A Full Satellite-Driven Method for the Retrieval of Clear-Sky Evapotranspiration

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Abstract Evapotranspiration (ET) plays an important role in the soil-vegetation-atmosphere system for its considerable effect in surface energy balance and water cycle. The determination of ET based on full satellite data has been a challenge. In the present study, a full satellite-driven method is proposed based on a newly developed pixel-to-pixel scheme of the land surface temperature-vegetation index trapezoidal feature space in the presence of clear-sky conditions. For the implementation of this approach, the three main meteorological parameters of net surface radiation, air temperature, and relative humidity were obtained solely based on satellite observations. With the exception of the three main satellite-derived meteorological parameters, different wind speed data—including actual measurements, the assimilated product, and an averaged value of meteorological observations—were used to investigate their effects on the retrieval of ET. Specifically, two pixel-to-pixel trapezoidal feature space schemes, namely an original and a two-stage scheme, were implemented to estimate ET over an arid region of the study area located in the northwest part of China. Comparison of the estimated ET with the values acquired from the eddy covariance systems yielded a reliable accuracy response with root-mean-squared errors of ~80 W/m² and ~70 W/m² for the original and two-stage trapezoidal methods with satellite-derived inputs, respectively, and constant wind speed data over the growing 2012 season from May to September. These results indicate that the full satellite-driven method is capable of estimating ET over the arid region of the study area.

1. Introduction

Evapotranspiration (ET) is commonly recognized as the loss of water owing to the soil surface evaporation and vegetation transpiration. ET is the only variable involved in the surface energy balance and water cycle and plays an important role in the soil-vegetation-atmosphere system. According to previous studies, ET can take values that are approximately equal to 80% and 65% of the net surface radiation (NSR) and precipitation, respectively (Dai, 2006; Goosse et al., 2012). Hence, accurate estimation of the spatially distributed ET is essential to the energy- and water-related domains at the regional or global scales, such as climate changes, drought monitoring, and agricultural irrigation (Yao et al., 2011; McEvoy et al., 2016; Valipour et al., 2017; Mathieu & Aires, 2018; Liu et al., 2019).

In comparison to the limited spatial representation of ground ET measurements, such as the eddy covariance technique and Bowen ratio method, remote sensing technology is most likely the only feasible way used to obtain spatiotemporal ET dynamics at the regional or global scales. To this date, various methods have been developed to obtain ET based on remote sensing observations at various spatial resolutions (Wang & Dickinson, 2012). Among these methods, the thermal remote-sensing-based surface energy balance algorithms have received considerable attention in past decades. Commonly used models can be broadly categorized into one-source and two-source models. The surface energy balance algorithm for land (SEBAL; Bastiaanssen et al., 1998) and surface energy balance system (Su, 2002) are two typical one-source models, whereas the two-source energy balance model proposed by Kustas and Norman (1999) is a frequently used two-source model. To this date, numerous studies have been conducted on satellite ET retrieval following these surface-energy-balance-based algorithms for different eco-environmental conditions (Bhattarai et al., 2019; Senkondo et al., 2019; Wagle et al., 2017).
Except for the aforementioned algorithms, the land surface temperature (LST)/vegetation index (VI) triangular (or trapezoidal) feature space method (hereafter denoted by T₅-VI), and its variants have become one of the most commonly used methods for the quantification of ET with thermal remote sensing observations in recent years owing to the preclusion of the calculation of surface resistance and the easy-to-use form (Moran et al., 1994; Jiang and Islam, 1999; Peng et al., 2017). Specifically, the original T₅-VI method is commonly based on the contextual information of remotely sensed LST and VI, whereby full ranges of variability in soil moisture and VI are required. Moreover, the meteorological conditions for the contextual-information-based feature space area should be uniform. In general, because only a total ET can be obtained, the original contextual-information-based T₅-VI should be recognized as a one-source model. For these types of original T₅-VI configurations, variation of soil moisture in the surface and root-zone are synchronous in the presence of the stress of soil evaporation and vegetation transpiration, and the dry and wet edges are commonly determined based on the image interpretation process. In recent studies, a method was proposed to divide the original trapezoid into two triangles based on the assumptions that soil moisture within the surface and root-zone layers should vary in a different manner compared to that described previously (Sun, 2016; Tang et al., 2015; Tang & Li, 2017). Subsequently, several studies have investigated the partition of ET into the soil surface evaporation and vegetation transpiration with a novel pixel-to-pixel scheme of the T₅-VI configuration (Leng et al., 2017, 2019; Jiang et al., 2019), rendering the T₅-VI configuration as a two-source model for estimating ET. It is noted that for each satellite pixel, a corresponding T₅-VI feature space exists. Hence, for the pixel-to-pixel scheme of the feature space, no rigorous demands are imposed on either the underlying surfaces or meteorological conditions in actual applications. Although comprehensive assessments have been conducted for the aforementioned thermal-remote-sensing-based algorithms, most of these evaluations are implemented at field scales owing to the fact that several necessary meteorological observations (i.e., NSR, air temperature, relative humidity [RH], and wind speed) are commonly required at near-satellite image acquisition times. Hence, it is difficult to obtain spatially distributed ET values at regional scales, especially over the meteorological data-limited regions. Although several globally assimilated meteorological products or reanalyzed data, such as the global land data assimilation system (GLDAS) and the recently released fifth generation of the European Center for Medium-Range Weather Forecast Atmospheric Reanalysis (ERA5), can directly provide necessary inputs for deriving ET at relatively coarser spatial resolutions (i.e., ≥ 0.25°). To obtain ET at higher spatial resolution for better use in watershed or field scales, disaggregation of either coarse meteorological data in advance or estimated ET subsequently at coarse spatial resolutions, are required. To this end, it is promising to apply the optical/thermal satellite-derived meteorological elements to the thermal-remote-sensing-based algorithms for the direct determination of ET at a high-spatial la previous study, a pixel-to-pixel scheme of the T₅-VI trapezoidal feature space was proposed for the determination of ET over clear-sky pixels (Leng et al., 2017). Like many other thermally remote sensing-based methods used to derive ET, the proposed approach also uses several meteorological data as inputs. Although this method has been evaluated using the data collected at the study site, further investigations should be conducted to obtain ET over meteorological data-limited regions. In this study, we overcame some of the aforementioned challenges associated with the implementation of the method in data-limited regions following the previous algorithm proposed by Leng et al. (2017). The primary objective of this study was the development of a pixel-to-pixel full satellite-driven method for the retrieval of ET over clear-sky conditions, whereby all the essential meteorological parameters are derived from satellite data at a fine spatial resolution. Moreover, given that the original and the newly developed two-stage T₅-VI trapezoidal configurations are in favor of the variation of soil moisture within different soil layers, a comprehensive evaluation of the two schemes for estimating ET is also implemented for specific climate conditions within an arid region.

The present study is organized as follows: section 2 presents the materials and methods of this study. The results and discussion are outlined in sections 3 and 4, respectively. The conclusions are listed in section 5.

2. Materials and Methods

2.1. Study Area and ET Measurements

In the present study, the Heihe river basin in China (Figure 1) was selected as the study area to retrieve ET. Located between 97.1°E–102.0°E and 37.7°N–42.7°N in the arid region of Northwestern China, the Heihe
The river basin is the second largest inland river basin and extends over the provinces of Qinghai, Gansu, and Inner Mongolia. From the upstream in the South to the downstream in the North, the study area reveals diverse landscapes, which primarily include alpine biomes, steppes, agricultural ecosystems, and the desert. These diverse landscapes of the study area make it important to investigate the exchange of water and energy between the earth and atmosphere, especially for the exploration of the competition of water resources between the agricultural and natural environments over arid regions.

An ET observation campaign, namely, the MUlti-Scale Observation EXperiment on ET over heterogeneous land surfaces 2012 (MUSOEXE-12), was carried out over the Heihe river basin in 2012 during the growing season from May to September. The MUSOEXE-12 campaign was the first thematic experiment in the Heihe watershed allied telemetry experiment research project (HiWATER) primarily launched in the middle stream area (Li et al., 2013). In the case of the MUSOEXE-12 campaign, a number of eddy covariance (EC) systems were located in different land-use types, including corn fields, sandy deserts, desert steppe, Gobi desert, wetlands, and orchards, to investigate the energy and water exchange between land and atmosphere. Owing to the availability of data records, 20 EC systems were selected in total in the present study. Except for the measurements of ET (with a temporal resolution of 30 min), meteorological variables (with a temporal resolution of 10 min) were also collected by an automatic weather station in each EC system.

2.2. Remote Sensing Data

During the MUSOEXE-12 campaign, Moderate Resolution Imaging Spectroradiometer (MODIS) data were acquired from May to September from the Level-1 and Atmosphere Archive and Distribution System (LAADS) of the National Aeronautics and Space Administration (NASA) website (https://ladsweb.modaps.eosdis.nasa.gov/). The MODIS instrument operates aboard the Terra and Aqua spacecrafts. It has a viewing swath width of 2,330 km and views the entire surface of the Earth every 1 to 2 days with the use of 36 spectral channels encompassing optical to thermal wavelengths. In the present study, several MODIS products were used to estimate meteorological variables and ET. Table 1 shows the MODIS data implemented in the present study.

Specifically, the MOD021KM, MOD03, MOD05_L2, and MOD11A2, were primarily used to obtain the NSR according to the methods proposed by Tang et al. (2006) and Tang and Li (2008). In addition, the air temperature was generated from MOD07_L2 and MOD11_L2 according to the algorithm proposed by Zhu et al. (2017), and was subsequently used to obtain the RH in conjunction with the MOD07_L2-derived dewpoint temperature. Except for these, the MOD11_L2, MOD35_L2, MOD09GA, MOD13A2, and MOD15A2, were essential parameters which were used to estimate ET with the pixel-to-pixel scheme of the $T_s$-VI trapezoidal feature space.

2.3. Overview of the Pixel-to-Pixel Scheme of the $T_s$-VI Trapezoidal Feature Space

A number of previous studies have investigated the feasibility of obtaining ET from the $T_s$-VI triangular or trapezoidal feature space (Carlson, 2007; Jiang & Islam, 1999; Norman et al., 1995; Sun et al., 2017). However, most of these studies were based on the contextual information of spatially distributed LST and
VI. For practical applications, two obstacles have limited considerably the application of the TS-VI feature space methods over large areas. The one is the subjectivity of the determination of the dry and wet edges through image interpretation. The other is the demanding requirements wherein the underlying surface should accomplish full-range vegetation coverage from zero to 100%, and soil moisture content from minimum to maximum values should occur within the study areas. In comparison to the contextual-information-based feature space, the pixel-to-pixel scheme of the TS-VI trapezoidal feature space has no strict requirements on the underlying surface conditions. However, it requires several meteorological variables as input. The main idea of the pixel-to-pixel scheme of the TS-VI trapezoidal feature space is that a suppositional trapezoid exists for each clear-sky pixel, and the suppositional trapezoid can be constituted by LST according to four extreme surface conditions including dry bare soil, full vegetation cover with zero water availability, well-watered full vegetation cover, and saturated bare soil at specific atmospheric conditions.

The present study aims to investigate two patterns of the pixel-to-pixel scheme of the TS-VI trapezoidal feature space in the presence of arid conditions, namely the original and two-stage TS-VI trapezoidal feature space. Figure 2 depicts the two TS-VI trapezoidal feature space methods in detail. The most noticeable difference between the two TS-VI trapezoidal feature spaces is that the two components of LST (the vegetation temperature and soil temperature) should vary differently (two-stage) rather than simultaneously (original) in the presence of natural conditions.

For the original trapezoidal feature space, the ET for a given pixel (e.g., for pixel P shown in Figure 2) can be expressed as,

$$ET = \frac{AE}{AD} \times ET_{w.}\;\text{s} + \frac{BF}{BC} \times ET_{w.}\;v$$

where $AE$, $AD$, $BF$, and $BC$, are the distances between the corresponding points, which can be determined from the LST values subject to the four extreme conditions and vegetation/soil component temperatures of pixel P. Additionally, $ET_{w.}\;s$ and $ET_{w.}\;v$ are the maximum soil evaporation and vegetation transpiration at extreme surface conditions of saturated bare soil (point D in Figure 2) and the well-watered full vegetation cover (point C in Figure 2), respectively.

If the given pixel P is located in the lower triangle within the two-stage trapezoidal feature space, the vegetation transpiration could be close to the potential maximum, owing to the sufficient water availability in the root zone. Similarly, a pixel located in the upper triangle reveals the lack of water availability in the surface soil layer, and the lack of subsequent soil evaporation. Hence, the ET for the given pixel in the lower and upper triangles can be respectively expressed as,

$$ET = \frac{MP}{MN} \times ET_{w.}\;v$$

$$ET = \frac{MP}{MN} \times ET_{w.}\;s$$

where $MP$ and $MN$ are the distances between the corresponding points, which can be determined from the optical/thermal infrared observations of the given pixel and LST values in the presence of the four extreme conditions. A detailed description of the determination of the aforementioned parameters can be referred to previous studies (Kustas & Norman, 1999; Leng et al., 2017; Tang & Li, 2017).

### 2.4. Determination of Meteorological Inputs Using Remote Sensing Data

For the retrieval of ET from the pixel-to-pixel scheme of the two trapezoidal feature spaces shown in Figure 2, four essential meteorological elements, namely the NSR, air temperature, RH, and wind speed, are required.
to determine the dry and wet edges of the trapezoidal feature space. With the exception of wind speed, in this study, we primarily focused on the other three elements that can be derived directly from optical/thermal remotely sensed observations at high-spatial resolutions. The following subsections describe the methods used to obtain the NSR, air temperature, and RH in detail.

2.4.1. NSR

For the estimation of ET from the $T_S$-VI trapezoidal feature space, the NSR is an essential and crucial input for the determination of the dry and wet edge based on the surface energy balance. In general, NSR can be expressed as the summation of the net surface shortwave radiation (NSSR) and net surface longwave radiation (NSLR) as follows,

$$\text{NSR} = \text{NSSR} + \text{NSLR}$$

In an early study, Tang et al. (2006) proposed an approach to estimate NSSR from MODIS data. This approach directly linked the narrowband apparent reflectance at the top of atmosphere (TOA) to the shortwave broadband albedo in the cases of clear and cloudy skies without performing any surface angular modeling. The NSSR can be estimated as,

$$\text{NSSR} = \alpha_s E_0 \cos \theta_s$$

where $\alpha_s$ is the flux absorbed at the surface, $E_0$ is the TOA solar irradiance at one astronomical unit, $\theta_s$ is the solar zenith angle, and $d$ is the Earth-Sun distance in astronomical units. Specifically, based on this approach, a method was developed for the parameterization of $\alpha_s$ using the TOA narrowband reflectance of MODIS at bands 1–7. A detailed description of the approach can be referred to Tang et al. (2006).

In addition to the NSSR, a practical approach using the MODIS satellite-based radiances measured at the TOA and the MODIS LST/emissivity products was proposed by Tang and Li (2008). In this approach, the downwelling surface longwave radiation (DSLR) was first derived from the TOA radiance as follows,

$$\text{DSLR} = a_0(\theta, z) + \sum_{i=1}^{n} a_i(\theta, z)(\pi x L_i(\theta))$$

where $a_0$ and $a_i$ are the conversion coefficients expressed as functions of the satellite viewing zenith angle ($\theta$) and the terrain altitude ($z$), $L_i$ is the TOA radiance measured by the MODIS thermal infrared (TIR) channel $i$. 

Figure 2. A sketch of the original (left) and the two-stage (right) trapezoidal feature space constituted by the LST (denoted as $T_s$) and fractional vegetation cover (FVC; denoted as $f$). Both the two space are constituted by LST under four extreme conditions: dry bare soil (A: $T_s=T_{s,\text{max}}$ and $f=0$), full vegetation cover with zero water availability (B: $T_s=T_{v,\text{max}}$ and $f=1$), well-watered full vegetation cover (C: $T_s=T_{v,\text{min}}$ and $f=1$) and saturated bare soil (D: $T_s=T_{s,\text{min}}$ and $f=0$). The red and blue solid lines are dry and wet edges, respectively. The black dashed lines are isopleths of the soil moisture availability. The black solid line linking A and C in the two-stage space is a critical boundary divides the original trapezoid into two triangles. A given satellite pixel (e.g., P with $T_s$ and $f$) can be located in either the lower triangle or upper triangle.
Subsequently, NSLR was defined as the difference between DSLR and the upwelling surface longwave radiation emitted and reflected by the earth’s surface as follows,

\[
\text{NSLR} = \text{DSLR} - \sigma T_s^4 - (1 - \varepsilon_s) \text{DSLR}
\]

where \(\sigma\) is the Stefan-Boltzmann constant \((5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4)\), \(\varepsilon_s\) is the land surface emissivity, and \(T_s\) is the LST derived based on the MODIS product.

### 2.4.2. Air Temperature

In a recent study, Zhu et al. (2017) proposed a parameterization scheme of daytime air temperature for all-weather condition, which was entirely based on MODIS data. In this method, the MOD06_L2 and MOD07_L2 data were used to obtain the all-weather air temperature. In the present study, we focus only on the clear-sky pixels according to the algorithms proposed by Zhu et al. (2017). In this situation, the air temperature was determined as the average value of the MOD07_L2 derived near surface air temperature and MOD11_L2 derived LST as follows,

\[
T_a = \frac{T_a^s + T_s}{2}
\]

where \(T_a\) is the air temperature measured at a height of 2 m above ground, \(T_a^s\) is the near surface air temperature retrieved from the MOD07_L2 product, and \(T_s\) is the remotely sensed LST from the MOD11_L2 product.

### 2.4.3. Relative Humidity

In general, the RH and the dewpoint temperature \(t_d\) are the two commonly used indicators of the amount of moisture in air. An RH of 100% indicates that the \(t_d\) is equal to the current temperature and that the air is maximally saturated with water under constant pressure. Hence, RH can be written as

\[
\text{RH} = \frac{e_a}{e_s(T_a)}
\]

where \(e_a\) is the ambient vapor pressure with air temperature being equal to \(t_d\) and \(e_s(T_a)\) is the saturation vapor pressure with an air temperature \(T_a\).

### 3. Results

#### 3.1. Comparison of Satellite-Derived Meteorological Elements Against Site Observations

##### 3.1.1. NSR

It is known that NSR is the main source of ET, and can theoretically determine the upper limit of ET. For the trapezoidal feature space, NSR is the most sensitive input for the determination of the dry and wet edge based on surface energy balance. Figure 3 depicts the comparison of the estimated NSR and those observed from the automatic weather stations. It is evident from the results that the estimated NSR is well correlated to the values acquired during the study period. A bias of 33.6 W/m² and a root-mean-square error (RMSE) of 58.2 W/m² can be obtained for clear-sky pixels, thus indicating an overestimation of the satellite-derived NSR. To decrease the possible error for ET estimation, a bias correction is finally implemented to all the estimated NSR outcomes, and results in an unbiased RMSE of 47.6 W/m². In general, this unbiased RMSE can be used to obtain better ET estimates using the \(T_S-VI\) trapezoidal feature space method.

##### 3.1.2. Air Temperature

In addition to NSR, air temperature is another parameter which directly affects the dry and wet edges. Comparison of the MODIS-derived air temperature and the observed values from the automatic weather stations is described in Figure 4. As shown by the results in this figure, the estimated air temperature data exhibit increased accuracy with a RMSE of 2.62 K in comparison to observed values. In general, this air temperature retrieval performance is within the scope of currently available algorithms (Prihodko &
Goward, 1997; Sun et al., 2005; Zhu et al., 2017). Moreover, similar to NSR, the estimated air temperature reveals an overestimation with a bias of 1.88 K. To decrease the possible error for ET estimation, a bias correction is finally implemented and applied to the estimated air temperatures. Finally, an unbiased RMSE of 1.82 K of the air temperature dataset can be obtained for the estimation of ET with the $T_\text{S}$-VI trapezoidal feature space method.

### 3.1.3. Relative Humidity

Figure 5 depicts the comparison of estimated and automatic weather stations observed RH values during the study period. As it can be observed, the two datasets are well correlated along the 1:1 line, with a slight bias of 0.8% and a RMSE of 10.0%, thus indicating an increased accuracy of RH retrieval within the study area. This performance of the RH retrieval method is beneficial for ET estimation in present study.

### 3.2. ET Retrieval From the Original and Two-Stage Trapezoidal Feature Configurations

Except for NSR, air temperature, and RH, wind speed is also an essential parameter for the pixel-to-pixel trapezoidal feature space method for estimating ET. Because wind speed is difficult to obtain directly from remote sensing observations at present, three wind speed datasets are used in the present study to estimate ET, including (a) the use of the actual wind speed data collected from the automatic weather stations, and (b) obtaining 1 km gridded wind speed data from the disaggregation of the 0.0625° of the Chinese meteorological administration land data assimilation system (CLDAS) product, and (c) implementing an averaged wind speed of approximately 2.0 m/s following the meteorological records over the study area. Specifically, we attempted to implement the third approach because wind speed is primarily used to determine an initial value of aerodynamic resistance for the iteration computing scheme to obtain LST in the cases of extreme surface conditions, as shown in Figure 2. In this regard, it is reasonable to take the pixel-to-pixel scheme of the $T_\text{S}$-VI trapezoidal feature space method as a full-satellite-driving method to estimate ET given that the other essential parameters can be obtained directly from satellite observations only.

Figure 6 depicts the scatter plots of estimated ET and observed values with the two trapezoidal feature space methods. It is evident that the two datasets are evenly distributed around the 1:1 line for most of the cases. Specifically, different wind speed data are used to estimate ET in conjunction with satellite-derived NSR, air temperature, and RH. As shown in Figure 6a, using the actual wind speed collected from automatic weather stations can result in a higher RMSE for ET retrieval with the original (82.3 W/m²) than the two-stage (72.9 W/m²) trapezoidal feature space. Similar results can also be obtained when the CLDAS wind speed product (96.2 W/m² for the original and 78.3 W/m² for the two-stage methods) and constant wind speed data (86.2 W/m² for the original and 74.2 W/m² for the two-stage methods) are used for ET estimation. These results preliminarily indicate that the two-stage trapezoidal feature space can generally yield better ET estimates than the original method over the arid region of the study area, although intensive assessments of the two $T_\text{S}$-VI trapezoidal feature space methods over other arid regions should be further investigated.

It is also noted that the original and the two-stage trapezoidal feature space methods will most likely underestimate and overestimate ET, respectively. Specifically, overall underestimations of 13.4 W/m², 27.1 W/m², and 21.9 W/m², are found in the estimation of ET with the original trapezoidal feature space when satellite-derived meteorological elements are used (NSR, air temperature, and RH) in association with wind speed data obtained from station measurements, CLDAS products, and constant values following the historically
Regarding the two-stage trapezoidal feature space, overall overestimations of 31.0 W/m², 24.7 W/m², and 30.7 W/m², are obtained for these three situations. Nevertheless, it is difficult to quantify the bias because of the uncertainties associated with input data, ground measurements, model physics, and stipulated assumptions. However, the significant discrepancy of overestimation and underestimation of the two methods probably depends on the basic assumptions associated with the methods used in the present study. For the original trapezoidal feature space, the soil evaporation and vegetation transpiration fractions are assumed to be the same because the two components of LST—namely the soil temperature and vegetation temperature—are assumed to vary simultaneously as a function of soil moisture. Hence, the original trapezoidal feature space probably ignores the fact that vegetation can absorb deep-layer soil moisture to maintain transpiration, especially for the peak season of growth for tall crops (mostly corn in the study area) within arid regions. Consequently, ET is most likely to be underestimated in such conditions. On the contrary, the two-stage trapezoidal feature space fully considers the capacity of absorbing soil moisture from the root-zone layer to maintain transpiration after the surface layer dries up. Hence, the two-stage trapezoidal feature space method can theoretically increase the ET retrieval, which can probably overestimate ET.

In summary, the bias and RMSE are within the scope of ET estimation using the feature space method according to previous studies (Bhattarai et al., 2019; Petropoulos et al., 2009), thus indicating that both the original and two-stage trapezoidal feature space methods are capable of obtaining reliable ET estimates with satellite-derived meteorological inputs over the arid region of the study area. Specifically, the two-stage trapezoidal feature space can yield ET with a RMSE of ~70 W/m², regardless of the sources of the wind speed data.

Figure 6. Comparison of estimated evapotranspiration (ET) and observed values over the study area. Three approaches are used to obtain wind speed for ET estimation with the proposed method. (a) Actual wind speed collected from automatic weather stations; (b) CLDAS wind speed product; (c) averaged value.
4. Discussion

4.1. Effects of Wind Speed on ET Estimation

Except for NSR, air temperature, and RH, wind speed is also an essential parameter for ET estimation for the proposed method. For the pixel-to-pixel scheme of the trapezoidal feature space method, an initial aerodynamic resistance is first determined from wind speed data, and is subsequently implemented to obtain the theoretical dry and wet edges by solving the surface energy balance equation based on an iterative procedure. To this extent, it is understandable that wind speed will likely not significantly affect ET estimation. This is also demonstrated in Figure 6 whereby similarly retrieved outcomes can be obtained for ET estimation when different sources of wind speed data are used with regard to both bias and RMSE.

Moreover, it is reasonable to assume that the use of the actual wind speed data collected from automatic weather stations should be an optimal choice for ET estimation. Nevertheless, a notable finding from Figure 6 is that use of a priori knowledge, namely averaged wind speed values according to meteorological records over the study area, can also yield ET estimates with equivalent accuracy regarding either the bias or RMSE. These results further indicate that wind speed is not a dominant parameter. However, it is necessary for ET estimation with the proposed method.

To further investigate the effects of wind speed on ET estimation, five constant wind speed data ranging from 1.0 to 3.0 m/s (at 0.5 m/s intervals) are used to retrieve ET in conjunction with other meteorological data. Table 2 depicts the results in detail. As shown, use of constant wind speed data can generate relatively stable ET estimates regarding the RMSE. Specifically, RMSE values in the ranges of 80–90 W/m² and 70–80 W/m² can be obtained for the original and two-stage trapezoidal methods, respectively. Moreover, a relative stable bias at approximately 30 W/m² was determined for the two-stage trapezoidal method. These results further demonstrate that use of a constant wind speed can generally obtain relatively stable ET estimates, especially for the two-stage trapezoidal method. Regarding the original trapezoidal method, an unstable bias varying from 15.8 W/m² for a low wind speed case to –26.3 W/m² for a high wind speed case, can be obtained in the present study. Although all the bias and RMSE values are within the scope for ET retrieval in accordance to previous studies, the pixel-to-pixel scheme of the two-stage trapezoidal method is regarded to be optimal for ET estimation over the study area because this approach yields a relatively lower RMSE and a stable bias. Regarding the present study, although the accurate determination of wind speed directly from satellite data at high spatial resolution is challenging at present, an averaged wind speed of approximately 2.0 m/s in conjunction with other satellite-derived meteorological inputs can also implemented to obtain reliable ET estimates with the pixel-to-pixel trapezoidal method, thus establishing the proposed approach as a full satellite-driven scheme for ET retrieval.

4.2. Advantages and Disadvantages

The present study displays a practical method for the generation of clear-sky ET by using satellite-derived land surface and meteorological parameters only, especially in view of the fact that wind speed data can be determined from meteorological records. A significant advantage of the proposed approach is that no auxiliary data are required to obtain ET, thus indicating that a full satellite-driven method for deriving ET is feasible. This achievement establishes the proposed method as a full satellite-driven method for obtaining ET, which can be freely used over data-limited regions. Moreover, unlike the original feature space constituted by spatially distributed scatter plots of LST and VI, the proposed methods required no contextual information of satellite images. This indicates that the application of the pixel-to-pixel scheme of the trapezoidal method can ignore the rigorous conditions, such as uniform weather conditions, and the full-range of soil moisture and vegetation coverage required by the original feature space methods, wherein the dry and wet edges are generally determined by image interpretation. Overall, the pixel-to-pixel scheme makes it possible to estimate ET over large areas.

As known, most of the currently available methods use the reanalyzed/assimilated meteorological data to generate ET datasets. However, because the reanalyzed/assimilated products commonly reveal a relatively

| Table 2 ET Estimation With Different Constant Wind Speed |
|-----------------|----------|----------|----------|
| Method          | Wind speed (m/s) | Bias (W/m²) | RMSE (W/m²) |
| Original        | 1.0      | 15.8     | 79.3     |
|                 | 1.5      | –0.7     | 85.1     |
|                 | 2.0      | –21.9    | 86.2     |
|                 | 2.5      | –23.5    | 91.7     |
|                 | 3.0      | –26.3    | 96.4     |
| Two-stage       | 1.0      | 35.7     | 78.1     |
|                 | 1.5      | 38.2     | 80.8     |
|                 | 2.0      | 30.7     | 74.2     |
|                 | 2.5      | 30.2     | 77.3     |
|                 | 3.0      | 27.9     | 83.1     |

Abbreviations: ET: evapotranspiration; RMSE: root-mean-square error
coarser spatial resolution, a disaggregation process of the reanalyzed/assimilated products is usually required to match the satellite pixels. Moreover, because the reanalyzed/assimilated data are generally produced to represent a fixed time or an average over a short time period over large regions, a significant time mismatch between the reanalyzed/assimilated products and satellite overpassing time normally exists, which can lead to uncertainties for ET estimation, especially over large regions. To this extent, because the satellite-derived meteorological parameters in the present study exhibit the same spatial resolution and acquisition time to those of the MODIS LST and VI, it can at least decrease the possible errors created by the spatial and temporal mismatches of the primary parameters for ET estimation with the proposed method.

Although the present study can obtain reliable ET values over the arid region of the study area, at least two critical issues need to be further investigated. The primary one is the assessment of the four LST values in the presence of extreme surface conditions, and consequently the dry and wet edges shown in Figure 2. Although some studies have assessed several currently available theoretical methods for the determination of the LST values in the presence of extreme conditions and the dry and wet edges (Sun et al., 2017), to our best knowledge, no other studies have been reported thus far that deal with this subject in conjunction with actual surface measurements. This is attributed to the difficulty of obtaining actual LST measurements in the presence of the given extreme surface conditions. Additional studies using thermal imaging systems can constitute a promising approach to investigate this issue. In a recent study, a hyperspectral TIR spectrometer (HyperCam) was used to obtain hyperspectral TIR images for the separation of temperatures and emissivities with high accuracy (Huo et al., 2019). Specifically, this experiment was taken with different soil water level in potted vegetation within the HyperCam view, which has provided a reference for the detection of LST under extreme surface conditions for further investigation. Another pending task is the improvement of the accuracy of the satellite-derived meteorological parameters. In the present study, RMSEs for the unbiased NSR, air temperature, and RH, were approximately equal to 47.6 W/m², 1.82 K, and 10%, respectively. Obviously, the uncertainties in these parameters will affect the retrieval of ET. Specifically, it is noted that NSR and air temperature are the most sensitive parameters for the determination of the dry and wet edges according to previous studies (Jiang et al., 2019; Leng et al., 2017; Tang & Li, 2017). Except for these, because remotely sensed land surface variables such as LST and VI, are essential components for the trapezoidal configuration, it is evident that errors in these variables will directly lead to uncertainties for ET estimation. To this end, it is necessary to further improve the accuracy of satellite products.

5. Conclusions

Based on MODIS data, a full satellite-driven method has been proposed to estimate ET in the presence of clear-sky conditions. The implementation of this method was based on a previously developed pixel-to-pixel scheme of the T₅ VI trapezoidal feature space, and original and two-stage schemes were investigated over an arid region of the Heihe river basin in China. The main meteorological inputs of the methods, including NSR, air temperature and RH, were obtained directly from satellite retrievals. Comparisons of the satellite-derived meteorological parameters against observations collected from automatic weather stations revealed considerable accuracy. The unbiased RMSEs for NSR, air temperature, and RH, were approximately 47.6 W/m², 1.82 K, and 10%, respectively. Except for these, wind speed data were determined from three sources, including the actual values collected from automatic weather stations, disaggregation of an assimilated product at a coarse spatial resolution, and an averaged value following meteorological records over the study area. With the MODIS-derived inputs and wind speed data, ET values were determined within the study area with the original and two-stage schemes of the T₅ VI trapezoidal methods. Results indicated that the two-stage trapezoidal method is capable of yielding ET values with a RMSE of ~70 W/m², regardless of the sources of the wind speed data. Further investigations also demonstrated that wind speed was not a dominated parameter for ET estimation using the proposed method. Hence, the method proposed in present study can be regarded as a full satellite-driven scheme for the derivation of ET in the presence of clear-sky conditions.

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