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Cloud motion and stability estimation for intra-hour solar forecasting

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Abstract

Techniques for estimating cloud motion and stability for intra-hour forecasting using a ground-based sky imaging system are presented. A variational optical flow (VOF) technique was used to determine the sub-pixel accuracy of cloud motion for every pixel. Cloud locations up to 15 min ahead were forecasted by inverse mapping of the cloud map. A month of image data captured by a sky imager at UC San Diego was analyzed to compare the accuracy of VOF forecast with cross-correlation method (CCM) and image persistence method. The VOF forecast with a fixed smoothness parameter was found to be superior to image persistence forecast for all forecast horizons for almost all days and outperform CCM forecast with an average error reduction of 39%, 21%, 19%, and 19% for 0, 5, 10, and 15 min forecasts respectively. Optimum forecasts may be achieved with forecast-horizon-dependent smoothness parameters. In addition, cloud stability and forecast confidence was evaluated by correlating point trajectories with forecast error. Point trajectories were obtained by tracking sub-sampled pixels using optical flow field. Point trajectory length in mintues was shown to increase with decreasing forecast error and provide valuable information for cloud forecast confidence at forecast issue time.

Keywords: Sky imager; Solar forecast; Cloud motion tracking; Cloud stability

1. Introduction

Short-term variability in the power generated by solar energy creates challenges for power system planners and operators because of the growing penetration rate. The highly predictable diurnal and annual irradiance pattern aside, clouds have the strongest impact on solar energy production. Transient clouds cause strong spatio-temporal variability and fluctuating solar power feed-into the grid. Large ramp events are of primary concern for relatively small microgrids and island grids, as their ability to absorb the fluctuations is limited. While distributed PV causes less variability to the grid in aggregate, it is less controllable by grid operators as it often lacks the ability for power curtailment (Eber and Corbus, 2013). The resulting imbalance motivates the need for regulation reserve that scale with both variability and forecast uncertainty (Helman et al., 2010). Different strategies have been studied to mitigate the operational problems with increased solar penetration (Eber and Corbus, 2013; Ela et al., 2013) and a simulation study by Ela et al. (2013) demonstrated that an increased power dispatch frequency and accurate short-term solar forecasts can reduce regulating reserve requirements and production costs. Therefore, reliable forecast information on the expected power production is essential for efficient integration. Since most solar variability (Hoff and Perez, 2012; Lave and Kleissl, 2013), and forecast models (e.g. Chow et al., 2011; Marquez and Coimbra, 2013; Perez et al., 2010) require cloud velocity as main input, accurate

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cloud motion estimation has become of increased interest (Bosch et al., 2013; Bosch and Kleissl, 2013; Fung et al., 2013; Huang et al., 2013; Quesada-Ruiz et al., 2014).

Cloud motion estimation and tracking has a long history in visible satellite imagery (e.g. Menzel, 2001) and solar irradiance forecasts up to a few hours ahead are strongly dependent on the apparent motion of cloud structures. Sparse cloud motion vectors (CMVs) are generally obtained by first locating salient image features such as brightness gradients, corners, cloud edges, or brightness temperature gradients (Bedka and Mecikalski, 2005; Menzel, 2001). Assuming the features do not change significantly over a short interval, CMVs are computed using pattern-matching techniques applied to successive images. The future cloud situation is then estimated by the extrapolation of motion assuming persistence of cloud speed, size, and shape (Lorenz et al., 2004).

CMVs as a basis for advecting such a frozen cloud field derived from ground-based sky imagers were developed and applied by Chow et al. (2011) and Yang et al. (2014). Similar to Hamill and Nehrkorn (1993), the cross-correlation method (CCM) was applied to obtain an average CMV for the entire cloud field. Forecast cloud field position is obtained by shifting the cloud decision images along the corresponding motion vector. Yang et al. (2014) found that CCM advection forecasts (hereinafter CCM forecast) exhibited a larger cloud matching error than image persistence forecast for forecast horizon (FH) of 5 min in 11 of 22 days partially because the spatial homogeneity of the cloud motion assumption is not appropriate given cloud deformation, topographically-induced wind speed variations, and the changing optical perspective. To overcome the above challenges for estimating multiple independent and non-rigid motions, a variational optical flow (VOF) technique is evaluated in this paper. Similar nonrigid registration techniques have also been implemented successfully to estimate cloud motion on sky images last year (Bernecker et al., 2014; West et al., 2014). Optical flow techniques estimate the two-dimensional dense motion field (i.e. every image pixel) with sub-pixel accuracy between two consecutive images (Szeliski, 2010). The variational technique is used in optical flow to minimize an objective function composed of a data model and a regularization term (Horn and Schunck, 1981). The objective function can be solved by well-founded and optimized numerical methods due to the theory of the calculus of variations. As a result of the flexibility of the data modeling process, VOF became a popular technique for motion estimation for fluid imagery such as satellite meteorological images (Corpetti et al., 2002; Héas et al., 2007; Héas and Mémin, 2008) and experimental fluid mechanics (Corpetti et al., 2006; Heitz et al., 2010).

Even though many advanced techniques to estimate cloud motion exist, little attention has been paid on cloud stability, i.e., how rapidly a cloud is changing, which is a key challenge to "frozen" cloud map advection. While time series of cloud fraction and brokenness in the sky imager field-of-view provide information about the cloud cover variability, changes in these metrics are often dominated by the Eulerian framework (i.e. the advection of clouds in and out of the sky imager field-of-view) and present little information on cloud stability in a Lagrangian sense.

In most cloud advection forecast models, cloud features are assumed constant over the forecast horizon. The validity of this assumption is scale-dependent. Over the sub-30 min forecast horizon of ground-based sky imagery, this assumption often holds for synoptic and even mesoscale cloud systems but is usually violated for individual clouds or small scale features. From highly granular imagery, clouds – especially those located in the atmospheric boundary layer – have often been observed to significantly deform, evaporate, and develop over time scales of a few minutes in the San Diego coastal area (Chow et al., 2011; Yang et al., 2014). Cloud dynamics are driven by cloud and boundary layer turbulence as well as topographic effects and present challenges to deterministic cloud forecasting. Therefore, a method to identify such circumstances and quantify cloud stability is highly desired.

Temporal invariance of cloud features is a characteristic of cloud stability. For that reason, we propose to establish a forecast confidence metric based on dynamic image features and the optical flow field extracted from the VOF method to infer cloud stability and the validity of the frozen-cloud advection technique. In fact, dynamic features have been shown to be of importance in many applications such as object segmentation (Brox and Malik, 2010), cloud classification and synthesis (Liu et al., 2013), and camera calibration (Jacobs et al., 2013).

The main goal in this study is to assess the performance of VOF estimation applied to sky images. In addition, forecast confidence is related to cloud stability through point trajectories that are constructed by tracking pixel points. In Section 2 methods to obtain cloud motion and point trajectories using VOF are described. Section 3 presents results and discussion on cloud forecast and stability. Conclusions follow in Section 4.

2. Methods

2.1. Data

The sky imager developed at UC San Diego (UCSD Sky Imager or "USI") mainly consists of a charge-coupled device (CCD) image sensor with 12 bits intensity resolution in each RGB channel, a 4.5 mm circular fisheye lens, and a neutral density filter. The USI utilizes high dynamic range (HDR) imaging and outputs lossless PNG images with a bit depth of 16 bits per channel, a dynamic range of 81 dB, and a useable size of the image of 1748×1748 pixels. Images were processed to remove the distortion caused by the fisheye lens, resulting in red–blue-ratios (RBRs) in a Cartesian coordinate system at the predetermined cloud height. Complete specifications of the USI system can be found in Urquhart et al. (2013, 2014). The November