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The Potential for Climate Impacts from Widespread Deployment of Utility-Scale Solar Energy Installations: An Environmental Remote Sensing Perspective

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Abstract

Solar energy systems directly benefit the environment by avoiding CO_2 emissions that would otherwise be generated from fossil-fuel power plants. Indirect impacts to climate may also result at local-, regional-, and global-scales, but these impacts are as yet poorly understood and characterized. Widespread deployment of utility-scale solar energy (USSE) installations may alter the radiative balance at the land-atmosphere interface by shifting radiative forcing that eventually changes climate. When USSE installations displace cropland or desert surface, this deployment introduces complicated effects on local radiative forcing. This article presents for the first time satellite-based measurements to assess USSE impacts on earth-atmosphere interactions relating to climate feedbacks. Long-term shortwave albedo and longwave emissivity data derived from NASA satellites were used for this case study to assess the potential radiative balance effects of USSE deployment. The results show that USSE deployment appears to change albedo and emissivity. Albedo decreased and emissivity generally increased in two of three instances when a USSE installation was constructed in semi-arid regions.

Keywords: Albedo; Emissivity; Radiative forcing; Utility-scale solar energy; Remote sensing

Introduction

Widespread installation of utility-scale solar energy (USSE) can affect local economies, regional greenhouse gas emissions, and global climate change. The direct benefit of USSE deployment is providing power with renewable electricity with greatly reduced greenhouse gases emissions. For example, Topaz Solar Farm in San Luis Obispo County, California, generates 1,096 GWh each year, sufficient electricity to power 160,000 California homes. The implementation of Topaz Solar Farm avoids 377,000 tons of CO_2 emissions annually, equivalent to taking 73,000 cars off the road. Benefits to the California economy amount to an estimated $417 million in positive impacts (Topaz Solar Farm Conditional Use Permit, DRC 2008-00009.

However, the deployment of USSE may also impact global climate change beyond emissions reduction. Secondary impacts of USSE production remain uncertain and incompletely studied, including effects on radiative forcing and the atmospheric boundary layer resulting from changes in surface roughness and albedo caused by USSE infrastructure [1]. USSE installations change earth surface land use and land cover (LULC) in complex ways, one of which is through altering surface albedo and, as a result, radiative forcing, air temperature, and regional weather patterns [2]. Albedo is the proportion of the incoming radiation that a surface reflects. USSE installations are thought to affect energy radiation balance by changing the net flow of outgoing shortwave radiation and infrared longwave radiation as a result.

Meteorological modeling for the Los Angeles region has suggested that no adverse impacts on air temperature and urban heat islands stem from large-scale solar energy deployment, but a 0.2°C cooling may occur in the Los Angeles region if the solar conversion efficiency reaches 30% [3]. Using the fully coupled Weather Research and Forecasting (WRF) regional model, Millstein and Menon [2] found no statistically significant air temperature changes in urban areas stemming from solar installations. Conversely, the model results suggested that some rural locations with USSE deployment showed summer afternoon temperature increases of up to 0.27°C and that these regions were correlated with less cloud cover and lower precipitation.

More importantly, Millstein and Menon's [2] study reported that simulated albedo change in desert areas will increase local afternoon air temperatures by up to 0.4°C. A decrease in albedo leads to a gain of radiative energy absorbed at the surface. Such positive radiative forcing (more incoming energy) warms the atmospheric system whereas negative forcing (more outgoing energy) cools it. The radiative balance at the earth-atmosphere interface can shift when the albedo of a USSE installation differs from the previous background albedo on site [2-4]. As a result, longwave emissivity changes at the earth-atmosphere interface, where heat trapped by greenhouse gases may also shift. With this climate feedback, the deployment of USSE will impact the pattern of climate change at local, regional, and global scales. Radiative forcing is a basis for assessing the variation in radiation budget in the earth-atmosphere system.

Materials and Methods

Inconsistent results from simulations about climate effects of solar installations cloud understanding about impacts of USSE deployment

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on climate change at multiple scales. Here we use long-term NASA satellite-derived measurements for shortwave broadband albedo and longwave broadband emissivity to investigate changes to radiative forcing from USSE deployment. The Global Land Surface Satellite (GLASS) products are the only available long-term land surface observations derived from MODIS (or Moderate Resolution Imaging Spectro radiometer).

Shortwave albedo and longwave emissivity data from the long-term GLASS model were used in this study to assess changes in energy budgets at USSE sites. We compared the shortwave albedo and longwave emissivity change before and after USSE construction to quantify the shift. This comparison is the first assessment of satellite-based measurements to document USSE impacts on earth-atmosphere interactions relating to climate feedbacks.

Studied solar fields

Photovoltaic (PV) and concentrating solar power (CSP) are the two main classes of solar energy generation. PV generates electrical power by converting solar radiation into direct current electricity. CSP systems use mirrors or lenses to focus a large area of sunlight, or solar thermal energy, onto a small area to heat a working fluid in a receiver.

We selected three utility-scale solar energy (USSE) systems, including one PV and two CSP solar facilities (equipped with parabolic troughs and heliostats with solar power tower, respectively), to evaluate the potential climate consequences from the USSE installation (Figure 1). The PV site and one CSP site were situated on desert surfaces, and one CSP site was located amid cropland in a semi-arid Mediterranean climate area.

The Huanghe Hydropower Golmud Solar Park in Golmud Desert Cluster is a 200 MW photovoltaic power station installed in Golmud, Qinghai Province, China (36°24′00″N 95°07′30″E). The installation uses flat-panel PV to generate electricity. The construction of Golmud Solar Park began in August 2009. It was commissioned on October 29, 2011 and extends over an area of 5.64 km^2.

Nevada Solar One is a CSP facility, with a nominal capacity of 64 MW, located in Eldorado Valley on the southwest edge of Boulder City, Nevada, USA (35°48′00″N 114°58′36″W). The project is the second solar thermal energy (STE) power plant built in the world since 1991. The plant went to operation in June 2007, covering 5.65 km^2 of desert surface. It uses parabolic troughs. Parabolic concentrator facilities track the sun's location and concentrate its rays onto receiver tubes to produce steam that runs a generator to produce electricity.

The Planta Solar 20 (PS20) solar power plant is a CSP solar facility with heliostats. It is located at Sanlucar la Mayor near Seville in Andalusia, Spain (37°26′38″N 06°15′34″W). It was the world's most powerful solar power tower (20 MW) until the Ivanpah Solar Power Facility in California became operational in 2014. The construction of PS20 began in 2006, and it was connected to the grid in 2009. The red ellipse indicates the footprint of PS20 (2.5 km^2) in Figure 1.

Surface radiation budget

A very general formulation of the surface radiation budget is defined as:

$$Q^* = S\uparrow + S\downarrow + L\uparrow + L\downarrow (1)$$

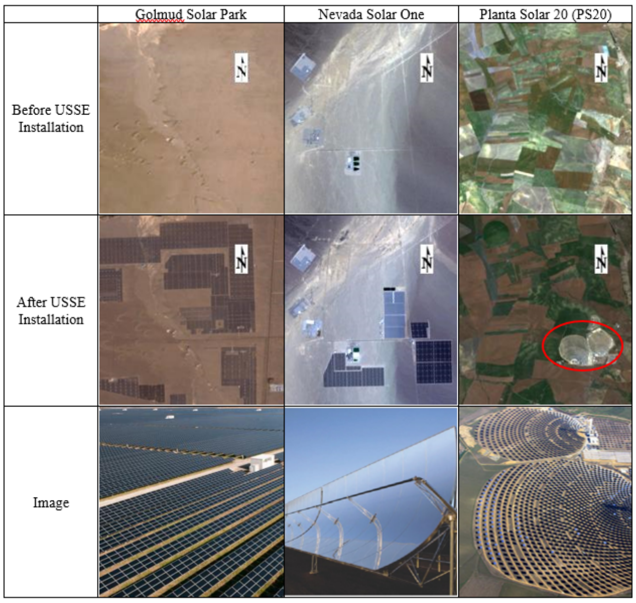

Figure 1: Earth surface change at three selected USSE sites (first two rows-Satellite true color images from Landsat TM and OLI).

where Q^* is the surface radiation (W/m^2), and S and S are upwelling and downwelling reflected shortwave solar radiation respectively. L and L are upwelling and downwelling longwave solar radiation respectively. Downward fluxes are negative, upward fluxes are positive. From Eq (1) the total surface radiation budget is the sum of the shortwave and longwave net radiation, rewritten as:

$$Q^* = (1-\alpha)S\downarrow + \varepsilon L\downarrow - \varepsilon\sigma T_s^4 (2)$$

where α is the surface shortwave albedo, ε the surface thermal broadband emissivity, σ the Stefan-Boltzmann constant, and Ts the air temperature.

The change in the surface radiation budget ΔQ^* is referred as radiative forcing or climate forcing. A positive forcing warms the earth-atmosphere system, while negative forcing cools it. Radiative forcing can be used to estimate a subsequent change in equilibrium surface skin temperature (ΔT_s) via the equation:

$$\Delta Ts = \lambda\Delta F \ (3)$$

where λ is the climate sensitivity, with units in $K/(W/m^2)$, and ΔF is the radiative forcing. Potential climate change originating from the widespread deployment of USSE can be quantified from Equations. (1), (2), and (3). Satellite-derived remote sensing datasets are used in this study to examine the variation in radiation forcing before and after USSE deployment.

Remote sensing datasets

The shortwave broadband albedo (ABD) and longwave broadband emissivity (EMT) products for each site were acquired from GLCF (Global Land Cover Facility. These two datasets are Global Land Surface Satellite (GLASS) products and have a spatial resolution of 1 km and a temporal resolution of 8 days.

Shortwave broadband albedo at land surfaces

Land surface shortwave broadband albedo is the ratio of upwelling to downwelling solar radiation at the surface and is equivalent to the surface hemispheric reflectivity integrated over the solar spectrum (0.3-3.0 µm). Shortwave albedo plays a central role in the radiation energy budget of the land surface, and is among the main radiative uncertainties in current climate modeling. Albedo at the land surface modulates radiative forcing and directly controls heat distribution in the earth-atmosphere system, therefore significantly impacting climate change at multiple scales.

The GLASS ABD was derived from MODIS optical bands with the angular bin (AB) regression algorithm and the statistics-based temporal filter (STF) algorithm [5,6]. STF fusion algorithm integrates the AB1 (surface reflectance) and AB2 (top-of-atmosphere radiance) into land surface shortwave broadband albedo [7]. Liu [7] compares the GLASS ABD to ground measurements at homogeneous FLUXNET sites. Reasonable consistency was obtained, with a bias less than 0.001 and root mean squared error less than 0.05 on clear days. FLUXNET is an observation network that coordinates regional and global analysis of observations from micrometeorological tower sites. The flux tower sites use eddy covariance methods to measure the exchanges of carbon dioxide (CO_2), water vapor, and energy between terrestrial ecosystems and the atmosphere.

Land surface longwave broadband emissivity

Longwave emissivity is the outgoing thermal infrared energy. Trace gases like greenhouse gases absorb parts of longwave emissivity initially, and cloud cover can reflect longwave radiation.

The GLASS EMT (8-13.5 µm) was retrieved from MODIS seven black-sky albedos for estimating surface longwave net radiation ε [8,9]. The GLASS EMT is the only thermal-IR broadband emissivity product from satellite measurements. In the generation of GLASS EMT from MODIS albedo product (MCD43B3), water and snow/ice were determined by the flag of MCD43B3, while bare soils, vegetated areas and transition zones were determined by the Normalized Difference Vegetation Index (NDVI) threshold values. GLASS EMT values are linearly related to shortwave spectral albedos and NDVI.

Results

Change in albedo and emissivity through USSE deployment

Figures 2 and 3 compare the change in shortwave broadband albedo and longwave surface broadband emissivity from the GLASS data.

Figure 2 shows shortwave albedo changes before and after the USSEs installed. At the desert sites, Golmud Solar Park and Nevada Solar One, albedo decreased around 20% after land cover change. Annual albedo change of parabolic trough mirror surfaces (Nevada Solar One) was more stable than that of flat PV panels (Golmud Solar Park). Annual albedo of parabolic troughs and PV panels are always lower than the albedo of previous intact earth surface. However, the variations of USSE among cropland backgrounds may be more complicated. In winter, the albedo of heliostat mirror are lower than cropland albedo, while from late spring till fall (Julian day 121-353) heliostat albedo is higher than cropland.

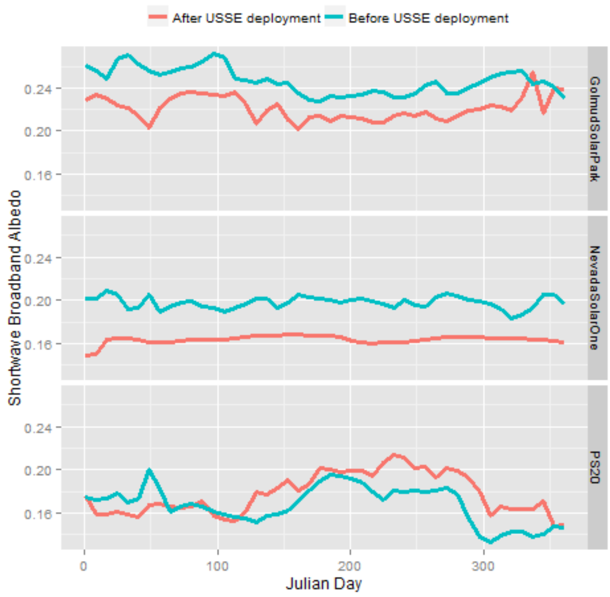

Figure 2: Shortwave albedo change through USSE deployment.

The comparison of results between longwave emissivity before and after USSE deployment is presented in Figure 3. Flat PV panels (Golmud Solar Park) generated more longwave emissivity than the native desert surface. Especially in the winter, the maximum difference can reach 5%. Parabolic trough mirror technology (Nevada Solar One) generates a little more emissivity in comparison to intact desert surfaces (absolute difference less than 1.1%). The longwave emissivity differences between Mediterranean cropland and heliostat (PS20) surfaces are larger in spring and fall, but the differences become narrow in summer and winter (Figure 3).

Change in radiative forcing

USSE installations generated a darker surface in desert, thus reducing shortwave albedo from the earth surface to the atmosphere (Figures 1 and 2). A decrease in albedo introduces positive radiative forcing, making the earth-atmosphere system warmer [10,11]. The shortwave albedo was not always lower than background when a USSE was situated in a setting of diverse ground surfaces (e.g., cropland). Flat PV panels generated more longwave emissivity than CSP (both parabolic trough and heliostat in Figure 3). More longwave emissivity means that greenhouse gases will trap more heat, thereby increasing radiative forcing and ultimately having a positive effect on increasing global surface temperatures. These preliminary results agreed well with the model-simulated conclusions from Millstein and Menon [2].

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Figure 3: Longwave emissivity change through USSE deployment.

However, the operation of a USSE installation always displaces significant fossil emission annually. Less fossil emissions result in less longwave emissivity trapped in earth-atmosphere system overall. In this way, USSE substitution might offset part of the longwave emissivity generated by flat PV panels. Figure 4 displays this feedback at the earth-atmosphere interface.

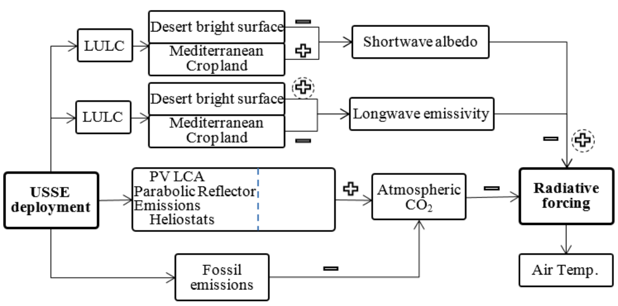

Figure 4: Influence on radiative forcing from USSE deployments. Signs (+) and (-) represent direction of relationship. LCA indicates lifecycle carbon emissions.

Research uncertainty about USSE deployment

People have significantly changed surface albedo through a variety of activities, such as deforestation [12], irrigation [13], and urbanization [14]. The widespread deployment of USSE installations is a new human activity that may change land surface albedo significantly as well.

Generally, white surfaces have a high albedo, while dark surfaces absorb most of the light that strikes, producing a low albedo. In semiarid regions, an increase in albedo leads to a loss of radiative energy absorbed at the surface, and convective turnover is reduced [15]. Published research shows that an increase in regional albedo may cause precipitation to decrease, and then induce a decrease in evaporation, which further depresses precipitation [16]. We found that albedo increased at a USSE site in a cropland setting (i.e., PS20) during warm seasons (Figure 2). Davin and de Noblet-Ducoudré [17] showed that surface albedo increases as a result of vegetation displacement (e.g., large-scale deforestation or loss of cropland) creating a cooling effect equivalent to 1.36°C globally.

However, the analysis found that longwave infrared emissivity decreased because of this albedo change. On average, a decrease of 0.1 in the soil emissivity increases the ground and air temperature by approximately 1.1 and 0.8°C, respectively, and decreases the net and upward longwave radiation by about 6.6 and 8.1 W/m^2, respectively [18]. Study of the PS20 site showed two-fold positive effects when USSE displaces cropland or vegetation cover. If the effect is actual, we must ask how much radiative forcing would result from this change in LULC. This study triggers an interesting topic: whether LULC managers will be able to deliberately increase sequestration of CO_2 from the atmosphere as carbon in trees and soils by introducing USSE installations to semiarid and desert ecosystems, where they displace vegetation and soil biotic crusts that would otherwise be sequestering carbon.

Conclusion

The global energy budget or radiative forcing is the net flow of energy onto earth in the form of shortwave radiation, minus the outgoing shortwave reflectance (albedo), and longwave radiation (emissivity) into the atmosphere. USSE installations convert inputs of shortwave irradiance into electricity, thus avoiding carbon dioxide emissions from fossil fuel combustion for energy. However, USSE deployment introduces changes to LULC that in turn cause variable responses in albedo and emissivity and disturb the balance of earth-atmosphere radiative forcing.

This paper uses a perspective based on environmental remote sensing to investigate albedo and emissivity modified by USSE installation. Environmental remote sensing can help quantify the change in radiative forcing. Under deliberate LULC management and implementation of solar energy technologies, the influences of USSE deployment to radiative equilibrium are predictable and controllable. Proper USSE deployment can cause positive effects on local-, regional-, even global-scale climate. Most analysis of albedo control through management of surfaces has focused on urban areas [19-22]. This study provides an analysis for basing future albedo control in previously undisturbed and agricultural ecosystems.

Further analyses of more USSE sites world-wide, but especially in semi-arid and arid ecosystems, would assist designers of solar technologies in perfecting designs that minimize side effects of warming from altered emissivity in solar installations. Understanding the long-term effects of USSE generation may be aided with an analysis of emissivity from USSE facilities that have already been in place for decades.

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