes a uniform emissivity and calculate one emission temperature for each band; then the maximum emission temperature derived in such way is kept and band emissivities are calculated according to this temperature. As an improvement to the NEM, the TES further characterizes the shape of emissivity spectra by calculating the spectral ratio, derives the minimum-maximum difference (MMD), and finally exploits an empirical relationship to specify the minimum emissivity. Other band emissivities and surface temperature can be refined afterwards. It enables the algorithm to dynamically retrieve the surface emissivities, but the accuracy heavily depends on the validity of the empirical relationship between MMD and minimum emissivity. Payan and Royer (2004) found that such empirical relation may hold true for most natural surfaces, but might not for metals. The MYD21A2 results here do show changes of surface emissivities before and after solar farm construction, but the magnitude of such changes varies significantly from one band to another. If aforementioned in situ and lab measurements of the surface emissivity of solar panels and solar cells are applicable to the six solar farms studied here, the surface spectral emissivity in MODIS Bands 29, 31, and 32 averaged over the solar farm site is expected to be noticeably lower than 0.94. It would be interesting to see that, after the empirical relation in the TES algorithm take measured solar cell spectral emissivities into account, how well the MYD21A2 TES algorithm can perform the retrievals over the solar farm sites.

6. Conclusions

This study attempted to understand how the solar farm deployments can affect the surface longwave radiative properties, namely surface spectral emissivities and LST. It exploited the monitoring capability of MODIS long-record and high-resolution global observations for solar panel deployment to understand the associated longwave radiation changes due to solar farm commissions. The same six solar farms studied in Fan and Huang (2020) were analyzed here. Case study of the DSSF confirms the causal link between the changes in MODIS retrieval products and solar farm construction. Results from both MYD21A2 and MYD11A2 products suggest that, during the daytime, solar panels reduce the upward longwave emission from the surface, thus leading to reduced upward longwave radiance at the TOA. The changes in the nighttime are much smaller. Since the MYD11A2 product employs a land cover classification-based algorithm that does not include solar farm as one type of land covers, the reduced daytime MODIS radiances lead to no change in surface emissivity but lower LSTs. MYD21A2 can dynamically retrieve the surface emissivity. As a result, MYD21A2 results indicate changes in surface emissivities with varying signs and magnitude across three MODIS bands and six farms, as well as negative changes in daytime LST but with a magnitude smaller than their MYD11A2 counterparts.

The MODIS observed changes are qualitatively consistent with the in situ measurements at a solar farm site in Arizona (Broadbent et al 2019), a geographically similar area. Specifically, the solar farm sites consist of three surface types: solar panels, ground shaded by the solar panels, and ground directly exposed under the Sunlight. The LSTs for the three surface types can be different, and they can be all different from the LST of barren ground at the adjacent control sites. Moreover, based on in situ and laboratory measurements, the broadband surface emissivity of solar panels is significantly lower than that of barren ground surface. As solar panel is not a type of land cover considered in the development of current land surface emissivity and skin temperature retrieval algorithms, the retrieval success over such solar farm site can be limited. Scarce in situ longwave radiation measurements at the solar farm sites prevent further quantitative understanding on this topic. With more in situ measurements, as well as spaceborne thermal-IR measurements at a higher spatial resolution with potential to resolve different surface types within a solar farm, e.g., ECOSTRESS with a 70-meter spatial resolution (Hulley 2019), further progress can be made on the effect of solar farm on surface longwave radiation budget and on the improvement of surface emissivity retrieval algorithm for handling such surface types.
While the shortwave effect of solar farms on local and large-scale climate effects have been studied using climate models with simple parameterizations (Hu et al. 2016, Li et al. 2018, Lu et al. 2020), the longwave effect of solar farms on climate has not been studied. This study provides some guidelines for how large-scale deployment of solar farms should be parameterized in the longwave radiation scheme of the climate models: (1) ideally the diurnally dependent LST differences between solar farm and adjacent land grids should be captured in such parameterization: solar farm as an entity, has a lower LST than surrounding land grids at noon but similar LST at midnight; (2) the solar farm surface emissivity should be different from surrounding land grids. While an overly dominant majority of climate models assume blackbody surface in their atmosphere model and broadband graybody surface in their land model, recent studies have shown the improvements when spectrally dependent surface emissivity was incorporated into the climate model, for global climate and for the regional climate over Sahara desert (Huang et al. 2018, Chen et al. 2019). Riverola et al. (2018) suggests the c-Si solar cell has its emissivity as large as 0.75 over the atmospheric window region. Such strong deviation from the blackbody behavior should be included for a realistic treatment of solar farm longwave effects in the climate models.

Fan and Huang (2020) and this study, together, have demonstrated the merit of long-term satellite observations beyond what the instrument was originally designed for. While land cover changes caused by solar farm deployment were not in the original target of MODIS observation, the two studies show that MODIS indeed can provide information for such specific land cover change. With the ongoing tide of renewable energy deployment and the continuation of MODIS-like instruments, i.e., VIIRS on Suomi-NPP and JPSS series satellites, the radiative effects of future solar farm operations can be continuously monitored from space.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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