Irradiance enhancement events in the coastal Stratocumulus dissipation process

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Abstract

We characterize the irradiance enhancement events that occur when coastal stratocumulus clouds dissipate, caused by the breakup of the cloud layer into smaller cloud elements. The analysis includes 91 days in 2016 and 2017 that presented transitions from stratocumulus to clear skies in Southern California, using solar irradiance measurements and a clear sky model to describe the enhancement events. We find that a breakup process that starts later in the day lasts longer and is linked to stronger enhancement, as well as stronger down-ramps. Strong enhancement events are also linked to higher wind speeds during the breakup and lower solar zenith angle. The potential benefit of an irradiance enhancement forecast is assessed by evaluating a battery ramp-rate control system. Compared to a forecast that does not capture the solar variability, a good forecast would allow to use a smaller battery and to cycle it less, extending its lifetime.

Keywords: irradiance enhancement, coastal stratocumulus, solar variability

1. Introduction

Stratocumulus (Sc) clouds are present in western coastal regions, attenuating the solar irradiance that reaches the surface and typically dissipating during the morning hours. But cloud dissipation is not a simple process: initially the cloud layer covers all the sky, cloud thickness diminishes throughout the morning, and when the cloud layer thins enough, broken cloud fields develop. These broken cloud fields generate strong solar variability.

Cloud Irradiance Enhancement (IE) consists of a measured solar irradiance that exceeds that of clear skies, a phenomenon that can occur with thin broken clouds. IE has been widely observed and characterized through analyses of ground measurements (i.e. Berg et al., 2011) and radiative transfer simulations (i.e. Pecenak et al., 2016). The magnitude of IE events has been related to the sun's position and cloud properties such as cloud cover (Pfister et al., 2003) or cloud optical depth (Pecenak et al., 2016). There are no studies that describe IE events linked to the dissipation of coastal Sc clouds.

Solar variability due to IE has several effects on a solar photovoltaic plant. First, the power output may exceed the inverter capacity at times, affecting its performance, and losing the excess power that could be generated by IE. Second, the solar variability linked to IE events can obstruct the compliance of ramp requirements set by the grid operators. Improving the understanding of IE events could help to develop an accurate forecast of solar variability that could be useful to control ramp rates.

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In this study, we analyze 91 days in 2016 and 2017 which display dissipating Sc clouds in Southern California, describing the magnitude and duration of the IE events as well as the down-ramp events in the same dissipation process. We also investigate how the IE events' properties relate to meteorological parameters of importance for Sc clouds. Lastly, we assess the value of an IE forecast for coastal Sc clouds by modeling a photovoltaic system with a battery ramp-rate control.

1. Data and methods

2.1. IE event characterization

We consider Global Horizontal Irradiance (G_h) data with 1 second resolution measured at the UC San Diego campus, (La Jolla, CA), and clear sky irradiance (G_{cs}) obtained with a clear sky model implemented in PV LIB (Ineichen and Perez, 2002; Holmgren et al., 2018). The selection of days with Sc to clear transitions is done first by visual inspection of the time series of G_h and G_{cs}, and is corroborated with sky imagery available at the site. We have only included single layer Sc clouds, excluding days with Cumulus clouds forming underneath (decoupled Sc) because the physical processes are different.

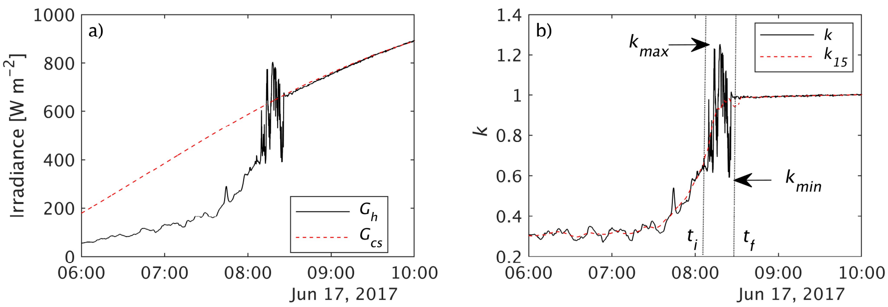

Fig. 1: Measured and clear sky irradiance for June 17, 2017 in La Jolla, CA (left), and clear sky index (right).

The clear sky index k is defined as the ratio between G_h and G_{cs}. Fig. 1 shows that a Sc cloud layer that is thinning undergoes an increase of G_h and k until strong variability develops around 08:15 LT. We define the breakup start time t_i before the first strong peak occurs (when k exceeds its 15-minute moving average k_{15} by more than 0.15), and the ending time t_f after clear skies prevail (when for the following 5 minutes, $k \approx 1$ and $dk/dt \vee 10^{-3}$). In the breakup window (when $t_i < t < t_f$), an IE event is detected when $k > 1.05$, and an extreme down-ramp is detected when $k < k_{15} - 0.15$. The strongest IE event during the breakup determines k_{max}, and the strongest down-ramp event determines k_{min}.

2.2. Meteorological parameters of interest for coastal Sc clouds

We obtain radiosonde and wind data from the closest meteorological station (NKX, located at the Marine Corps Air Station in San Diego, CA). The radiosonde data allows us to derive variables that describe the state of the atmospheric boundary layer (ABL), the lower part of the atmosphere where Sc clouds develop. From the radiosondes, launched at 03:00 LT, we obtain the cloud top height (z_i), the ABL averaged potential liquid water temperature (θ_l) that represents the ABL thermal state, and the capping temperature inversion jump ($\Delta\theta_l$) which is known to influence the presence of marine Sc (Wood, 2012). The wind speed at 10 m is available during the whole day, and we gather the wind speed at the start of the breakup (u_i) and an average wind speed during the breakup process (u).

2.3. A PV system with ramp-rate control

In order to assess the value of an IE forecast, we consider a PV system with battery ramp-rate control operating in June 22, 2017, a day with strong IE events. Our system consists of a small section of a rooftop photovoltaic system at the UC San Diego campus consisting of 42 modules connected to a 7 kW inverter. In order to model the generated electric power, the solar irradiance (G_h) is converted to electric DC power (P) using PV LIB (Holmgren et al., 2018). The ramp-rate control system takes in a power forecast, and calculates the ramp rate r at each second as the difference between the forecasted power (P_f) and the last generated power (P_g), normalized by the inverter power (P_{inv}) (Eq. 1).

$$r(t) = \frac{P_f(t) - P_g(t-1s)}{P_{inv}} \times 100[\%/s] \qquad \text{(eq. 1)}$$

For the ramp-rate control, the maximum permissible ramp rate r_{max} is set as 0.16%/s, which is equivalent to the common ramp-rate requirement of 10%/min (de la Parra et al., 2015). The control system sets the generated power to either be limited by r_{max} or to take all the incoming power in, depending on the expected ramp rate (Eq. 2).

$$P_g(t) = \begin{cases} P(t) & \text{,if } r(t) \leq r_{max} \\ P_g(t-1s) + \text{sign}(r)\frac{r_{max}}{100}P_{inv} & \text{, if } r(t) > r_{max} \end{cases} \qquad \text{(eq. 2)}$$

After the generated power is decided by the control system, the battery power (P_{bat}) is the difference between the DC power before the inverter P and generated power P_g.

2. Results and discussion

3.1. IE caused by Stratocumulus clouds

The strongest IE event with $k = 1.699$ occurred on July 3rd, 2016 and the minimum down ramp of $k = 0.245$ on June 25, 2016. Breakups can start as early as 05:23 LT or as late as 12:06 LT, and they last from 3 minutes to 6 hours and 22 minutes. The time at which the breakup ends is also the time when the Sc layer dissipates, and it ranges from 06:16 LT to 14:14 LT. In this section, we review and discuss the relationships of the timing and magnitude aspects of the IE events during the Sc breakup process.

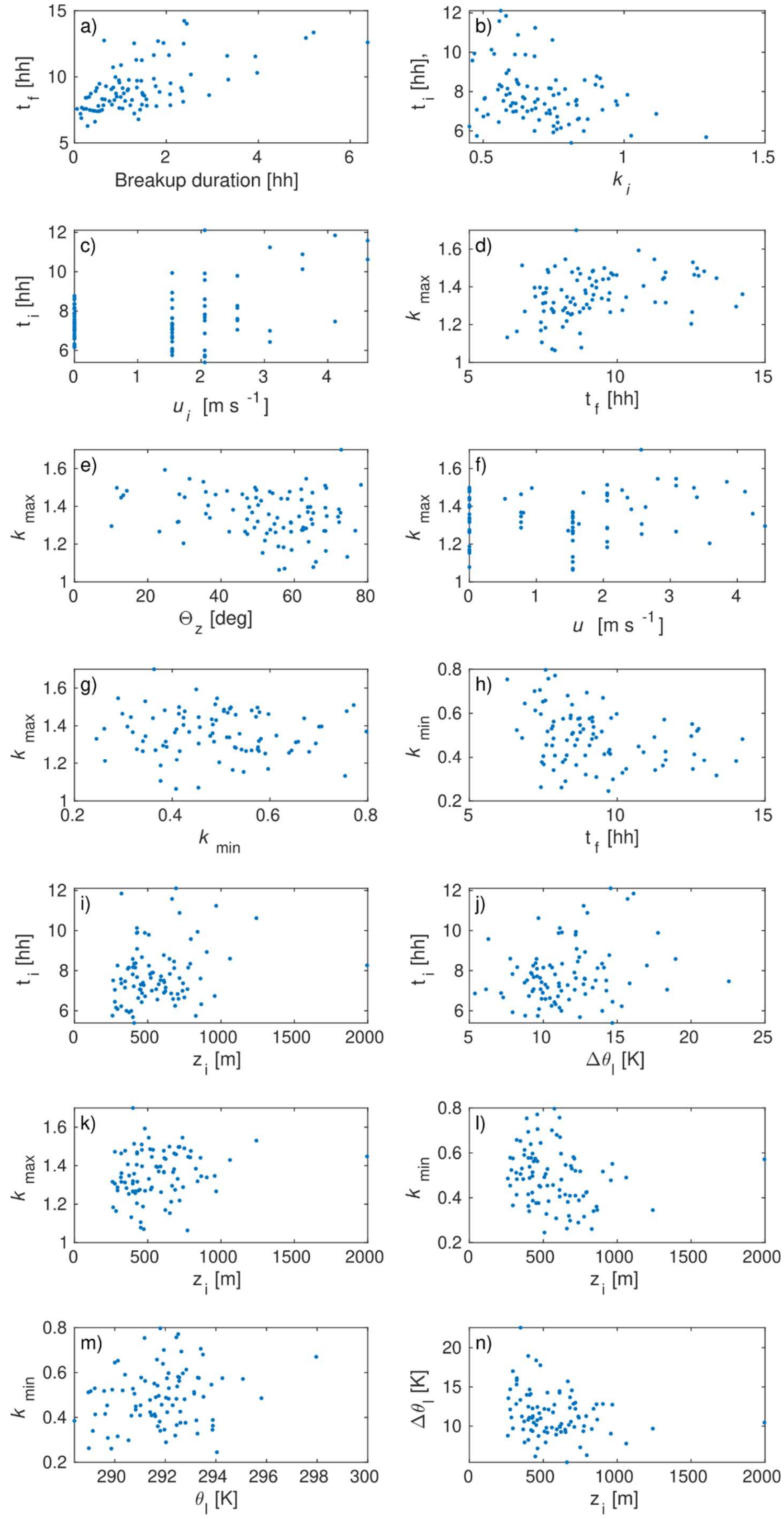

Fig. 2: Observed relationships for different parameters of importance for the Sc breakup process.

The timing of the Sc breakup processes comprises the duration, start time, and end time. While the start and end times are logically correlated since an event that starts later with end later (correlation coefficient of $\rho = 0.77$), we also observe that the breakups that end later in the day last longer (Fig. 2a, $\rho = 0.61$). A cause of this relationship is that only the later breakups can display longer durations, but physics may also play a role. Solar heating and sea breeze compete to thin or thicken the Sc cloud layer, and both processes become the dominant factors to determine coastal cloud evolution as the morning advances (Ghonima et al., 2016). Consequently, only the clouds that manage to stay for longer are subjected to this balance, meaning they could experience a longer breakup process.

While previous works have studied important factors in cloud thinning (van der Dussen and de Roode, 2014), there is a lack of understanding on what causes the start of the Sc breakup. Since the initial cloud thickness is strongly related to Sc dissipation time (Burleyson et al., 2015), one may think that there is a critical cloud thickness at which the breakup occurs. Due to the lack of a measurement of cloud thickness, we use the clear sky index prior to the breakup, $k_i = k(t_i)$, as an indicator of how thick the cloud is when the breakup starts. Fig. 2b shows firstly that there is not a critical value of k_i linked to the start of the cloud breakup, although there is still a weak correlation ($\rho = -0.3$). Secondly, early breakups occur for any k_i, while later breakups are linked to smaller k_i. This suggests that later breakups start when clouds are thick and early breakups occur at different cloud thicknesses, so other factors must influence the breakup. One of these factors could be the wind speed, as the sea breeze is important in coastal cloud evolution. Fig. 2c shows that the wind speed at the beginning of the breakup u_i is weakly linked to t_i ($\rho = 0.4$), but this could be a consequence of the wind speed diurnal cycle rather than a physical process. Also, the resolution of the available wind speed data is not fine enough to correctly identify if the values of u_i are below or above the average diurnal cycle. Meteorological variables such as the initial cloud top height z_i and the temperature inversion $\Delta\theta_l$ are also related to t_i, although their relationships are not as strong as the other timing parameters (Fig. 2i and 2j, $\rho = 0.22$ and 0.21, respectively).

The maximum magnitude of the IE events k_{max} increases with t_f (Fig. 2d, $\rho = 0.33$) and decreases with the solar zenith angle Θ_z (Fig. 2e, $\rho = -0.22$). This contradicts the general trend of increased k with Θ_z modeled by Pecenak et al. (2016), but as Sc clouds are thin at the onset of the breakup, the state of the cloud could lie in the nonlinear region of their reported relationship between k, cloud optical depth, and Θ_z. A measure of cloud optical depth at the occurrence of each IE event would be needed to further clarify this issue. We also observe that k_{max} is greater for stronger wind speeds during the breakup (Fig. 2f, $\rho = 0.67$), which agrees with the relationship between k_{max} and t_f because the wind speed increases when it is closer to noon. Of the initial meteorological parameters, only the cloud top height z_i is related to k_{max} (Fig. 2k, $\rho = 0.19$).

There is no trend between the maximum and minimum clear sky indices of the breakups k_{max} and k_{min} (Fig. 2g, $\rho = -0.06$), but for k_{min} we see a robust trend with t_f (Fig. 2h, $\rho = -0.33$). The fact that k_{min} is related to cloud thickness because the shading effect of thicker clouds can lead to lower k (Pecenak et al., 2016) also suggests that early Sc dissipation occurs for a variety of cloud thicknesses, while later dissipation only occur for thicker clouds. Of the initial meteorological parameters, the cloud top height z_i and ABL thermal state θ_l indicate a weak influence on k_{min} (Fig. 2l and 2m, $\rho = -0.19$ and 0.2, respectively). It is interesting to note that initial parameters do not have a strong influence on the IE event features, even though they are known to be important for cloud dissipation time. This suggests that the physical processes that influence cloud evolution might be more important than the initial state to determine both the timing and magnitude of the IE events. Also, existing correlations between the meteorological parameters exist, such is the case for z_i and θ_l (Fig. 2n), and they can affect further correlations with the breakup characteristics. From this point of view, detailed meteorological observations at the time of the breakup should be explored, along with their correlations, including variables related to surface heating, radiative cooling and sea breeze advection processes.

3.2. The value of a Sc dissipation IE forecast

A better understanding of the Sc dissipation process can improve the forecast of solar irradiance, including the prediction of up and down-ramp events. In order to assess the value of such a forecast, we illustrate its possible influence on a PV system with battery ramp rate control.

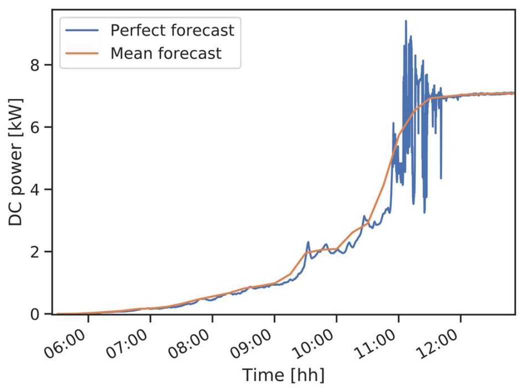

Fig. 3: Idealized power forecasts for the ramp-rate control assessment for June 22, 2017

Fig. 3 shows the two idealized power forecasts built from the observed solar irradiance as described in Section 2.3.: a perfect forecast with 1 s resolution, and a 15 min averaged time series that is not able to include solar variability. The latter idealized forecast resembles the output of a numerical weather prediction model. Since the two forecasts have a different time step (1 s and 15 min), the control will assume a 1 s forecast, interpolating from the 15 min time-series. Fig. 4a shows the results of the ramp-rate control for generated power P_g considering the two forecasts, focusing on the breakup duration, and Fig. 4b shows the resulting state of charge (SOC) of the battery. Compared to the perfect forecast, the mean forecast induces a lot of extra variability into the generated power and also the battery (not shown). The control system tends to limit the ramp rate for some time until it approaches the predicted value, and then decides to take all power in. Since the actual power differs from the prediction, undesired ramps are generated. This process occurs very frequently, developing a zig-zag performance. Consequently, the battery is used more, which can lower its lifetime. Another outcome of using a poor forecast is that a larger battery capacity is needed: the SOC of the battery reaches a cumulative discharge 4 times greater than the charge using the perfect forecast (Fig. 4b).

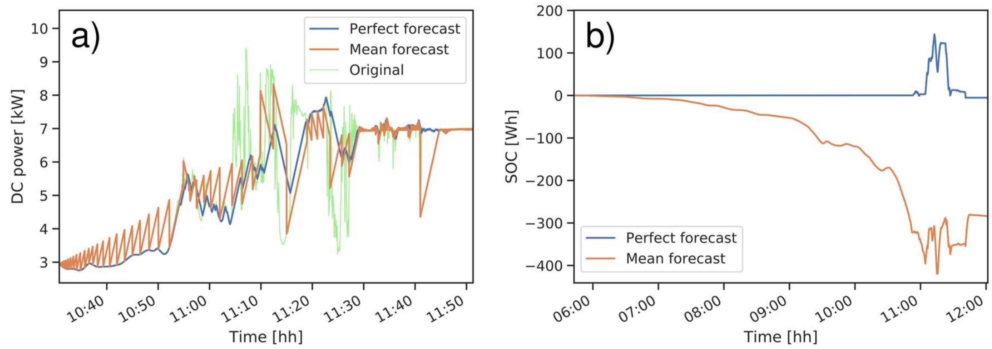

Fig. 4: Ramp-rate control results for the (a) generated power and (b) the state of charge (SOC) of the battery

While a solar power forecast with 1 s resolution could be used in ramp-rate control systems, the current real-time technology operating at PV plants can detect the actual generated DC power of a PV system in timescales shorter than 1 s (de la Parra et al., 2016). Since ramp-rate control is based in a short-term decision and does not consider future behavior, real-time data will be preferred over a 1 s forecast, thus reducing the value of the forecast.

3. Conclusions and future work

We have analyzed and described 91 Sc breakup processes for Southern California, finding that clouds that break later in the day lead to stronger IE events, their breakup process lasts longer, and they are accompanied by lower solar zenith angles and stronger wind speed. Our results suggest that the clouds that dissipate later in the day correspond to thicker clouds, and that they also start to break later than thinner clouds. The starting time of the breakup does not seem to be determined by cloud thickness alone, and although wind speed can be of importance, it is hard to isolate its effect because of its diurnal cycle and poor data resolution. Future work should examine how Sc clouds can break into smaller components either using a physical model to analyze the effect of each physical process, or with more detailed meteorological data during the breakup process.

We have assessed the value of an IE forecast, by modeling a PV system with a battery that regulates the ramp rates delivered to the inverter, evaluating a day with strong IE events. An accurate forecast allows to reduce the battery capacity and its use, which can result in less degradation and a longer battery life. We also note that currently, operational ramp-rate control is possible, which may not require a forecast to operate.

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5. References

Berg, L., Kassianov, E., Long, C., Mills, D., 2001. Surface Summertime Radiative Forcing by Shallow Cumuli at the Atmospheric Radiation Measurement Southern Great Plains Site. J.

Geophys. Res. 116, D01202.

Burleyson, C. D., Yuter, S.E., 2015. Patterns of Diurnal Marine Stratocumulus Cloud Fraction Variability. J. Appl. Meteor. Climatol., 54, 847–866.

De la Parra, Í., Marcos, J., García, M., Marroyo, L., 2015. Control strategies to use the minimum energy storage requirement for PV power ramp-rate control. Solar Energy 111, 332–343.

Ghonima, M., Heus, T., Norris, J., Kleissl, J., 2016. Factors Controlling Stratocumulus Cloud Lifetime over Coastal Land. J. Atmos. Sci. 73 (8), 2961–83.

Holmgren, W., Hansen, C., Mikofski, M., 2018. pvlib python: a python package for modeling solar energy systems. Journal of Open Source Software 3 (29), 884.

Ineichen, P., Perez, R., 2002. A New Airmass Independent Formulation for the Linke Turbidity Coefficient. Solar Energy 73 (3), 151–57.

Pecenak, Z., Mejia, F., Kurtz, B., Evan, A., Kleissl, J., 2016. Simulating Irradiance Enhancement Dependence on Cloud Optical Depth and Solar Zenith Angle. Solar Energy 136, 675–81.

Pfister, G., McKenzie, R., Liley, J., Thomas, A., Forga, B., Long, C., 2003. Cloud Coverage Based on All-Sky Imaging and Its Impact on Surface Solar Irradiance. J. App. Meteorol. 42 (10), 1421–34.

Van der Dussen, J., de Roode, S., 2014. Factors Controlling Rapid Stratocumulus Cloud Thinning. J. Atmos Sci. 71 (2), 655–664.Wood, R., 2012. Stratocumulus clouds. Mon. Wea. Rev. 140 (8), 2372–2423.