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Journal

Geophysical Research Letters, 45(11)

ISSN

0094-8276

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Publication Date

2018-06-16

DOI

10.1029/2018gl077319

Peer reviewed

Geophysical Research Letters

RESEARCH LETTER
10.1029/2018GL077319

Effect of Reduced Summer Cloud Shading on Evaporative Demand and Wildfire in Coastal Southern California

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Key Points:

- Warm-season daytime cloud frequency significantly declined in much of coastal Southern California over the past half century
- Based on a statistical model, observed reductions in coastal cloud frequency significantly increased net radiation and evaporative demand
- Correlation analysis suggests that summer cloud frequency significantly affects fuel moisture and burned area in coastal Southern California

Supporting Information:

- Supporting Information S1

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Citation:
Williams, A. P., Gentine, P., Moritz, M. A., Roberts, D. A., & Abatzoglou, J. T. (2018). Effect of reduced summer cloud shading on evaporative demand and wildfire in coastal Southern California. *Geophysical Research Letters*, *45*, 5653–5662. https://doi.org/10.1029/2018GL077319

Received 26 JAN 2018
Accepted 17 MAY 2018
Accepted article online 24 MAY 2018
Published online 5 JUN 2018

Abstract Cloud shading limits surface radiation, thus reducing vegetation water stress and, presumably, flammability. Since the early 1970s, cloud observations from airfields in coastal Southern California (CSCA) indicate reductions of ~25–50% in warm-season frequency of daytime stratus clouds at many sites, including fire-prone wildland-urban interface zones. We use 10 years of meteorological, surface radiation, and cloud observations to statistically model the effects of clouds on warm-season surface energy fluxes in CSCA. Forcing our model with cloud observations, we estimate that reduced warm-season cloud shading since the 1970s significantly enhanced daytime solar radiation and evaporative demand throughout much of CSCA, particularly in greater Los Angeles and northern San Diego. Correlation with burned area and live fuel moisture implicates stratus cloud shading as an important driver of warm-season wildfire activity in CSCA. Large reductions in cloud shading have likely enhanced warm-season wildfire potential in many CSCA areas when and where fuels are not limiting.

Plain Language Summary In much of coastal Southern California, the frequency of summer clouds has declined rapidly in recent decades due to warming from urbanization and greenhouse gases. These reductions have significantly reduced cloud shading and increased evaporative demand, particularly in greater Los Angeles and northern San Diego, such that a relatively cloudy summer today is similar to a relatively clear summer in the 1970s. Clouds appear to be important regulators of summer wildfire activity in this region, as the shade they provide slows loss of moisture from vegetation. On the vegetated mountainsides that ring coastal Southern California's large cities, increases in summer sunlight and evaporative demand have likely enhanced summer wildfire potential over the past several decades. This effect is expected to continue due to continued urban expansion and positive feedbacks, where warming due to cloud loss promotes further warming and cloud loss.

1. Introduction

Stratus clouds provide vital shade and occasional direct moisture deposition for coastal vegetation during the rain-free warm season on North America's west coast (Baguskas et al., 2018; Dawson, 1998; Emery et al., 2018; Fischer et al., 2009; Iacobellis & Cayan, 2013; Williams et al., 2008). Coastal stratus clouds form within the cool and humid marine boundary layer and are most frequent during the warm season when synoptic frontal disturbances are infrequent, northerly winds promote coastal upwelling of cold water, and subsiding warm air on the east side of the North Pacific High enforces stability aloft (Clemesha et al., 2017; Wood, 2012). In coastal Southern California (CSCA), observations from airfields indicate that warm-season stratus clouds have decreased in frequency and risen in altitude at many sites over the past 40–70 years (LaDochy & Witiw, 2012; Williams, Schwartz, et al., 2015). These trends are strongest in the greater Los Angeles and San Diego areas and appear largely driven by the urban heat island effect and background anthropogenic greenhouse warming (Williams, Schwartz, et al., 2015). Warming forces the altitude of condensation to rise and increases the frequency of cloud-free conditions when saturation is not achieved within the boundary layer (Gautam & Singh, 2018; Gentine et al., 2013; Lin et al., 2009; O'Brien, 2011; Wood, 2012).

Williams, Schwartz, et al. (2015) speculated that as a result of reduced warm-season cloud shading, increased solar radiation at the surface has enhanced the evaporative demand and decreased fuel moisture on the vegetated mountains that ring the large coastal cities of CA. However, fire activity in CSCA has not increased in recent decades as it has in many other parts of the western United States (Dennison et al., 2014;

Jin et al., 2014). This is likely because fire regimes in the relatively dry CSCA ecosystems are not purely limited by aridity, as other important factors in this region are fuel availability, human activities, and extreme wind events (e.g., Abatzoglou & Kolden, 2013; Bryant & Westerling, 2014; Davis & Michaelsen, 1995; Keeley & Fotheringham, 2001; Moritz et al., 2010; Syphard et al., 2007; Westerling et al., 2004). Nonetheless, increased evaporative demand enhances wildfire potential when fuels are abundant (e.g., Bradstock, 2010) and we therefore here investigate the influence of warm-season cloud shading on evaporative demand, fuel moisture, and fire potential in CSCA.

We use a unique set of decade long observations of radiative flux, meteorology, and cloud-base heights from a CSCA site to quantify the effects of warm-season cloud cover on surface radiation and evaporative demand. We then estimate how observed changes in cloud frequency and altitude have affected evaporative demand since the early 1970s. We hypothesize that warm-season cloud shading is an important determinant of evaporative demand, fuel moisture, and burned area in CSCA, and that reduced cloud shading in recent decades has enhanced wildfire potential in the highly flammable ecosystems surrounding the region's large urban areas.

2. Methods

We define CSCA as the region of Southern CA (southeast of Point Conception) that is within the warm-season coastal stratus zone, as defined by Clemesha et al. (2016; Figure 1). We focus on the warm season, which we define as May–September (May-Sep). We define daytime as 08:00–17:00 Pacific Standard Time. All data used in this study are publicly available and the sources are listed in the Acknowledgments section.

2.1. Airfield Observations of Cloud-Base Height

Hourly or subhourly cloud-base heights are recorded at airfields globally and archived by the National Climate Data Center. We consider the 26 airfields in CSCA for which mean May-Sep daytime stratus frequency could be calculated for at least 75% of years during 1973–2017 (supporting information Table S1). We consider stratus clouds to be all clouds with bases below 1,000 m above sea level, following previous work (Iacobellis & Cayan, 2013; Schwartz et al., 2014). Particular focus is paid to airfields in Santa Barbara (SBA), Burbank (BUR), Santa Monica (SMO), and Santa Ana (SNA). SBA is adjacent to the coastal weather station that we use to quantify effects of clouds on surface meteorology and energy balance (described below). BUR, SMO, and SNA are of interest because they are near the Wildland Urban Interface (WUI) surrounding Los Angeles and experienced large reductions in warm-season stratus cloud frequency in recent decades (Williams, Schwartz, et al., 2015).

2.2. Surface Meteorology at Coal Oil Point Reserve

Coal Oil Point Reserve (COPR) is a coastal site near Santa Barbara, CA (34.413695°N, 119.880226°W, 6-m elevation) and has a decade long (2008 to present) record of 15-min meteorological observations, including surface radiation, temperature, humidity, and wind speed (Roberts et al., 2010). Vegetation at COPR consists of a mixture of native and introduced grassland and forbs, typical of the CSCA coastal plain. Radiation measurements include downward and upward shortwave (SWd and SWu, respectively) and downward and upward longwave (LWd and LWu, respectively). This decade long record of high-quality 15-min observations of the four surface radiation components is unique, particularly because COPR is only 2.75 km from SBA, where regular cloud observations are made. Missing observations were replaced using an adjacent weather station approximately 100 m from the COPR station (supporting information Text S1).

2.3. Effect of Clouds on Evaporative Demand

We quantify the atmosphere's evaporative demand as reference evapotranspiration (ETo), the theoretical rate of evapotranspiration (mm/hr) that would occur from a well-watered reference crop as determined from the formula of the American Society of Civil Engineers (Allen et al., 1998, 2005), derived from the Penman-Monteith equation (Monteith, 1965; supporting information Text S2). There are two additive contributions to ETo, a radiative component driven by net radiation (Rnet) and an advective component driven by wind speed and vapor pressure deficit (VPD; Hobbins et al., 2016).

To empirically model cloud effects on ETo, we related the 15-min meteorological record from COPR to all co-occurring ($\leq$7 min apart) cloud observations at adjacent SBA during May-Sep 2008–2017 ($N \geq 81{,}748$, depending on the variable). The statistical model uses clear-sky radiation and cloud presence/absence and base

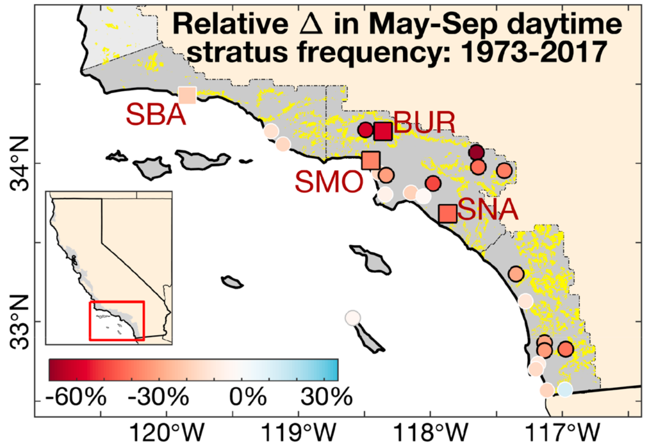

Figure 1. May–September (May-Sep) change in daytime (08:00–17:00) frequency of stratus clouds during 1973–2017. Change expressed as linear trend relative to mean expected value at beginning of time series. (Boxes) Santa Barbara (SBA), Burbank (BUR), Santa Monica (SMO), and Santa Ana (SNA). Significant trends ($p < 0.05$, Kendall's tau) are indicated with thick black boundaries. Grey area: Coastal stratus zone, with the darker grey area indicating coastal Southern California. Thin black boundaries within coastal Southern California define subregions (from north to south, greater Santa Barbara, Los Angeles, and San Diego areas). Yellow areas: 2010 Wildland Urban Interface (Radeloff et al., 2018). Airfield values: supporting information Table S1.

altitude to estimate net solar radiation at the surface (SWnet). This estimate is then propagated to estimate cloud effects on the other insolation-dependent variables in the ETo calculation: 2-m air temperature (T_{air}) and vapor pressure (e_a), LWd, and LWu (supporting information Texts S3 and S4 with corresponding supporting information Figures S1–S9).

We used the empirical model to investigate how mean warm-season ETo at COPR would be affected by changes in cloud conditions. We conducted two idealized experiments. The first experiment explored how ETo changes as a function of prescribed cloud presence and base height. The second experiment explored effects of observed trends in cloud cover at airfields throughout CSCA on ETo. For this experiment, we estimate 15-min records of SWnet, T_{air}, e_a, LWd, and LWu forced by cloud observations from each airfield during each of two 10-year periods: 1973–1982 and 2008–2017. These periods coincide to the period of record at COPR (2008–2017) and the first decade when cloud observations were made regularly at a high density of CSCA airfields (1973–1982). Bias corrections were made to account for geographic differences in the monthly climatologies of daily cycles of clear-sky SWd, T_{air}, and e_a using the National Solar Radiation Database for clear-sky SWd and airfield observations for T_{air} and e_a. For all simulations, anomalies in SWnet, T_{air}, e_a, LWd, and LWu caused by the idealized conditions were isolated by subtracting away the estimated values when the empirical model was forced by 2008–2017 cloud observations at SBA. These anomalies were added to the 2008–2017 observations from COPR to add back in meteorological variability not due to clouds. Instrumental and model uncertainties were propagated through model predictions using a Monte Carlo approach (supporting information Text S5).

Additional uncertainty arises because COPR is at a coastal site on the northern end of CSCA and 150–350 km from most CSCA airfields, some of which are tens of km inland. More inland sites experience less advection of cool humid air from the ocean, less cloud shading, and, likely, drier soils, enabling variations in cloud shading to have a greater influence on temperature and VPD (supporting information Figures S10 and S11). Our estimates of cloud effects on VPD and ETo are therefore likely to be biased low at inland sites. There are also uncertainties due to the uncoupled nature of our model (prescribed cloud changes drive surface conditions but not vice versa) and the effects of soil moisture on surface energy fluxes, but effects of these caveats appear small (Seneviratne et al., 2010; supporting information Text S6 and Figures S11 and S12). Surface characteristics and vegetation type also affect energy partitioning at the surface, adding complexity to the effects of cloud shading across space.

2.4. Link Between Coastal Stratus Clouds and Wildfire

We related interannual variations in May-Sep live fuel moisture (LFM) and wildfire area to May-Sep daytime stratus frequency within the summer stratus zone of CSCA. LFM observations came from the National Fuel Moisture Database. We considered five records of mean May-Sep LFM during 1990–2017, all in the greater Los Angeles area, within the CSCA stratus zone, and near airfields with cloud observations (supporting information Text S7). CSCA wildfire area was assessed over 1984–2015 using data from CalFire and the Monitoring Trends in Burn Severity data set (MTBS; Eidenshink et al., 2007; supporting information Text S8 and Figure S13).

3. Results

3.1. Cloud Trends

Warm-season daytime stratus frequency declined throughout CSCA during 1973–2017 (Figure 1). The declines were strongest in the most heavily urbanized and inland areas, as these areas have experienced the most rapid warming in recent decades (Williams, Schwartz, et al., 2015). Of the 22 airfields in greater Los Angeles and San Diego, 21 experienced negative trends (13 trends were significant with >95%

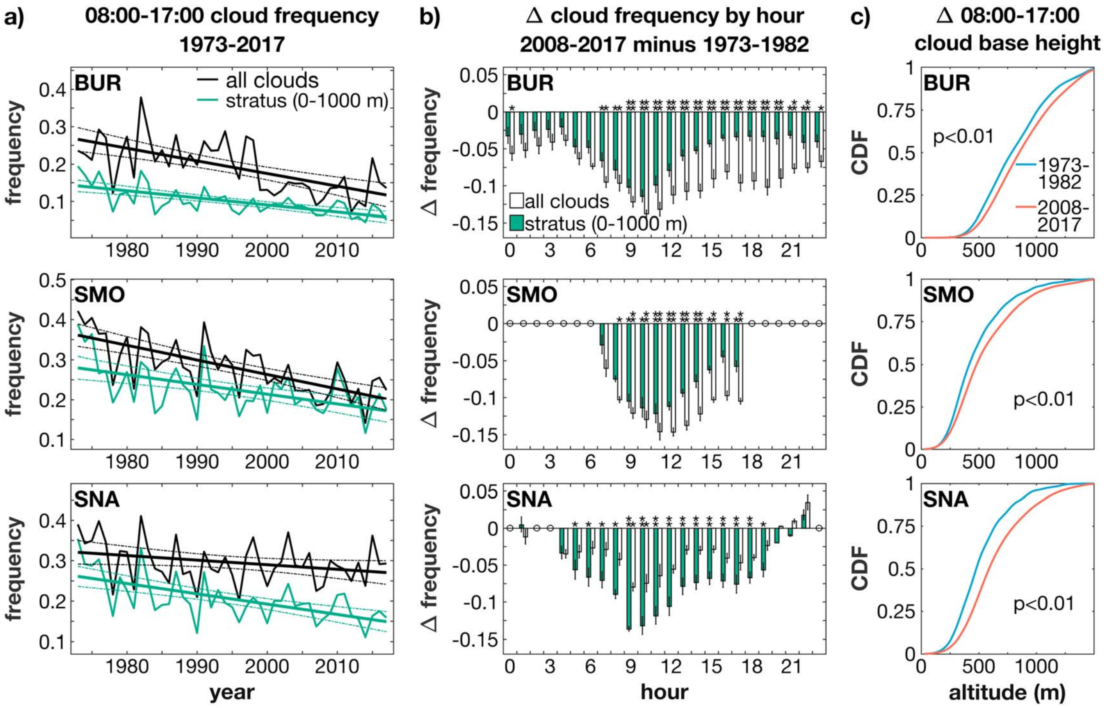

Figure 2. May–September (May-Sep) changes in cloud frequency and base height at Burbank (BUR), Santa Monica (SMO), and Santa Ana (SNA). (a) Daytime (08:00–17:00) frequency of (black) all clouds and (green) stratus clouds (trends and 95% confidence intervals included). (b) Difference in decadal cloud frequencies for each hour: 2008–2017 minus 1973–1982. Whiskers: Standard errors. Circles: Insufficient data. Asterisks indicate significance at (*) 95% and (**) 99% according to the Student's *t* test. (c) Cumulative distributions of base heights of low daytime clouds (<1500 m) for (blue) 1973–1982 and (red) 2008–2017. *P* values indicate significant positive shifts (two-sample Kolmogorov-Smirnov test).

confidence according to Kendall's tau), with an average relative reduction of 30% (supporting information Table S1). All but two airfields that experienced significant negative trends are near (<5 km) the WUI, where urban areas are surrounded by and intermix with fuels (Figure 1). Stratus reductions were not associated with instrumentation changes in the mid-1990s, as the eight military airfields in CSCA, which did not change instrumentation (Dai et al., 2006), did not exhibit systematic mid-1990s shifts in stratus frequency relative to nonmilitary airfields (supporting information Figure S14).

Decreases in *overall* cloud frequency were significant ($p < 0.01$) according to Kendall's tau at BUR and SMO, with relative reductions of 56% and 44% at these sites (Figure 2a). SNA daytime cloud cover decreased by 16%. Comparing the most recent decade (2008–2017) to the first decade of the analysis period (1973–1982), BUR, SMO, and SNA showed increases of 1.0, 1.1, and 0.4 hr/day of cloud-free daytime conditions, respectively. Reduced cloud frequency at these sites was driven mainly by significant decreases in stratus frequency (Figure 2a, green lines). Losses of stratus peaked in midmorning (Figure 2b), the period when coastal stratus often lift, break apart, and dissipate due to diurnal surface warming. As stratus became less frequent, they also developed at higher altitudes (Figure 2c). Among daytime cloud-base measurements lower than 1500 m, BUR, SMO, and SNA experienced significant increases in median cloud-base heights of 56, 61, and 111 m, respectively, between the two decades. See supporting information Table S1 for data from all airfields.

3.2. Cloud Effects on Evaporative Demand at COPR

Averaged across May-Sep daytime hours at COPR (box plots in Figure 3), SWnet during cloudy days was simulated to be approximately 242 W/m^2 (43%) lower than on cloud-free days. Cloud-base height also substantially affected SWnet. Low stratus clouds with a 300-m base reduced daytime SWnet by approximately 81 W/m^2 more than higher stratus clouds with a 900-m base. Increases in base heights beyond approximately 1,000 m showed no additional influence on SWnet (Figure 3a), likely because, unlike stratus clouds that are confined by the top of the marine boundary layer, higher clouds within the free troposphere are generally thicker than high stratus clouds.

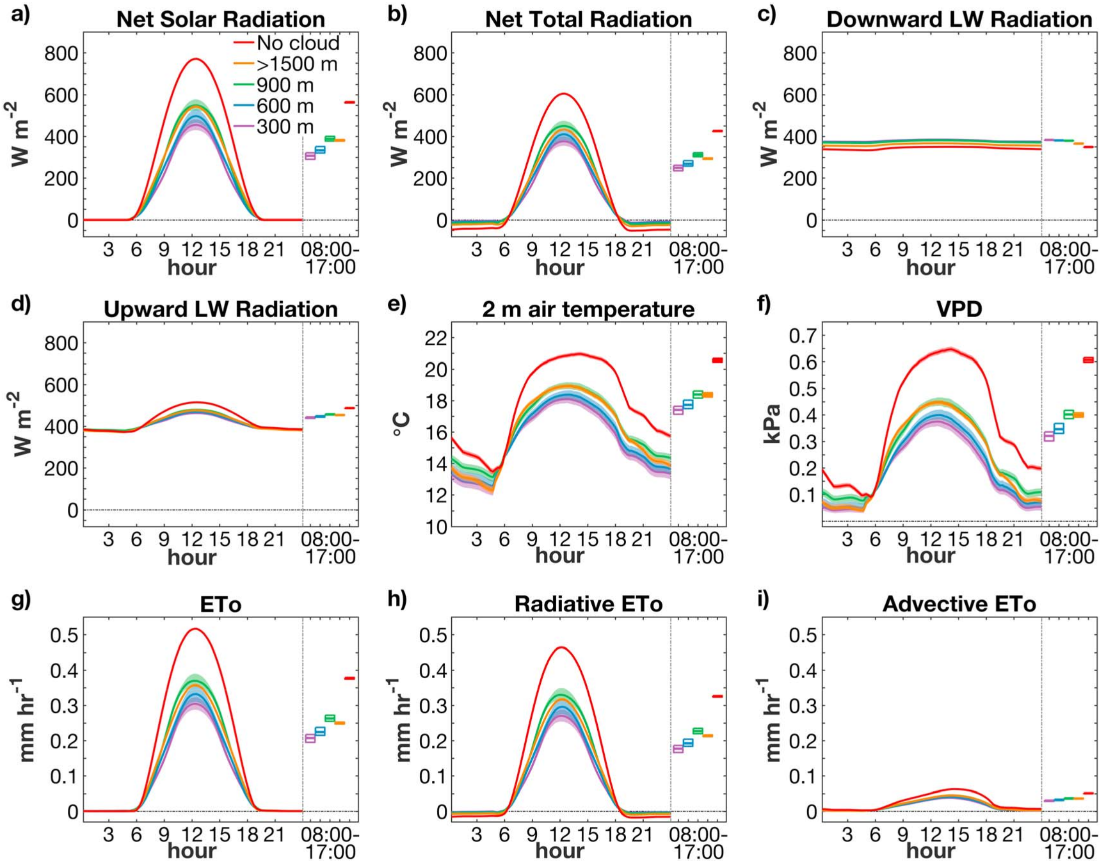

Figure 3. Cloud effects on surface meteorology and reference evapotranspiration (ETo). Estimated mean May–September 2008–2017 (curves) daily cycles and (boxplots) daytime (08:00–17:00) for (red) no clouds and clouds with various base heights (legend in a). Shading behind curves and boxes on boxplots: 95% confidence for mean values. VPD = vapor pressure deficit; LW = longwave. All panels (a-i) represent the variable listed above each panel.

Clouds significantly reduced surface Rnet despite their positive forcing on net longwave radiation at the surface (Figures 3b–3d). During the day, cloudy conditions reduced Rnet by approximately 166 W/m^2 (39%), with lower cloud-base height again corresponding to further reductions in downward radiation flux (daytime Rnet was 62 W/m^2 lower when cloud base was 300 m instead of 900 m). As was the case for SWnet, Rnet did not continue increasing with cloud-base height among clouds with bases above 1,000 m. In fact, mean daytime Rnet was significantly lower (by 18 W/m^2; $p < 0.01$) for $>$1,500-m cloud base than for 900-m cloud base because higher clouds are relatively cool and emit less downward longwave radiation (Figure 3c).

Cloud shading also reduced daytime temperature by 3.0 °C at COPR, reducing VPD by 45% (Figures 3e and 3f). Among cloudy observations, higher cloud-base heights corresponded to higher temperatures and VPD. Notably, the effect of cloud shading on temperature and VPD may be underrepresented in Figures 3e and 3f, because a continuous May-Sep period with no clouds would likely be warmer (due to accumulated net radiation) than expected from the statistical model, which restarts each day with observed temperature and humidity at sunrise.

Clouds reduced mean daytime ETo by approximately 43% (0.161 mm/hr; Figure 3g). Among stratus clouds, lower clouds corresponded to lower ETo, with 300-m cloud bases corresponding to 21% lower mean daytime ETo than 900-m cloud bases. The vast majority (88%) of cloud-induced reductions in ETo were due to the Rnet-driven radiative component (Figures 3h and 3i).

3.3. Effects of Observed Cloud Trends on Evaporative Demand

Figure 4 shows mean simulated changes in May-Sep SWnet and ETo in response to observed changes in cloud frequency and base height from 1973–1982 to 2008–2017 at airfields throughout CSCA. At BUR,

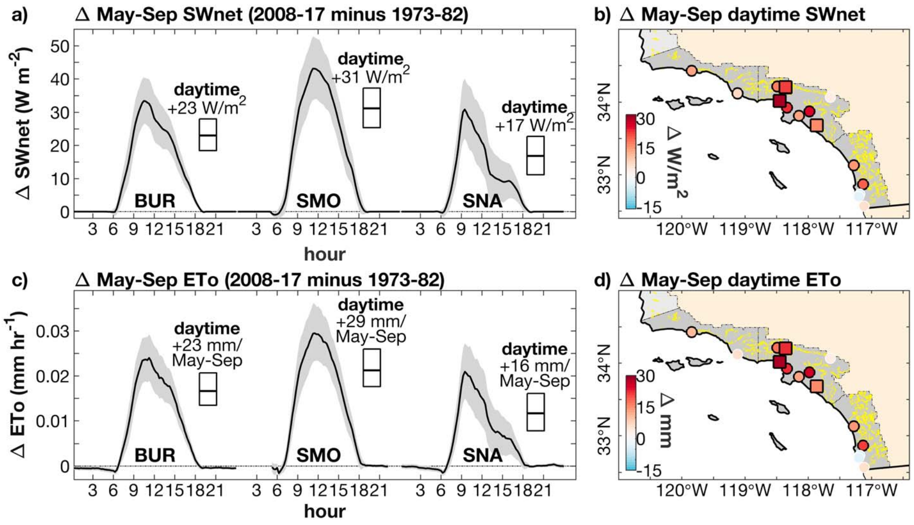

Figure 4. Modeled change in May–September (May-Sep) mean (a and b) net solar radiation (SWnet) and (c and d) reference evapotranspiration (ETo) due to observed mean changes in cloud cover (2008–2017 minus 1973–1982). (a and c) Changes in daily cycles at Burbank (BUR), Santa Monica (SMO), and Santa Ana (SNA). Box plots: Mean daytime (08:00–17:00) change. In c, the text above box plots indicates the change in cumulative daytime ETo during May-Sep. Shading and boxes: 95% confidence around mean values. (b and d) Maps of changes in mean daytime SWnet and cumulative ETo forced by cloud observations at the 16 CSCA airfields with adequate data. Significant changes ($p < 0.05$, paired *t* test) are indicated with thick black boundaries. Squares: Locations of BUR, SMO, and SNA. Grey area: Coastal stratus zone, with the darker grey area indicating CSCA. Yellow areas: 2010 WUI. Values in maps: supporting information Table S1.

SMO, and SNA, modeled increases in mean daytime SWnet are 17–31 W/m^2 (Figure 4a), driving significant increases in daytime Rnet of 11–22 W/m^2. The cloud cover changes also induce significant modeled increases in mean daytime VPD of 0.028–0.039 kPa at these sites. The modeled increases in Rnet and VPD at BUR, SMO, and SNA positively force modeled daytime ETo by 0.012–0.021 mm/hr, translating to 16–29 mm per May-Sep (Figure 4c). These results for BUR, SMO, and SNA are within the range of estimates for other CSCA airfields (Figures 4b and 4d; supporting information Table S1). Among sites in greater Los Angeles and northern San Diego, the estimated positive forcing of reduced May-Sep cloud shading on daytime SWnet and ETo averaged 16 W/m^2 and 16 mm per May-Sep season, respectively (supporting information Table S1). The simulated SWnet and ETo increases are substantial relative to interannual variability, as observed standard deviations (σ) at COPR during 2008–2017 were 17 W/m^2 for SWnet and 22 mm per May-Sep season for ETo.

3.4. Correlation Between Daytime Stratus Frequency and Wildfire

Has reduced daytime stratus frequency promoted enhanced fuel aridity and wildfire potential? May-Sep CSCA daytime stratus frequency correlated negatively and significantly ($r = -0.54$, $p < 0.01$) with the logarithm of May-Sep CSCA burned area during 1984–2015, with a 1σ reduction in stratus frequency corresponding to an approximate doubling of burned area (Figures 5a and 5b). For comparison, 1973–2017 losses in daytime stratus frequency were approximately 2σ at airfields in greater Los Angeles and northern San Diego (e.g., Figure 2a). The mechanistic connection implied by the negative correlation between stratus frequency and burned area in Figure 4b is supported by long-term LFM observations. Indeed, during 1990–2017, May-Sep daytime stratus frequency correlated positively and significantly ($r = 0.51$, $p < 0.01$) with May-Sep LFM averaged over five sites northwest of Los Angeles (Figure 5c). Correlation with summer LFM strengthens slightly when May or May–June LFM are excluded, possibly reflecting a lag between the onset of the summer stratus season and its detectable effects on LFM.

Although the relationship between May-Sep stratus frequency and burned area is relatively weak compared to fire-climate correlations in other parts of the western United States (e.g., Abatzoglou & Kolden, 2013), it is stronger than correlation with other commonly considered multimonth climate variables (supporting information Figure S15). Correlation between stratus frequency and burned area generally remains significant ($p < 0.05$) in an analysis of residuals after using regression to remove climate effects such as

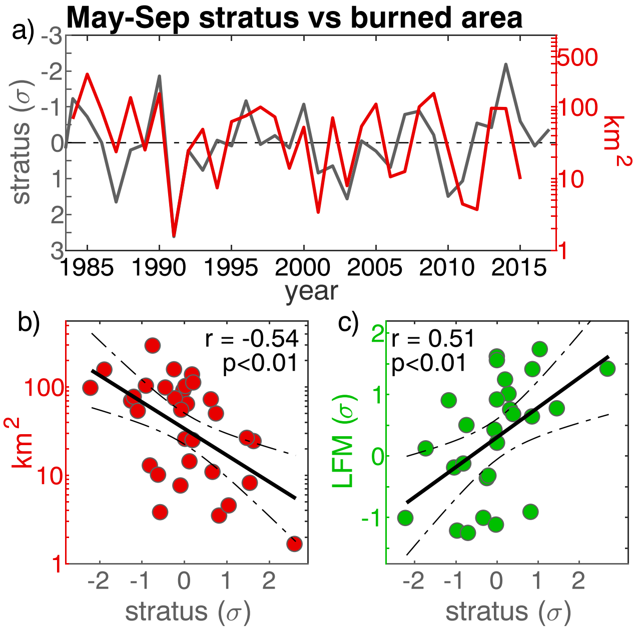

Figure 5. Stratus and wildfire. (a) Time series of (left axis, note reverse sign) standardized anomalies of May–September (May-Sep) daytime coastal Southern California (CSCA) stratus frequency (σ) and (right axis) May-Sep burned area. CSCA stratus frequency: Area-weighted average of standardized stratus frequency for the three subregions shown in Figures 4b and 4d. (b) Regression of time series from (a; note log-scale y axis). (c) Regression of mean standardized May-Sep live fuel moisture at five long-term monitoring sites northwest of Los Angeles versus May-Sep daytime CSCA stratus frequency at the five airfields closest to the live fuel moisture sites. Regression lines are shown with 95% confidence intervals.

antecedent winter precipitation (promotes fuel growth), post-winter precipitation (reduces flammability), and May-Sep wind speed (spreads fire and enhances ETo; supporting information Figure S16). Stratus correlation with LFM also remains significant ($p < 0.05$) after removing correlations with precipitation (supporting information Figure S17).

The relatively strong effect of May-Sep daytime stratus frequency on CSCA fire activity appears to not carry over into fall. May-Sep stratus frequency correlates only weakly with October–December LFM ($r = 0.31$, $p = 0.13$) and not at all with October–December burned area ($r = 0.00$).

4. Discussion and Conclusions

At airfields throughout the greater Los Angeles and northern San Diego areas of CSCA, daytime frequency of warm-season stratus clouds reduced significantly since the early 1970s and stratus cloud-base heights increased by several tens of meters, suggesting a thinning of the cloud deck. These trends appear driven by warming caused by urbanization and background greenhouse forcing (Williams, Schwartz, et al., 2015), which enhance sensible heat fluxes at the surface and boundary layer entrainment (Gentine et al., 2013). Effects of these trends on cloud shading, evaporative demand, and wildfire had not been explored previously.

Long-term measurements of surface energy fluxes do not exist to directly assess the effects of observed cloud reductions over the past several decades, and climate reanalysis efforts do not adequately capture stratus effects in CSCA. For example, the solar forcing data set used for operational drought monitoring by the National Land Data Assimilation System (Xia et al., 2012) does not correlate well with solar observations at COPR or CSCA daytime stratus frequency (supporting information Figure S18). This problem arises because the records of solar radiation are generally simulated rather than observed and the atmospheric models used for such simulations are too coarse to resolve stratus clouds, marine layer dynamics (especially entrainment; Mellado, 2017), and fine-resolution features of coastal climate (Huang et al., 2013; Koračin & Dorman, 2001; O'Brien et al., 2013; Qu et al., 2014).

The unique pairing of a 10-year observational record of surface radiation fluxes with a record of cloud observations at a neighboring airfield in CSCA allowed us to empirically model how changes in warm-season cloud frequency and base height affect evaporative demand. Applying our empirical model to observed cloud records, we estimate that changes in daytime cloud frequency and cloud-base height since the early 1970s have forced significant multidecade increases in incident surface radiation and evaporative demand throughout greater Los Angeles and northern San Diego. These forced increases are similar in magnitude to the fluctuations expected from year-to-year variability.

The CSCA fire regime is notoriously complex and has been believed to be only weakly linked to variability in climate (Jin et al., 2014; Keeley, 2004; Keeley & Syphard, 2017). Our finding of significant apparent effects of daytime stratus frequency on LFM and burned area lend new insight into the drivers of wildfire during May-Sep, which contributes to approximately half of the annual burned area in the region (Jin et al., 2014). The unique strength of the interannual relationship between stratus frequency and burned area suggests that observed large declines in May-Sep daytime stratus frequency have indeed enhanced wildfire potential throughout the WUI areas surrounding highly developed areas of greater Los Angeles and northern San Diego. Further, while this study focuses on 1973 to present to capitalize on a high density of airfield cloud observations, Williams, Schwartz, et al. (2015) indicate that warm-season stratus clouds have been rising in altitude and declining in frequency in heavily urbanized parts of CSCA since at least 1948.

Importantly, decreased cloud shading must be viewed as a *positive forcing* on fuel aridity and burned area specifically in the areas where cloud shading has declined, and not as a definitive driver of region-wide trends. While Jin et al. (2014) use a longer, less spatially resolved wildfire record over a broader geographic domain in Southern California to show that annual measurements of May-Sep burned area *did* increase during 1959–2009, we find using an updated version of the same data set that this was not the case for our more narrow CSCA domain (supporting information Figure S13). Other important drivers of CSCA fire activity over the past several decades were repeated severe droughts in the 2000s (Williams, Seager, et al., 2015), which limited growth of fine fuels and probably inhibited fire spread, and human activities. Humans are responsible for essentially all ignitions in this region (Balch et al., 2017; Westerling et al., 2004) and also limit fire growth through aggressive suppression and landscape alteration (Mann et al., 2016; Westerling et al., 2011). Surface radiation in the greater Los Angeles and San Diego areas has also likely been affected by changes in pollution (Warneke et al., 2012) and high-altitude cirrus clouds produced by airplane contrails (Minnis et al., 2004), which we did not explicitly consider in this study. In addition, many fires in coastal CA are driven by strong easterly Santa Ana wind events, which may dry fuels and spread fire in otherwise unremarkable years (Dennison & Moritz, 2009; Jin et al., 2014; Keeley, 2004; Westerling et al., 2004). Our finding that the effect of warm-season stratus on CSCA burned area appears to decay in the fall season (when Santa Ana wind events are common) suggests that reduced warm-season cloud shading did not play a large role in promoting the extreme fire activity observed in CSCA in December 2017.

Results of this study suggest that among the complex processes governing fire activity in CSCA, reductions in warm-season cloud shading in recent decades have caused evaporative demand and wildfire potential to be higher than they would otherwise be when and where fuels are not limiting, in particular in WUI areas that ring greater Los Angeles and San Diego. Effects of reduced stratus cloudiness on evaporative demand and wildfire in coastal California should be further researched through live fuel-moisture observations, satellite monitoring, and modeling (e.g., Davis & Michaelsen, 1995; Dennison & Moritz, 2009; Peterson et al., 2008), particularly given projections of continued urbanization and expansion of the WUI (Syphard et al., 2011) and the likelihood for positive feedbacks where warming due to reduced cloud shading promotes further declines in cloud frequency and shading.

Acknowledgments

All data used for this study are publically accessible: Airfield cloud and meteorological observations (ftp://ftp.ncdc.noaa.gov/pub/data/noaa), COPR (www.geog.ucsb.edu/ideas/home.html), Climate Reference Network meteorology (www.ncdc.noaa.gov/crn), CalFire (http://frap.fire.ca.gov/data/frapgisdata-sw-fireperimeters_download), MTBS (https://www.mtbs.gov), satellitedatausedtodefine coastal region of interest (http://tenaya.ucsd.edu/~rclemesha/data.html), WUI (http://silvis.forest.wisc.edu/maps/wui/2010/download), live fuel moisture (https://www.wfas.net/nfmd/public/index.php), NationalSolar Radiation Database (https://nsrdb.nrel.gov), gridded monthly climate data from Williams et al. (2017; www.ldeo.columbia.edu/~williams/seus_drought_jgr/forcing/). Williams was supported by Columbia University's Center for Climate and Life, a Palisades Geophysical Institute fellowship, and the NASA Modeling, Analysis, and Prediction program (16-MAP 16-0081). Lamont contribution 8222.

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