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Coastal Stratocumulus cloud edge forecasts

Elynn Wu[a,*], Rachel E.S. Clemesha[b], Jan Kleissl[a]

[a] Center for Renewable Resources and Integration, Department of Mechanical and Aerospace Engineering, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0411, USA

[b] Scripps Institution of Oceanography, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0230, USA

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ABSTRACT

Improved coastal stratocumulus (Sc) cloud forecasts are needed because traditional satellite cloud motion vectors (CMV) do not accurately predict how Sc clouds move or dissipate in time, which often results in an underprediction of irradiance in the morning hours. CMV forecasts assume clouds move in the direction of the average regional wind field, which is not necessarily the case for Sc clouds. Sc clouds over the land form at night and typically reach their maximum coverage before sunrise. During the day, heating from solar radiation at the surface and entrainment of dry and warm air from above causes Sc clouds to dissipate. A Sc cloud edge forecast using Geostationary Operational Environmental Satellite is proposed to improve Sc cloud dissipation forecasts during the day. The inland edge of the Sc clouds is tracked in time and extrapolated into the future. For coastal regions where land elevation increases away from the coast, such as coastal California, the Sc cloud inland boundary is correlated to the land elevation. Dissipation after sunrise often follows land elevation as the mass of air required to be heated to become cloud-free decreases with increasing elevation as cloud top height is fairly constant along the cloud edge. The correlation between land elevation and the Sc cloud eastern boundary is exploited by extrapolating the evolution of cloud edge elevation in time. This method is tested in central and northern California on 25 days and in southern California on 19 days. When compared to the CMV (persistence forecasts), the proposed Sc cloud edge forecasts show a reduction of 30 W m^{-2} (104 W m^{-2}) in hourly mean absolute error (MAE) of global horizontal irradiance (GHI). Additionally, out of 11 stations the Sc cloud edge forecast results show a higher forecast skill than CMV (persistence) at 7 (9) stations.

1. Introduction

Stratocumulus (Sc) clouds are the most common cloud type on Earth, with an annual mean coverage of 22% for the ocean surface and 12% for the land surface (Hahn and Warren, 2007). Sc clouds strongly reflect incoming solar radiation. Due to their low cloud height they emit a similar amount of outgoing longwave radiation as the surface. Therefore, Sc clouds have a strong net negative radiative effect on the Earth's radiative balance (Hartmann et al., 1992; Wood, 2012). Sc clouds form in a shallow planetary boundary layer and are capped by a strong temperature inversion. The inversion limits the vertical mixing of warm dry air above, and cool moist air beneath (Klein and Hartmann, 1993), which keeps the clouds from evaporating. Geographically, the highest Sc cloud land coverage is found in the mid-latitude coastal region next to eastern boundary currents (Wood, 2012), where the temperature inversion in this region is associated with the warm dry descending branch of the Hadley cell.

Coastal California is an area of high Sc cloud coverage during the late spring and summer months when the semi-permanent North Pacific High has the greatest intensity (Clemesha et al., 2016). Sc clouds greatly influence the weather, water, and energy of the ecosystem and have been a topic of extensive research for many years (e.g., Beer and Leopold, 1947; Iacobellis and Cayan, 2013; Johnstone and Dawson, 2010; Williams et al., 2015). In recent years, an aggressive renewable energy mandate in the state of California has attracted more than half a million rooftop solar photovoltaic (PV) installations. As solar PV becomes an important source of generation to the grid, it is critical for the utilities and system operators to maintain reliable service while maximizing solar energy utilization (Denholm et al., 2016). With a majority of rooftop solar PV along the densely-populated coast of California, an accurate forecast of Sc clouds during the summer months becomes important as these clouds reduce solar irradiance substantially.

Two types of methods are traditionally used in solar irradiance forecasting depending on the forecast horizon. For short-term solar forecasting, imagery-based cloud advection is used. Ground-based sky imager systems are used for intra-hour forecasting (Chauvin et al.,

* Corresponding author.
E-mail address: elw014@eng.ucsd.edu (E. Wu).

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2016; Chow et al., 2011; Dev et al., 2017; Huang et al., 2013; Peng et al., 2015; Yang et al., 2014), while satellite cloud motion vectors (CMV) are used for forecasting up to 5-h ahead (Perez et al., 2010). Traditional image-based cloud advection assumes "frozen" clouds to move in the direction of the regional wind field. While this assumption generally holds true for a few hours, it loses validity for longer term forecast. For longer-term solar forecasting, ranging from hours-ahead to days-ahead, physics-based numerical weather prediction (NWP) is used (Jimenez et al., 2016; Lara-Fanego et al., 2012; Mathiesen and Kleissl, 2011). NWP uses current weather observations to solve a set of primitive equations and numerically integrate the weather forward in time. Forecast accuracy varies considerably depending on the time, location, and weather condition. Perez et al. (2010) found that hourly-averaged satellite CMV forecast mean bias error (MBE) and root mean square error (RMSE) on an annual basis range from 0.2 W m^{-2} and 104 W m^{-2} in an arid region like Desert Rock, NV to 30 W m^{-2} and 159 W m^{-2} in a semi-arid elevated place like Boulder, CO. Mathiesen and Kleissl (2011) found that NWP models generally under-predict cloudy conditions, resulting in an over-prediction of solar irradiance. Recent studies have combined satellite images and NWP to better improve short-term solar forecasting (Arbizu-Barrena et al., 2017; Lee et al., 2017). For example, in addition to using traditional CMV techniques, Arbizu-Barrena et al. (2017) use a NWP to allow both advection and diffusion to the cloud index derived from Meteosat Second Generation. It is shown that this technique outperforms traditional CMV in areas with low topographic complexity, but struggles in areas where cloud patterns are influenced by the terrain, as is the case for coastal California.

NWP forecasts of Sc clouds in coastal California have been improved through better cloud initialization (Mathiesen et al., 2013; Yang and Kleissl, 2016) or by modifying inversion base height in NWP to better represent the clouds (Zhong et al., 2017). Imagery-based cloud advection forecasts have received less attention. Traditional satellite CMV forecasts do not accurately predict how Sc clouds move or dissipate in time largely because Sc clouds do not typically follow the synoptic wind direction. An example of false Sc cloud advection by traditional satellite CMV forecast has recently been reported by Miller et al. (2017). Sc clouds over land often form at night and reach their maximum coverage before sunrise. During the day, Sc clouds dissipate because of solar heating at the surface (and the resulting surface sensible heat flux), solar heating of the cloud, and entrainment of drier warmer air from aloft (Ghonima et al., 2016). As dissipation of Sc clouds is not considered, frozen cloud advection in satellite CMV often under-predicts solar irradiance.

The objective of this paper is to improve solar irradiance forecasting during Sc cloud days primarily through quantifying the dissipation time of Sc clouds. A Sc cloud edge forecast (hereinafter called "line forecast") using the Geostationary Operational Environmental Satellite (GOES) is proposed to improve solar irradiance forecasting by allowing for Sc cloud dissipation. The forecast is based on tracking the most inland edge of Sc clouds. The novelty of the method is that it can track evolution (dissipation in this case) of a stationary cloud, while standard cloud motion approaches only consider advection of frozen clouds. The method combines physical insights into lower atmospheric cloud top heights under a strong inversion with statistical methods. While applied here to Sc cloud forecasting in California, we expect the cloud edge tracking to be equally valid for other overcast stationary clouds such as coastal Sc cloud forecasts elsewhere and inland fog forecasts. For example, fog and low stratus in Germany pose a challenge for the transmission system operators. In addition to the low stratus risk forecast system designed for day-ahead warnings (Köhler et al. 2017), line forecasts for short-term forecasting could also help support the decision makings.

This paper is organized as follows. Section 2 explains the conceptual motivation and assumptions of the line forecast (2.1), followed by a description of Sc cloud dissipation time and cloud thickness evolution (2.2 and 2.3). Then error metrics are presented in (2.4). Section 3 contains input data (3.1 and 3.2), case study setup (3.3, and validation sites and data (3.4). Section 4 contains the validation results and discussion. Validation of assumptions are investigated in 4.1, followed by validation against satellite observations (4.2), and discussion of geographical error distributions (4.3). Finally, Section 5 provides conclusions.

2. Methods

2.1. Cloud edge line forecast – conceptual motivation and assumptions

In coastal California, the Sc cloud eastern (inland) boundary edge elevation is typically found to be at a maximum during the early morning and then decreases in time. Conceptually, clouds thicken and spread at night due to longwave cooling, but start to thin when longwave radiative cooling is balanced by solar heating, which occurs shortly after sunrise (Akyurek and Kleissl, 2017). In southern California, the terrain rises nearly monotonically and peaks at about 1.5 km elevation 40 to 80 km inland. The eastern boundary of Sc clouds usually follows isolines of land elevation. Iacobellis and Cayan (2013) showed that the inland penetration of Sc clouds is limited by the height of the inversion base and coastal topography. In other words, Sc clouds extend inland up to where the land elevation reaches the inversion base height, and the inversion base height equals the cloud top height. Dissipation of Sc clouds occurs after sunrise, often following land elevation as the mass of air required to be heated in order to become cloud-free decreases with increasing elevation.

The line forecast employs the correlation between land elevation and the Sc cloud eastern boundary, by extrapolating the evolution of cloud edge elevation in time to predict the future cloud edge location. The line forecast assumes: (i) constant inversion height (and cloud top height) along the cloud edge; (ii) a constant rate of decrease in the cloud edge boundary elevation; (iii) an exponential increase in the ratio of GHI to clear sky GHI (clear sky index, k_t) from sunrise to one when the clouds dissipate; and (iv) no satellite parallax effect. Assumptions (ii) and (iii) will be tested in Section 4.1. Rastogi et al. (2016) investigated the inversion base height at San Diego Miramar (NKX: 32.85°N, 117.11°W), Vandenberg Air Force Base (VBG: 34.75°N, 120.56°W), and the northern Channel Islands (approximately 34°N, 120°N) during 1965–2015 using radiosonde data and the Modern-Era Retrospective Analysis for Research and Applications (MERRA) (Rienecker et al., 2011). While radiosonde data showed that inversion height is generally 100 m lower at VBG than NKX, MERRA data showed nearly identical inversion base height for the three points. Although radiosonde data showed differences between VBG and NKX, the lack of spatial coverage made it hard to determine the inversion height everywhere in the domain. As such, assumption (i) was treated as valid for this study. As the GOES satellite is at a zenith angle of approximately 43° and 50° in the southern and northern end of California, the projection of the cloud edge on the surface will be displaced horizontally by tan (zenith angle) times cloud top height above ground level. However, because average cloud top heights are only 400 m above mean sea level the parallax error is small relative to the scales of terrain elevation changes and the horizontal resolution of the satellite images.

2.2. Cloud dissipation time

The GOES visible channel captures a new image every 15 min. At each satellite image time stamp, a visible reflectance cloud test (Iacobellis and Cayan, 2013) is performed, and the eastern boundary of Sc clouds with its corresponding land elevation are extracted. The median land elevation of all the points over the boundary is used to represent the elevation at each time step. Any missing satellite images are ignored. The time step of the line forecast model is every 15 min. An example of the Sc cloud inland boundary moving towards lower land elevation is shown in Fig. 1. The median land elevation of the boundary