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Estimating multidirectional cloud movements from single sky camera using directional statistics

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A R T I C L E I N F O

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A B S T R A C T

Highly accurate forecasting of solar irradiation and power generation is essential for efficient operation of solar power generation. Among various forecasting methods, the methods based on ground observation—including all-sky image photography and solar irradiation measurement—show excellent performance concerning time and spatial resolution. In the forecasting method using all-sky images, the direction of cloud movement is estimated using optical flow or the like to forecast solar irradiation. In this case, the direction of a single-layer cloud movement is usually assumed. However, there is also multilayer cloud in reality. In addition, according to a recent report (T. Bando et al., *Renew. Energy Environ. Sustain* **8**, 1 (2023)), multilayer cloud has been observed even when the power generation is large, which suggests the necessity of estimating the cloud movement direction in each layer when multilayer clouds are present. Although techniques for estimating the direction of multilayer cloud movement have been developed, they use multiple sky cameras or supervised learning and have high development costs. Herein, we developed a simple method that can estimate the direction of multilayer cloud movement using a single sky camera. Optical flow algorithms suitable for the estimation of the direction of cloud movement were compared and examined, and DeepFlow was adopted to estimate the cloud movement direction. Moreover, we showed that cloud flow can be discriminated in one and two directions using the circular standard deviation when the target was a cloud of up to two-layers with a large ratio of the layer number. Further, it was shown that the direction of cloud movement can be properly evaluated if the direction temporally switches from one (two directions) to two directions (one direction). We suggested the effectiveness of directional statistics in the estimation of multidirectional cloud movements using sky cameras for the first time.

1. Introduction

For efficient operation of solar power generation, forecasting of power generation with high accuracy has to be achieved and much efforts have been made on developing forecasting method for solar irradiation. Methods of solar irradiation forecasting [1–13] include the numerical weather prediction, satellite data observation, and ground observation or the like, and each forecasting range is different concerning time and space. Ground observation enables the forecasting of solar irradiation variation [3–12,14] caused by cloud shadows within a short period of several minutes to 30 min. There are various forecasting methods for ground observation, such as those that use several pyranometers [4,5] and an all-sky image photographed by an all-sky camera [6–12]. One of the forecasting methods using an all-sky image estimates the direction of cloud movement from the image use optical flow [15,16] and forecasts solar irradiation variation using the results [3,7–11]. In most studies, the direction was estimated by assuming that the cloud is a single-layer; however, in reality, multilayer clouds may be observed. Moreover, multilayer clouds are observed regardless of the power generation is large, suggesting the necessity of estimating the direction of each layer movement in multilayer observation cloud [17,18]. The technique for estimating the direction of this multilayer cloud movement has been developed in previous studies [11,15,19]. In Peng et al. [11] research, after classifying the cloud using a support vector machine, cloud height was obtained by triangulating three cameras; the directions of each cloud movement were determined by optical flow and clustering, respectively. Nori et al. [19] obtained cloud height using a stereoscopic approach involving two cameras after the

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