Solar Energy 146 (2017) 50–64

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

WRF inversion base height ensembles for simulating marine boundary layer stratocumulus

Xiaohui Zhong *, Dipak K. Sahu, Jan Kleissl

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

ARTICLE INFO

Article history:
Received 21 September 2016
Received in revised form 30 January 2017
Accepted 13 February 2017

Keywords:
WRF
IBH
MBL
Stratocumulus

ABSTRACT

Increasing distributed rooftop solar photovoltaic generation in the southern California coast necessitates accurate solar forecasts. In summertime mornings marine boundary layer stratocumulus commonly covers the southern California coast. The inland extent of cloud cover varies primarily depending on the temperature inversion base height (IBH, i.e. boundary layer height) and topography as confirmed using radiosonde sounding measurement and satellite irradiance data. Most operational numerical weather prediction models consistently overestimate irradiance and underpredict cloud cover extent and cloud thickness, presumably due to an underprediction of IBH. A thermodynamic method was developed to modify the boundary layer temperature and moisture profiles to better represent the boundary layer structure in the Weather and Research Forecasting model (WRF). Validation against satellite global horizontal irradiance (GHI) demonstrated that the best IBH ensemble improves GHI accuracy by 23% mean absolute error compared to the baseline WRF model and is similar to 24-h persistence forecasts for coastal marine layer region. The spatial error maps showed deeper inland cloud cover. Validation against ground observations showed that IBH ensembles were able to outperform persistence forecast at coastal stations.

1. Introduction

Stratocumulus clouds are critical to the Earth's radiative budget as a result of their strong net negative radiative effect and enormous spatial coverage (Hartmann et al., 1992; Wood, 2012). Annually, 22% of the ocean surface and 12% of the land surface is covered by stratocumulus (Hahn and Warren, 2007; Eastman et al. 2011). Stratocumulus preferably occur in a shallow planetary boundary layer (PBL) capped by a strong temperature inversion. The strong inversion inhibits warm dry air from above from penetrating the inversion that would otherwise facilitate cloud evaporation (Bretherton and Hartmann, 2009).

Marine boundary layer (MBL) stratocumulus clouds are an important climate and weather feature along the California coast, and are especially dominant in Southern California during the summer months (Iacobellis and Cayan, 2013). In California, the majority of rooftop solar photovoltaic (PV) panels are installed near the coast, thus the PV power generation is strongly affected by the formation and dissipation of MBL stratocumulus (Jamaly et al., 2013). Accurate solar forecasts facilitate the reliable and economical integration of solar PV into the electric grid. Generally, two approaches are utilized for solar forecasting: imagery-based cloud advection techniques using ground-based sky imager systems (e.g. Yang et al., 2014; Chow et al., 2011; Urquhart et al., 2015) or satellites (e.g. Perez et al., 2010; Marquez et al., 2013), and physics-based numerical weather prediction (NWP). For either method, post processing corrections through statistical learning techniques generally improve the forecast skill. Although NWP forecasts were found to be the most accurate method for forecast horizons longer than 5 h (Perez et al., 2010), many previous studies have shown NWP consistently underpredicts cloud cover. Siebesma et al. (2004) assessed nine NWP models over the northern Pacific Ocean for June/July/August 1998 using satellite observations. They concluded that all models strongly underpredicted stratocumulus cloud cover and cloud amount and typically overpredicted global horizontal irradiance (GHI) by 60 W m^{-2} in daytime. Similarly, by comparing with satellite measurements, Zhang et al. (2005) showed that half of the atmospheric general circulation models tested underestimated low clouds. Mathiesen and Kleissl (2011) found that when SURFRAD ground observations showed cloudy conditions, 52% of the North American Model (NAM), 54% of the Global Forecasting System (GFS) and 31% of the European Center for Medium-range Weather Forecasts (ECMWF) forecasts were

* Corresponding author.
E-mail address: x6zhong@eng.ucsd.edu (X. Zhong).

http://dx.doi.org/10.1016/j.solener.2017.02.021
0038-092X/

false clear. Furthermore, Mathiesen et al. (2013) showed errors are exacerbated for the California coast during summertime when MBL stratocumulus is common. In summary, all studies agree that MBL stratocumulus are challenging to predict and are often underpredicted by NWP models.

Understanding the causes of NWP biases is difficult due to the complexity of interactions between radiation (both shortwave and longwave), turbulence, surface fluxes, phase change, subsidence, and entrainment, and the variety of scales involved. Myers and Norris (2013) argued that stronger subsidence lowers cloud tops and reduces the cloudiness while a stronger inversion reduces entrainment drying and warming, thickening clouds. At night, cloud top longwave cooling is the main driver for turbulence that transports surface moisture to the cloud layer and maintains a well-mixed layer under the inversion (Lilly, 1968). During the day, solar radiation absorbed within the clouds suppresses turbulence driven by longwave cooling (Wood, 2012). Clouds may then dissipate due to a weakened coupling between clouds and surface moisture. Compared to the ocean, the land surface has a smaller heat capacity. A large portion of incoming solar radiation at the land surface is returned to atmosphere as sensible and latent heat flux which tends to shorten stratocumulus life times. Brenguier et al. (2000) demonstrated that radiative properties of MBL stratocumulus also depend on aerosol properties. The processes that controls formation and dissipation of MBL stratocumulus range from planetary scale to droplet scale making MBL stratocumulus extremely challenging to understand and predict.

Increasingly, researchers are finding that NWP biases are largely due to misrepresentation of PBL properties. In particular for MBL stratocumulus, several lower atmospheric properties related to the temperature inversion have been linked to enhanced cloud cover. Klein and Hartmann (1993) demonstrated a correlation between MBL stratocumulus cloud cover and lower troposphere static stability (LTS) which is a proxy measure of the inversion strength and defined as difference in potential temperature between 700 mb and the surface. Koračin et al. (2003) demonstrated that accurate prediction of the inversion base height (IBH) is crucial to the success of simulating the structure and evolution of the MBL. However, many studies evaluating NWP models in simulating stratocumulus show that the simulated PBL/MBL is too shallow. Hannay et al. (2009) examined several NWP models in representing regions of stratocumulus using cruise observations (Bretherton et al. 2004). They found that modeled PBL ranging between 400 and 800 m are substantially shallower than the observed IBH of about 1100 m. Although they suggested the model PBL can be deepened by modifying the underestimated entrainment, they also argue that increasing entrainment increases the surface evaporation and can make overall simulation results worse. Similarly, Wyant et al. (2010) demonstrated that a wide range of contemporary atmospheric models from fourteen modeling centers underpredict the IBH but the interaction between mean IBH bias and mean cloud fraction bias was not clear. Rahn and Garreaud (2010a, 2010b) compared the Weather and Research Forecasting (WRF) modeled MBL with observations from the VOCALS Regional Experiment over the subtropical southeast Pacific. They found that WRF is able to simulate the spatial variability of MBL but underestimates the IBH. In addition, Iacobellis and Cayan (2013) showed that the inland penetration of MBL stratocumulus is controlled by where the IBH intersects with the coastal topography. The IBH controls the cloud top height, and the MBL stratocumulus can only extend inland when the ground elevation is lower than cloud top height. Therefore, we hypothesize that underestimation of the IBH limits the ability of WRF to accurately predict inland cloud cover.

In attempting to improve MBL height, most researchers focused on the PBL parameterizations which are most influential to atmospheric tendencies of temperature, moisture, and horizontal momentum in the PBL (Skamarock et al., 2008). Hu et al. (2010) concluded that the Mellor–Yamada–Janjic (MYJ) PBL scheme, which models mixing strength based on local gradients only, predicts lower PBL heights than two non-local schemes, the Yonsei University (YSU) scheme and the asymmetric convective model version 2 (ACM2), because of less vertical mixing and entrainment in MYJ than YSU and ACM2. They further confirmed their conclusion by showing that the PBL height varies monotonically with altered vertical mixing strength in ACM2. Jousse et al. (2016) suggested that the differences in mixing strength formulations between the MYJ and the Mellor-Yamada Nakanishi and Niino PBL schemes (MYNN) cause MYNN to outperform MYJ in representing PBL height. Banks et al. (2015) revealed large difference in WRF simulated PBL heights using eight PBL schemes. They proposed that different definitions of PBL height and differences in the entrainment formulations are responsible for the differences.

Despite intense research efforts, accurate forecasts of PBL height and stratocumulus are still elusive. Independent of the skill of a particular regional NWP model, the bias in initial conditions is still inherited from the parent model. Therefore, improving the initial conditions is pertinent such as in Koračin et al. (2003) who used satellite data to modify mesoscale NWP initial conditions. This led to better representation of the IBH and more accurate prediction of cloud development. Kann et al. (2009) developed an empirical subinversion cloudiness enhancement scheme which keeps the temperature inversion and cloudiness more realistic. Thus, the positive feedback of condensation, cloud top cooling and vertical mixing is initiated and improves the cloud distribution. The objective of our approach is to improve representation of boundary layer temperature and moisture to correct IBH before sunrise. Firstly, we briefly describe meteorological conditions of 8 continuous marine layer days (Section 2). We hypothesize that underprediction of cloud cover in WRF (Section 3) over the California coastline is correlated with IBH biases. The MBL stratocumulus inland penetration is quantified using satellite irradiance data (Section 4.2) and the correlation between IBH derived from sounding data (Section 4.1) and MBL stratocumulus inland penetration is investigated in Section 5. We develop an IBH correction method in Section 6.1 and different IBH ensembles are run for eight June days. In Section 7, vertical temperature, moisture and relative humidity profiles of IBH ensembles are compared with sounding data. Also, the GHI forecasts of IBH ensembles are evaluated using irradiance measurements by both satellite and ground stations and persistence forecasts. Finally, we discuss our findings and conclude in Section 8.

2. Meteorological conditions for the case study

WRF (version 3.6) is initialized at 0 UTC and run for 26 h each day from June 1 to June 8, 2013. The period was characterized by daily occurrence of MBL stratocumulus along the Southern California coastline. Starting on June 1, a trough of low pressure developed along the west coast and strengthened onshore flow. The stronger coastal eddy deepened the MBL and extended coastal clouds into the inland valleys. On June 2 and 3, clouds persisted over much of coastal areas throughout the day and retreated from the inland valleys in the afternoon (see Fig. 1a). For June 4, a high pressure system over the eastern Pacific expanded into northern and central California bringing about a warming trend. The low pressure system off the southern California coast moved slowly westward and continued to maintain the marine layer west of the mountains. The lowered IBH limited the inland extent of the MBL stratocumulus. Thus, on June 4 and June 5, clear skies prevailed over the inland region and even the coastal clouds cleared