Solar Energy 158 (2017) 753–759

Contents lists available at ScienceDirect

Solar Energy

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

A virtual sky imager testbed for solar energy forecasting

Benjamin Kurtz*, Felipe Mejia, Jan Kleissl

Center for Renewable Resources and Integration, Department of Mechanical and Aerospace Engineering, University of California, San Diego, United States

ARTICLE INFO

Keywords:
Whole sky imager
Forecast
Large Eddy Simulations

ABSTRACT

Whole sky imagers are commonly used for forecasting irradiance available for solar energy production, but validation of the forecast models used is difficult due to sparse reference data. We document the use of Large Eddy Simulations (LES) and a 3D Radiative Transfer Model to produce virtual clouds, sky images, and radiation measurements, which permit comprehensive validation of the sky imager forecast. We then use this virtual testbed to investigate the primary sources of sky imager forecast error on a cumulus cloud scene. The largest source of nowcast (0-min-ahead forecast) errors is the converging-ray geometry implied by use of a camera, while longer-term forecasts suffer from overly-simplistic assumptions about cloud evolution. We expect to use these findings to focus future algorithm development, and the virtual testbed to evaluate our progress.

1. Introduction

In recent years, whole-sky imagers have become popular for forecasting solar energy availability on short time horizons (Yang et al., 2014; Gauchet et al., 2012; Schmidt et al., 2016; Cazorla et al., 2015; Peng et al., 2015). However, validation of these forecasts can be tricky; reference data is often limited to at most a few irradiance sensors, and even in the case where many sensors are present over a large area, detailed validation data on the cloud field itself is uniformly unavailable. Under these circumstances, validation can determine the forecast accuracy, but apportionment of the forecast error to different components of the algorithm is difficult due to the lack of data about the actual state of the atmosphere and the resulting radiation field. Therefore prioritization of forecast development work is usually not well-informed and is unable to follow cost-benefit principles.

We propose to address some of these limitations by producing a virtual sky imager testbed, in which the configuration of the clouds and resulting irradiance is known. The purpose of this paper is to describe the setup of the virtual testbed and briefly illustrate its potential through a case study. The virtual testbed is used to design and test improvements to whole-sky imager forecast methodology developed at UC San Diego, but it is straightforward to adapt it to any other algorithm.

Simulating clouds is one of the grand challenges of atmospheric physics as it includes scales from micrometers (cloud condensation nuclei) to kilometers (cloud size), multiple phases (vapor, liquid, ice), and even chemistry (hydrophobicity of aerosol species). In terms of short-term (order of 10 min) cloud dynamics that are most relevant to sky imager solar forecasting, the multi-scale and multi-phase fluid dynamics need to be represented. In particular atmospheric turbulence plays a critical role in cloud formation (e.g. thermals) and cloud dynamics. Not only do clouds "live" in the turbulent atmospheric boundary layer flow field, but they also generate their own turbulence due to longwave radiative cooling at the cloud top and latent heat release. Large Eddy Simulation (LES) is a uniquely suited tool to simulate these boundary layer and cloud dynamics. In LES the large turbulent eddies that are responsible for most of the momentum, heat, and moisture transport are explicitly resolved and simulated faithfully based on the Navier Stokes equations. The small scales (less than about 10 m) cannot be resolved due to computational cost and are parameterized through subfilter scale models (Meneveau and Katz, 2000). LES also simulates all modes of heat transfer, water vapor transport and phase change, as well as cloud microphysics. LES is a mature field in engineering and atmospheric science and the resolution, subfilter scale models, and microphysics models have been continually improved over the past decades (Moeng, 1984; Stevens and Seifert, 2008).

Virtual cloud fields will be produced using LES. Surface-level irradiance fields and simulated whole-sky images will be derived from a 3-dimensional radiative transfer model (3D RTM). These tools (LES and 3D RTM) are significantly more physically grounded and accurate than current sky imager forecast algorithms, so there is considerable scope for improving sky imager forecasts based on the virtual testbed. It is worth noting that the virtual testbed need not reproduce a given observed cloud field for this to be useful, so long as the virtual clouds behave similarly to real clouds. Why not just use the LES and 3D RTM for forecasting in the first place? First, while recent GPU-accelerated LES codes (Schalkwijk et al., 2012) approach the speeds necessary to

---

* Corresponding author.
E-mail address: bkurtz@ucsd.edu (B. Kurtz).

http://dx.doi.org/10.1016/j.solener.2017.10.036
Received 28 May 2017; Received in revised form 26 September 2017; Accepted 9 October 2017

produce operational forecasts, the computational requirements for LES and 3D RTM tools are currently too large to be feasible for short-time-horizon forecasting. Furthermore, even in those cases where LES has been run operationally on a wide variety of measured data (Gustafson et al., 2016; Neggers et al., 2012), the cloud fields are statistically accurate on timescales from tens of minutes to hours. To produce meaningful forecasts of individual clouds, LES would require input of a detailed state of the atmosphere including detailed humidity and velocity fields which, as noted, are generally unavailable. Even here, the virtual testbed is useful, as it allows improved testing of 3D cloud detection algorithms for whole-sky imagers, which could eventually be used as input to an LES-based forecast.

In Section 2, we present the virtual testbed and whole-sky imager forecast. Section 3 compares the results of the sky imager forecast to those of the virtual testbed, paying special attention to the newfound ability to determine errors of difficult-to-measure quantities such as wind speed aloft and 3D cloud structure. Differing geometrical perspectives and cloud field dynamics constitute the largest sources of error in the current forecast, with geometry playing a larger role at short forecast horizons, and cloud evolution dominating the error for further-ahead forecasts. Discussion and conclusions are provided in Section 4.

2. Virtual testbed components

2.1. Large eddy simulation

LES are carried out using the UCLA LES (Stevens et al., 1999, 2005, 2015), which has been thoroughly validated and tested for a number of cases including continental cumulus (Brown et al., 2002), raining cumulus (Stevens and Seifert, 2008), and stratocumulus clouds (Stevens et al., 2005). The UCLA LES uses the Smagorinsky sub-gridscale model, and parameterizes cloud microphysics following Stevens and Seifert (2008). Interactive radiation is implemented via a Monte Carlo version (Pincus and Stevens, 2009) of the delta-four-stream model (Liou et al., 1988). Cloud droplet radius for both radiation and microphysics is modeled by assuming a fixed cloud droplet mixing ratio.

A single 14.5 h simulation was carried out using example input data modeled for continental cumulus clouds, following the base case in Hinkelman et al. (2005), which is itself based on a detailed LES study of measurements taken at the Southern Great Plains (SGP) site of the Atmospheric Radiation Measurement (ARM) program (Brown et al., 2002). Following prior simulations (Hinkelman et al., 2005), precipitation was disabled in the microphysics model, leaving cloud liquid water diagnosed as the total water mixing ratio in excess of the saturation mixing ratio, and with the fixed cloud droplet mixing ratio of 70×10^6/kg. Initial profiles of atmospheric temperature and humidity, as well as input surface fluxes are shown in Fig. 1. Small volumetric forcings are applied as in Brown et al. (2002) in order to represent observed large-scale advection in the periodic simulation domain. This day represents typical formation of a convective boundary layer due to surface heating, with cumulus clouds forming at the top of the (initially clear) boundary layer. As the day progresses, the cloud base rises from 1000 m to around 1500 m, with maximum cloud thickness of around 1250 m. Both the boundary layer and the clouds continue to deepen until late afternoon when solar radiation has decreased significantly. Typical horizontal cloud size is 400 m. Hemispherical cloud cover peaks just above 65% around solar noon; Fig. 6 later shows hemispherical cloud cover over the course of the day.

LES grid cells are 50 m across in both horizontal dimensions and 40 m high, spanning a 6.4 km domain that is 5.1 km deep. Periodic boundary conditions are used in the horizontal dimensions. A 10-cell thick sponge layer is used at the top of the domain to prevent wave reflection, while the lower surface uses a no-slip boundary with roughness length of 0.035 m, representative of long grass.

LES requires on the order of an hour of simulation time to properly "spin-up" the turbulent flow and cloud field. After spin-up, the 3D state of the atmosphere (velocity, temperature, pressure, humidity, and liquid water content) is saved every 60 s of simulation time for input into the 3D RTM and reference against the sky imager forecast results.

2.2. 3D radiative transfer model

The Spherical Harmonic Discrete Ordinate Method (SHDOM) (Evans, 1998) is used to solve the 3D Radiative Transfer Equation. SHDOM is the most computationally intensive portion of the virtual testbed, requiring over half of the approximately 5000 CPU-core-hours used for the run presented here. SHDOM inputs are derived from the liquid water content output by UCLA LES, combined with the aerosol loading shown in Fig. 2, which is based on the `nauru19990707` data file included with SHDOM adjusted to match the observed annual-average aerosol concentration, and effective radius at the ARM SGP AERONET site in 2013. This rapid decrease in aerosol concentration with height matches the exponential decay proposed in Gueymard and Thevenard (2009). SHDOM also uses atmospheric temperature when computing scattering properties; input vertical temperature profiles were derived from LES outputs. In order to simplify interpretation of the results, SHDOM is run with a constant sun position (solar zenith angle of 45°) for the entire simulation time period; this avoids changing clear sky irradiance and geometric perspectives.

At each time step, SHDOM produces a map of surface global horizontal irradiance (GHI) across the simulation domain. In addition, it produces one or more simulated sky images (essentially a map of radiance versus direction at a single location) that can be fed into the sky imager forecast routines. SHDOM results at three different wavelengths (450 nm, 550 nm, and 670 nm) are combined to produce full-color images, and are averaged to approximate broadband GHI. As in the LES, periodic boundary conditions are used.

Fig. 3 shows an example of clouds from the LES and the corresponding virtual sky image from SHDOM.

2.3. Sky imager forecast

The sky imager forecast (Yang et al., 2014) investigated here models clouds as occurring in a single plane at the height of the cloud base. Current cloud positions are detected based on the color of the input image, and future positions are forecast using the "frozen cloud advection" assumption, which assumes that the entire cloud field moves in a uniform direction without changing shape. Inputs to the sky imager forecast are a sky image, cloud base height usually derived from lidar (Light Detection and Ranging) data, and recent measured GHI—used to estimate average cloud optical thickness, which is difficult to determine from the image. Fig. 4 illustrates data flow through the sky imager forecast algorithm, along with inputs from the virtual testbed. In addition, several variations of the algorithm are discussed as part of the virtual testbed; naming conventions for these variations are given in Table 1.

2.3.1. Cloud detection and geometrical mapping

In the virtual sky imager testbed, cloud base height is determined based on the first grid cell to have significant liquid water content. As lidar point measurements of cloud base height are generally accurate, the "correct" LES-derived cloud height is used directly for forecasting. In practice, errors would be introduced in the process of interpolating point measurements of cloud height into an accurate height for an entire layer, particularly in the presence of topography or heterogeneous land surface and over larger areas. In the interest of brevity, we do not address these errors here.

Cloud detection operates on the virtual sky images in the same manner as real sky images, and classifies each pixel of the input image as clear sky, thin cloud, or thick cloud, by applying thresholds to the difference between the red-blue ratio (RBR) of the image being