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Estimation of cloud motion vectors: exploring different approaches using a dense network of solar radiation sensors

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At small time scales, the spatio-temporal variability of downwelling surface solar radiation can be considered in a first approximation as resulting from the advection of clouds. It is common in the solar energy and atmospheric science communities to use a quantity called Cloud Motion Vector (CMV) to quantify this displacement.
Intuitively, cloud advection is expected to be a direct result of wind patterns at cloud-height levels. This idea is reflected, for example, in various works where wind information at cloud height is used as a driver of solar variability in solar forecasting applications [1]–[6]. However, relating spatio-temporal characteristics of the solar radiation to the wind speed is not obvious. In some meteorological situations, such as orographic clouds, the wind speed and the apparent cloud movement can be decoupled. More generally, the coexistence of different layers of clouds advecting in different directions question the validity of the use of wind information at a single level.
Other inference techniques can be used to estimate the cloud motion vectors such as the calculation of block matching or optical flow algorithms applied to sequences of satellite images [7], [8] or the cross-correlation analysis of high-resolution measurements of dense networks of sensors [9], [10], like the ones from the HOPE [11] or Oahu [12] campaigns. Yet, these alternative methods have their own weaknesses: the conclusion of cross-correlation analysis can be hampered when the characteristics of the clouds are not appropriate to track their motion (e.g., absence of texture, edges), while satellite-based CMV may miss local advection due to limited spatial and temporal resolutions.
To better understand cloud advection dynamics and understand the strength and weaknesses of the different estimation methods, a benchmark has been done using the HOPE measurement campaign [11] as a reference, with 99 pyranometers with time step of 0.1 s and inter-sensor distances ranging from 100 m to 10 km. CMV timeseries have been inferred from three different approaches:
• Applying an optical-flow method to sequences of images of surface solar irradiance from the HelioClim-3 database [13], [14], derived from Meteosat Second Generation satellite.
• Evaluating the lagged cross-correlation between different pairs of ground sensors.
• Extracting vertically-resolved wind estimates from the ERA5 reanalysis [15].
The evaluation has been conducted in two steps. Firstly, a global evaluation was conducted to assess and rank the performance of CMV-based solar forecasting from the different

sources/methods using as reference quality-checked measurements from the HOPE campaign. In a second step, a comprehensive compilation of relevant and typical situations, selected from a systematic visual inspection of time series, is proposed to explain the difference between the CMV sources/methods using illustrative examples.