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Upscaling evapotranspiration measurements from multi-site to the satellite pixel scale over heterogeneous land surfaces

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ABSTRACT

The acquisition of "ground-truth" land surface evapotranspiration (ET) data at the satellite pixel scale over heterogeneous land surfaces is crucial to develop ET estimation models and improve the accuracy of remotely sensed ET values. However, few studies have focused on methods of acquiring ET data at the satellite pixel scale. Based on multi-site eddy covariance (EC) system measurements from the "Multi-Scale Observation Experiment on Evapotranspiration over heterogeneous land surfaces" in the middle reaches of the Heihe River Basin, five upscaling methods were compared and a combined method was developed to acquire "ground-truth" ET data at the satellite pixel scale. First, this study evaluated the performances of three simple upscaling methods (the arithmetic average, area-weighted and footprint-weighted methods). The results showed that the three simple upscaling methods perform well in the relatively homogeneous pixels. For the area-weighted method, the mean absolute percentage error (MAPE) for these pixels was 6.1%. However, the accuracy was worse in the relatively heterogeneous pixels, with a MAPE of 10.8% due to the surface heterogeneity significantly affecting the accuracy of the upscaled results. Second, the upscaling of ET results from heterogeneous land surfaces at the satellite pixel scale can be significantly improved by using two upscaling methods introducing auxiliary variables (the integrated Priestley-Taylor equation method and the area-to-area regression kriging method), that can characterize the heterogeneity of the surface water and heat conditions. Finally, a combined method (applied the area-weighted method for relative homogeneous surfaces, otherwise used the method introducing auxiliary variables) was proposed to acquire both instantaneous and daily "ground-truth" ET data at the satellite pixel scale at the time of a MODIS overpass. The uncertainties of the "ground-truth" ET data were evaluated, taking the large aperture scintillometer (LAS) measurements as the satellite pixel reference. The results show that the proposed upscaling method is reasonable and feasible, and therefore could bridge the gap between in situ ET measurements and remote-sensing estimates of ET.

1. Introduction

Land surface evapotranspiration (ET) is not only a key component of surface water circulation but also an indispensable component of surface energy balances, and plays an important role in aspects of meteorology, hydrology, and ecology, etc. The high-precision acquisition of ET at the regional-to-global scale provides important scientific information that is valuable to high-interest research fields, such as global environment change, the management of basin water resources, and the sustainable development of agriculture.

With the development of new technologies since the 1970s, methods for estimating ET via remote sensing have become an effective way to obtain spatially and temporally continuous ET data at the regional scale. Consequently, these methods have attracted increasing attention from researchers and management departments and have been widely applied to various fields of study (Kalma et al., 2008; Allen et al., 2011; Wang and Dickinson, 2012). However, several uncertainties still remain in remote-sensing estimates of ET and are primarily related to model mechanisms, model inputs, parameterization schemes, and scaling issues (Jia et al.,

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2012). The mean absolute percentage errors (MAPEs) of the current remote-sensing estimates for ET at the instantaneous, daily, monthly, and annual scales are approximately 15–30%, 14–25%, 9–35%, and 5–21%, respectively (Kalma et al., 2008; Wang and Liang, 2008; Yao et al., 2013; Velpuri et al., 2013). Therefore, remote-sensing products must be validated and calibrated based on ground measurements to provide higher-precision ET products for applications.

It is difficult to match in situ measurements with a satellite-based ET estimation using the current instrumentation (e.g., the eddy covariance (EC) system or large-aperture scintillometer (LAS)) due to the variations in the orientation, shape and size of the source areas of in situ measurements. To solve this problem, Jia et al. (2012) proposed a pixel selection method based on footprints, which was superior to the method of directly comparing in situ measurements with satellite-based estimates for a single pixel or the method of multi-pixel averaging. However, because of the spatial heterogeneity at the sub-pixel scale, the in situ measurements over heterogeneous land surfaces only approximate the "ground-truth" ET data at the satellite pixel scale (1–10 km for medium-low spatial resolutions) and can introduce errors in the validation results. If the "ground-truth" ET at the satellite pixel scale can be obtained, these problems, including spatial-scale mismatch and spatial heterogeneity at the sub-pixel scale, can be reasonably solved.

Methods for the acquisition of "ground-truth" ET data at the model grid scale (10–100 km) have been widely studied and can provide useful references for obtaining "ground-truth" ET data at the satellite pixel scale. A number of observational experiments on multi-site surface fluxes and the related parameters have been conducted over various underlying surfaces, including The First ISLSCP Field Experiment (FIFE; Sellers et al., 1988), the Hydrologic Atmospheric Pilot Experiment–Modélisation du Bilan Hydrique (HAPEX-MOBILHY; André et al., 1986), the Hydrologic Atmospheric Pilot Experiment in the Sahel (HAPEX-Sahel; Goutorbe et al., 1994), the Boardman Experiment (The Boardman Regional Flux Experiment; Doran et al., 1992), the Northern hemisphere climate Processes land surface Experiment (NOPEX; Halldin et al., 1999), Lindenberg Inhomogeneous Terrain-Fluxes between Atmosphere and Surface: a Long-term Study (LITFASS-98; Beyrich et al., 2002), and LITFASS-2003 (Beyrich and Mengelkamp, 2006). In these experiments, surface fluxes were observed at multiple sites, and surface flux values at the model grid scale were obtained using various upscaling methods. The upscaled flux values were also compared to those obtained from airborne EC systems, LASs, remote sensing estimation methods, and model simulations. The methods commonly used in previous studies of flux upscaling include the arithmetic average method (Shuttleworth et al., 1989; Peng et al., 2008), the area-weighted method (Gottschalk et al., 1999; Beyrich et al., 2006; Ezzahar et al., 2009), the footprint-weighted method (Ezzahar et al., 2007; Timmermans et al., 2009; Lu et al., 2010), numerical models (André et al., 1990; Gryning et al., 2002; Heinemann and Kerschgens, 2005), and geostatistical methods (e.g., the area-to-area kriging (ATAK) method). For example, Ge et al. (2015) proposed the area-to-area regression kriging (ATARK) method to upscale the sensible heat flux from multi-site to the satellite pixel scale over heterogeneous land surfaces and compared the results with LAS measurements.

Although the above-mentioned upscaling methods have been applied to the data analysis of various large-scale experiments conducted around the world, the upscaled results of previous studies have primarily focused on the model grid scale and have their own limitations, including how to select an optimized upscaling method according to the surface heterogeneity, and how to assess the uncertainties of the upscaled results, etc. (Shuttleworth, 1991; Heinemann and Kerschgens, 2005; Li et al., 2009).

To date, few studies have focused on methods of acquiring ET data at the satellite pixel scale, especially for medium-low spatial resolutions (1–10 km). The following issues were studied based on the multi-site measurements of the "Multi-Scale Observation Experiment on Evapotranspiration over heterogeneous land surfaces 2012 (HiWATER-MUSOEXE)" in the Zhangye area, located in the middle reaches of the Heihe River Basin: (1) three simple upscaling methods (the arithmetic average method, area-weighted method, and footprint-weighted method) to obtain ET at the satellite pixel scale were evaluated, taking LAS measurements as the satellite pixel reference; (2) for the heterogeneous condition, two upscaling methods introducing auxiliary variables (the integrated Priestley-Taylor equation method and the area-to-area regression kriging method), which can characterize surface heterogeneity, were developed and validated; and (3) both instantaneous and daily "ground-truth" ET data were acquired at the satellite pixel scale at the time of a MODIS overpass, and their uncertainties were evaluated.

2. Materials

2.1. Experiment

The HiWATER-MUSOEXE was conducted in the middle reaches of the Heihe River Basin between May and September 2012 and involved a flux observation matrix that was composed of two nested matrices: one large experimental area (30 km × 30 km) and one kernel experimental area (5.5 km × 5.5 km) (Li et al., 2013; Xu et al., 2013). In this study, the dataset observed in the 5.5 km × 5.5 km kernel experimental area of the HiWATER-MUSOEXE was used to study ET upscaling methods (Fig. 1). The kernel experimental area was located in the Yingke and Daman irrigation district, and the main surfaces were maize, residential area, vegetable, and orchard. These areas were separated into rows and columns by shelterbelts. Together, they represent the land cover and planting structure in the oasis of the middle reaches of the Heihe River Basin. Moreover, 17 elementary sampling plots were divided according to the distribution of crops, shelterbelts, residential areas, roads, and canals, as well as according to soil moisture and irrigation status. These divisions resulted in one residential area site (site 4), one orchard site (site 17), one vegetable site (site 1), and 14 maize sites. In each plot, one EC and automatic weather station (AWS) was installed to observe sensible heat flux (H), latent heat flux (LE), and meteorological elements. Two EC sets and seven layers of meteorological gradient observation systems were installed at site 15. Moreover, the transpiration of shelterbelts with different heights and diameters at breast height (DBHs) was measured using a thermal dissipation probe (TDP) around sites 6, 8, and 17. Three poplar trees in each site were each instrumented with three TDP probes installed at a height of 1.3 m. Additionally, four groups of optical large-aperture scintillometers (LASs) (eight sets with two sets in each group) were installed in the 3 × 3 and 2 × 1 MODIS pixels within the kernel experimental area (three groups in three 3 × 1 MODIS pixels, named LAS1 to LAS3 from west to east, and one group in one 2 × 1 MODIS pixels, LAS4). In each LAS group, we primarily used the Boundary Layer Scintillometer (BLS) series scintillometer data and only used the data measured by another scintillometer (zzLAS developed by our group or Kipp & Zonen LAS) if the BLS scintillometer measurements were missing. The sites located in the three 3 × 1 and one 2 × 1 MODIS pixels were selected to study the ET upscaling methods based on the 11 EC and AWS sets, 4 LAS groups, and 3 TDP groups at sites 4–8, 11–15, and 17 (Table 1).

To estimate the differences among these flux instruments, a comparison experiment of the surface energy flux measurement systems was conducted during May 14–24, 2012, prior to conduct-