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Validation of Global Evapotranspiration Product (MOD16) Using Flux Tower Data from Panjin Coastal Wetland, Northeast China

DU Jia, SONG Kaishan

(*Northeast Institute of Geography and Agroecology*, *Chinese Academy of Sciences*, *Changchun* 130012, *China*)

Abstract: Recent advances in remote sensing technology and methods have resulted in the development of an evapotranspiration (ET) product from the Moderate Resolution Imaging Spectrometer (MOD16). The accuracy of this product however has not been tested for coastal wetland ecosystems. The objective of this study therefore is to validate the MOD16 ET product using data from one eddy covariance flux tower situated in the Panjin coastal wetland ecosystem within the Liaohe River Delta, Northeast China. Cumulative ET data over an eight-day period in 2005 from the flux tower was calculated to coincide with the MOD16 products across the same period. Results showed that data from the flux tower were inconsistent with that gained form the MOD16 ET. In general, results from Panjin showed that there was an underestimation of MOD16 ET in the spring and fall, with *Biases* of –2.27 and –3.53 mm/8d, respectively (–40.58% and –49.13% of the observed mean). Results for *Bias* during the summer had a range of 1.77 mm/8d (7.82% of the observed mean), indicating an overestimation of MOD16 ET. According to the *RMSE*, summer (6.14 mm/8d) achieved the lowest value, indicating low accuracy of the MOD16 ET product. However, *RMSE* (2.09 mm/8d) in spring was the same as that in the fall. Relationship between ET and its relevant meteorological parameters were analyzed. Results indicated a very good relationship between surface air temperature and ET. Meanwhile a significant relationship between wind speed and ET also existed. The inconsistent comparison of MOD16 and flux tower-based ET are mainly attributed to the parameterization of the Penman-Monteith model, flux tower measurement errors, and flux tower footprint vs. MODIS pixels.

Keywords: Moderate Resolution Imaging Spectrometer (MODIS); MOD16; evapotranspiration; validation; coastal wetland; eddy covariance; flux tower

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1 Introduction

Apart from precipitation and runoff, evapotranspiration (ET) is the principal component of the hydrological cycle which is affected by both biophysical and environmental processes at the interface among soil, vegetation and atmosphere (Budyko, 1974; Bouwer et al., 2008). Monitoring of ET has important implications for global and regional climate models, as well as increasing our understanding of the hydrological cycle and assessing environmental stress that affects forests and agricultural ecosystems (Kustas and Norman, 1996). As atmospheric temperatures are affected by gas concentrations, precipitation, cloudiness, humidity and wind distribution (Flannigan et al., 2009), ET can be affected by changes to any of these factors (El Maayar and Chen, 2006). An increase in ET while precipitation remains constant, or is reduced, can decrease water availability for natural and agricultural systems, as well as human needs (Miller et al., 2007; Du et al., 2013). As a result, hydrological

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Corresponding author: Du Jia. E-mail: jiaqidu@iga.ac.cn

balance methods, such as ET modeling, have been widely used to estimate global change effects, as well as crop and vegetation water demand (McKenney and Rosenberg, 1993).

The Panjin wetland, located in the southern part of Liaoning Province, Northeast China, is the largest reed field in the world. This region is also an important commodity grain base (Zhou et al., 2006), therefore making water supply and demand a major area of concern. Dynamic estimates of ET from constituent ecosystems are important for water management of Panjin wetland, especially as the coastal habitats in this area provide essential ecosystem services for people and the environment; services which are valued at billions of dollars (Pendleton, 2008). Over the past two decades, coastal wetlands have been increasingly recognized for their high biodiversity and the important hydrological functions they perform, including flood protection, erosion control, wildlife food and habitat protection, water quality conservation, and carbon sequestration (Costanza et al., 1997). Wetland hydrology is a primary driving force influencing wetland ecology, its development and persistence (Soucha et al., 1996). For most wetlands, ET is the major component of water loss and, when considered as its energy equivalent (latent heat flux, LE), ET is the largest consumer of solar radiation (Přibáň and Ondok, 1985).

Estimating ET on a regional scale is problematic, resulting in limited availability of spatial information. Although some field techniques have provided ET measurements, such as soil water balance residual methods, the Bowen ratio, and eddy covariance systems (ECS) (Dugas et al., 1991), these measurements are obtained across small scales or are limited to the local environment in which the instruments are installed. Large scale methods used to estimate ET are often based on physical–mathematical procedures, i.e. simulation models or remote sensing algorithms (Droogers and Bastiaanssen, 2002; Bastiaanssen et al., 2005). Due to landscape heterogeneity, topography, climate, vegetation type, soil properties, management and environmental constraints, ET is highly variable over space and time (Allen et al., 1998a; Mu et al., 2007). Conventional point-based ET estimation methods not only fail to capture large spatial scale variability, they are also very difficult to obtain due to time and cost constraints.

With the development of remote sensing technologies, it is possible to retrieve land surface parameters at a watershed scale using remotely sensed data which can be used to estimate large scale ET rates (Mo et al., 2005). Among the remote sensing ET models currently used or under development, surface energy balance models including the surface energy balance algorithm for land (SEBAL) (Bastiaanssen et al., 1998a; 1998b), surface energy balance system (SEBS) (Su, 2002) and mapping evapotranspiration at high resolution with internalized calibration (METRIC) (Allen et al., 2007) are currently widely used. These methods are effective for calculating ET from an individual pixel to an entire raster image. Emerging developments in remote sensing will enable limitations in information on soil water status to be overcome which will enable evaporative depletion and estimation of net groundwater use for agriculture and the environment to be calculated (Ahmad et al., 2005).

Remote sensing-based global estimates of ET have been produced using the algorithm of Mu et al. (2011), for example the Moderte Resolution Imaging Spectroradiometer (MODIS) MOD16 (Mu et al., 2007, 2011). The MOD16 ET product has a spatial resolution of 1 km and is available with 8-day, monthly and annual intervals for the 109.03 million km^2 global vegetated land area. The MOD16 ET is estimated as the sum of evaporation from water intercepted by the canopy (which accounts for a substantial amount of ET in ecosystems with a high leaf area index after rainfall/ sprinkler irrigation events), transpiration from the dry canopy surface, and evaporation from the moisture soil surface and saturated soil surface. Although several studies (Mu et al., 2007; 2011; Ruhoff et al., 2013) have previously attempted to validate the MOD16 ET product under different climatic and land use/land cover conditions, almost all of these validation experiments used eddy covariance (EC) measurements as ground-truth data; a technique which includes a more limited source area compared with a MODIS pixel footprint. Moreover, the MOD16 ET averaged over 3 km × 3 km centered at the validation site has typically been used for comparison with EC measurements in previous studies (Mu et al., 2007; Mu et al., 2011; Kim et al., 2012; Ruhoff et al., 2013), a method which further increases spatial scale inconsistency between the two ET datasets. Previous studies have shown that the fetch of the EC measurements are typically on the order of tens to hundreds of meters, whereas the large aperture scintillometer (LAS) can provide more spatially representative ET measurements over the satellite pixel scale compared with the EC system (Tang et al., 2011). The majority of validations for MOD16 ET were undertaken using traditional landscapes and not for covered wetlands, especially coastal wetlands. There is therefore a need to evaluate global remote sensing products at monitoring sites for typical coastal wetlands.

The main objective of this study is to evaluate the MOD16 global ET product using eddy covariance flux tower-derived ET in Panjin coastal wetland, Northeast China. Daily latent heat fluxes (LE) were acquired and converted to daily ET from the Panjin eddy flux tower located at Panjin Wetland Ecosystem Research Station. The flux tower-derived ET was then summed to an 8-day ET corresponding to the MOD16 ET values for comparison. Base on this study, MOD16 global ET in coastal wetland can be improved to analyze dynamic of ET, which is important for water management of Panjin wetland, especially as the coastal habitats in this area provide essential ecosystem services for people and the environment.

2 Materials and Methods

2.1 Study area

Panjin eddy flux tower (41°08′N, 121°54′E) is located about 15 km west of Panjin City in Liaoning Province, Northeast China (Fig. 1). This region is located on the transition zone between the Bohai Sea and dry land, at the convergence of salty water and fresh water from the Shuangtaizi River and the Raoyang River. This area is characterized by a continental semi-humid monsoon climate, having wide seasonal variations with a mean annual temperature of 8.6℃, mean annual precipitation of 631 mm, a frost-free period of 171 d and more than 2700 h of sunshine annually. The terrain is quite flat, with a slope grade of about 1∶10 000. The plant community for this wetland ecosystem is dominated by *Phragmites australis*, covering an area of 900 km^2, making it the largest reed field in the world. The soil at the study site is a silty clay (Zhou et al., 2006).

The wetlands in the Liaohe River Delta are of great importance for biodiversity as a large number of species, including some that are rare and endangered, live and breed in the wetlands, or use the wetlands as a resting

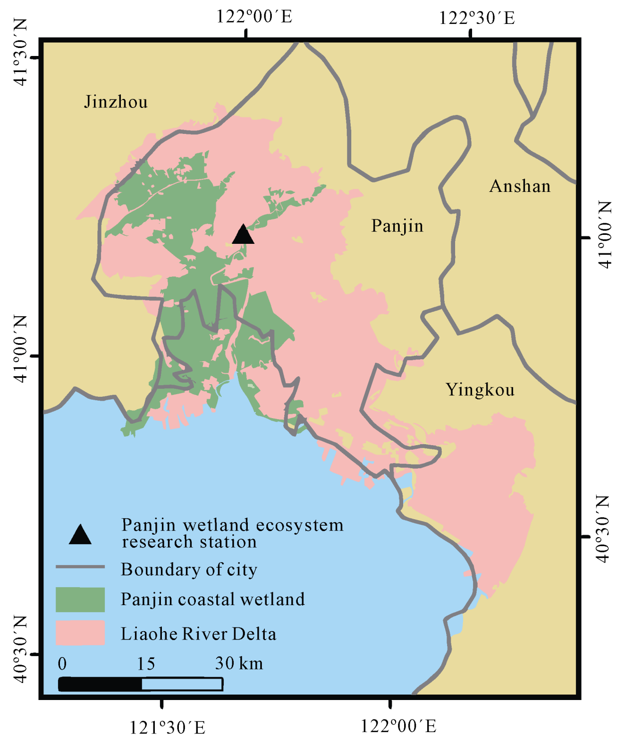

Fig. 1 Location of the Liaohe River Delta and the Panjin eddy flux tower

and feeding place during migration. Records indicate that there are 411 species (124 families) of vertebrates, including the red-crowned crane (*Grus japonensis*), white-naped crane (*Grus vipio*), and the Chinese black-headed gull (*Chroicocephalus saundersi*). The importance of this wetland has been recognized with the designation of the Shuangtaizihekou (Liaohe kou) national Nature Reserve (in 1986), as well as the wetland being listed as a Ramsar site since 2004 (Li et al., 2012).

2.2 Flux tower data

To evaluate the global 1-km, 8-day MOD16 ET product, eddy covariance LE data from the Panjin flux tower for 2005 were used. This station is equipped with a microclimate gradient observation system as well as an eddy covariance system. The eddy covariance system, installed at a height of 3-m, is mainly composed of a 3-dimensional supersonic anemoscope (CSAT3, Campbell Scientific Inc., USA), an open path CO_2/H_2O analyzer (Li-7500, Li-Cor Inc., USA), and a data logger (CR5000, CSI, USA) having a sampling frequency of 10 Hz. The primitive output data from this system includes horizontal wind speed (U_x, U_y), vertical wind speed (U_z), absolute carbon dioxide density (CO_2), absolute steam density (H_2O), sonic virtual temperature (T_s) and atmospheric pressure (p). The observation heights of the microclimate gradient system are located at 2.5-m and 4-m, and the observation terms include wind speed, air temperature, relative humidity, soil heat flux (G) at the depth of 5-cm, net radiation (R_n), effective photosynthetic radiation (*PAR*), total solar radiation and soil water capacity at different depths (10, 20, 30 and 50 cm). The sampling frequency records data every 30 minutes. Data recorded in 2005 at the research station used in this investigation included the microclimate gradient data and half-hour online flux data from the eddy covariance system. Data from this system was corrected by removing noise, revolving coordinates 3 times, Webb-Pearman-Leuning (WPL) adjustment and declining tendency.

The MOD16 ET products were spatially averaged over a 3 × 3 1-km pixels window centered on the Panjin eddy flux tower to achieve spatial representativeness of the measured data. The size of eddy covariance source area, or footprint, does not only depend on instrument height (Burba and Anderson, 2010), but also on the wind direction and velocity, atmospheric stability and the underlying surface conditions (Liu et al., 2013). Source area or footprint modeling was not undertaken as the location of the flux tower was homogeneous. The LE data observed every 30 min were MODIS-driven estimation of terrestrial latent heat flux in China based on a modified Priestley-Taylor algorithm converted to daily ET using equations presented in Mu et al. (2011). In addition, only reliable 30 min measurements were prioritized, exceeding 40 per day. The derived daily ET was further summed over eight days for each year to match the MOD16 ET product. Due to insufficient ET measurements, some data points were excluded from the analysis. The number of the 30 min ET measurements per day (over 40) was prioritized in the validation process to avoid compromising the completeness and reliability of the flux tower data. For further analysis, eight day summations were undertaken to create monthly ET for the Panjin eddy flux tower.

2.3 MOD16 global ET data

The MOD16 algorithm was developed by Mu et al. (2011) based on the Penman-Monteith equation (Monteith, 1965) to estimate actual global ET over vegetated land surface from wet and moist soil evaporation, evaporation of rain intercepted by the canopy (an important water flux for ecosystems with a high leaf area index), and transpiration through plant leaf and stem stomata. To calculate latent heat flux, the following equation was used:

$$LE = \frac{s(R_{\mathrm{n}} - G) + \rho C_{\mathrm{p}}(e_{\mathrm{s}} - e_{\mathrm{a}})/r_{\mathrm{a}}}{s + \gamma(1 + r_{\mathrm{s}}/r_{\mathrm{a}})} \quad (1)$$

where LE is the latent heat flux; s is the slope of the saturated vapor pressure versus the air temperature curve; e_a is actual vapor pressure; R_n is surface net radiation; e_s is saturation vapour pressure; G is the soil heat flux; ρ is air density; C_p is the specific heat capacity of air; r_a is aerodynamic resistance; γ is the psychometric constant; and r_s is the surface bulk resistance. A detailed description of the computations for the parameters and each of the four terrestrial ET components in the MOD16 algorithm are presented in Mu et al. (2011).

Input for the MOD16 ET algorithm includes: 1) the global 1-km^2 Collection 4 MODIS land cover type 2 (MOD12Q1) (Friedl et al., 2002); 2) the global 1-km^2 MODIS Collection 5 LAI/FPAR (MOD15A2) (Myneni et al., 2002); 3) the tenth band of the White-Sky-Albedo from Collection 5 8-day MCD43B2 and MCD43B3 products (Lucht et al., 2000; Jin et al., 2003); and 4) the global GMAO daily meteorological reanalysis data at a 1.00° × 1.25° resolution. The output from the MOD16 ET algorithm consists of 8-day, monthly and annual ET and LE. To monitor environmental water stresses and droughts, potential ET and potential LE on 8-day, monthly and annual time scales were also produced.

Mu et al. (2011) produced a MOD16 global ET/LE/potential ET/potential LE dataset spanning 2000 to 2014 by summing the four components estimated from the Penman-Monteith equation. This data is available at ftp://ftp.ntsg.umt.edu/pub/MODIS/Mirror/MOD16/. Future products will be produced and distributed periodically, but not in near real time. The MOD16 ET product is the first regular 1 km × 1 km land surface ET dataset over vegetated areas covering the entire globe. The 8-day ET (with a unit of mm/8d) for a given day is the sum of ET during the following 8-day time period (during the following 5-day time period for a year in a non-leap year and during the following 6-day time period for a year in a leap year). The valid value range of the 8-day ET product is −32 767 to 32 700 and the scale factor is 0.1. Actual ET equals the value retrieved from the MOD16 ET product multiplied by 0.1.

2.4 Evaluation methods

To assess the relationship between the MOD16 ET and flux tower derived ET, the coefficient of determination (R^2), root mean square error (*RMSE*, Equation (2)), *Bias* (Equation (3)) and percent bias (*PBias*, Equation (4)) were used. These statistical techniques are commonly used for comparing pairs of variables, e.g., Sun et al. (2012). The R^2 was used to determine the strength of the relationship between the results from the flux tower and MOD16 modeled ET. *Bias*, on the other hand, is a measure of how a modeled value deviates from the true value, and indicates whether there is under- or over-estimation. The percent bias is a percentage of bias relative to the observed mean.

The *RMSE*, *Bias* and *PBias* were calculated using the following equations:

$$RMSE = \sqrt{\frac{\sum (FET - MET)^2}{N}} \quad (2)$$

$$Bias = \frac{\sum (MET - FET)}{N} \quad (3)$$

$$PBias = \frac{Bias}{(\frac{1}{N})\sum FET} \times 100 \quad (4)$$

where *FET* is flux tower ET; *MET* is MOD16 ET; and *N* is the number of measurements. *Bias* and *RMSE* values close to zero signify that the MOD16 ET does not deviate from the true ET value (flux tower), indicating that MOD16 is deemed accurate; values greater than zero reflect a high level of inaccuracy. A negative value of *Bias* signifies underestimation, while a positive value shows overestimation by the modeled value or MOD16.

3 Results

3.1 Validation of MOD16

For the Panjin eddy flux tower, our results show an inconsistent comparison of the flux tower and MOD16 ET values over the studied time period (Fig. 2; Table 1). The highest correlations obtained in 2005 achieved an R^2 of 0.58 during the fall period in the growing season. According to the *RMSE*, summer (R^2 = 0.34, *RMSE* = 6.14 mm/8d) achieved the lowest value, indicating low accuracy of the MOD16 ET product. Results from the flux tower measurements were almost complete during the spring period; the validation results (R^2 = 0.39) were poorer compared to those from the fall based on the lower coefficient of determination. However, *RMSE* (2.09 mm/8d) in spring was the same as that in the fall. In general, results from Panjin showed that there was an underestimation of MOD16 ET in the spring and fall, with *Biases* of –2.27 and –3.53 mm/8d, respectively (–40.58% and –49.13% of the observed mean) (Table 1). Results for *Bias* during the summer had a range of 1.77 mm/8d (7.82% of the observed mean), indicating an overestimation of MOD16 ET. The trends of *PBias* and *RMSE* in the different seasons were various because *PBias* was determined by the difference between flux tower ET and MOD16 ET, the number of measurements and flux tower ET but *RMSE* was calculated by the former two values. The flux tower ET in spring and fall was much lower than that in summer due to Panjin wetland's continental semi-humid monsoon climate. Validation for the growing season was similar to that in summer in terms of *RMSE*; R^2 for the growing season was the highest (0.67). Generally, results for the growing season showed that MOD16 ET was underestimated (*Bias* = –1.07 mm/8d, *PBias* = –8.62% of the observed mean).

The 8-day and monthly comparison of ET in Panjin for spring, summer and fall are shown in Figs. 3a and 3b. Flux tower ET values were generally higher than MOD16, especially during the growing season. During the summer season (June–August), MOD16 and flux tower ET were closely related, confirming the systematic underestimation of ET by MODIS ET as shown in the results for Bias and *PBias*.

3.2 Relationship analysis between ET and its relevant parameters

As shown in Fig. 3, general trends indicate that both the flux tower and MOD16 ET were related to surface air temperature and wind speed, especially surface air temperature. Results indicate a very good relationship between surface air temperature and measured flux tower ET. Eight-day and monthly comparisons recorded R^2 values of 0.84 and 0.92, respectively. By contrast, results showed a weaker relationship between surface air temperature and MOD16 ET; R^2 results for 8-day and monthly comparisons were 0.60 and 0.73, respectively. In this study, the high values of determination coefficient surface air temperature and ET between the growing season indicated that ET at the study site was mainly

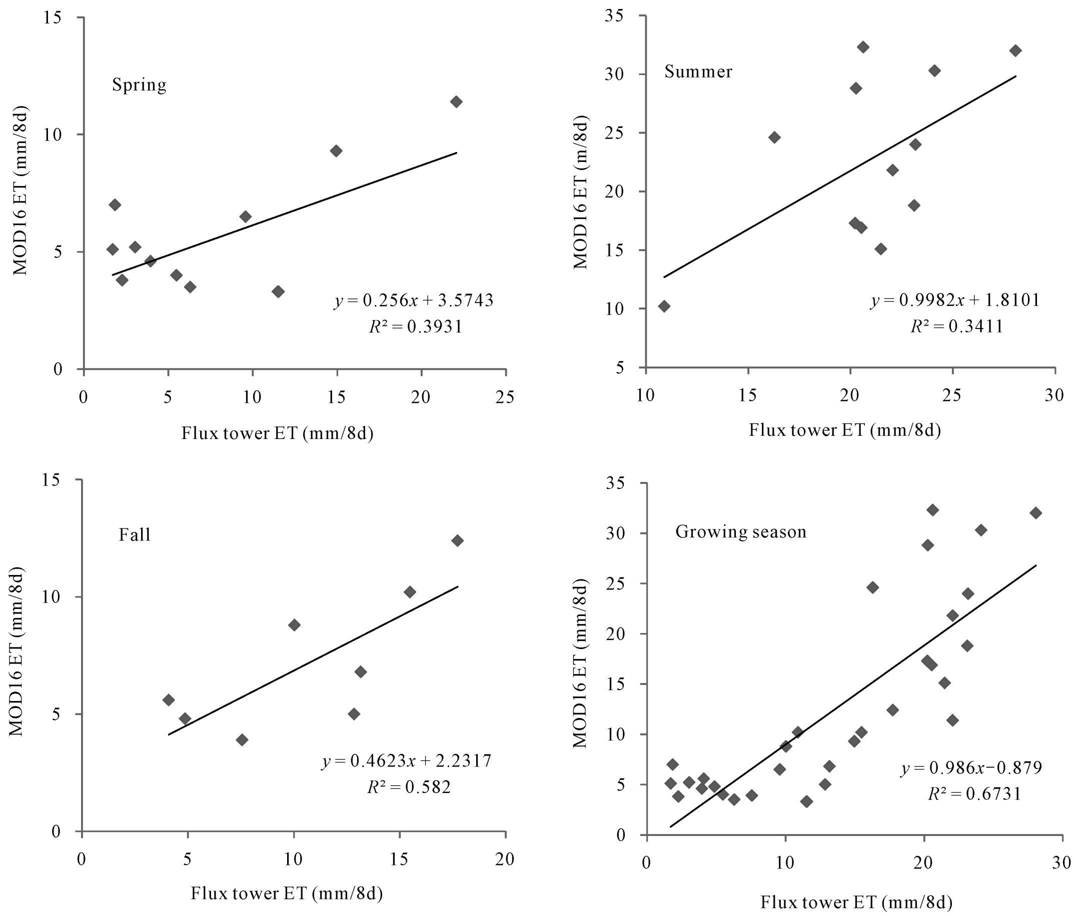

Fig. 2 Eight-day validation results of evapotranspiration (ET) product from the Moderate Resolution Imaging Spectrometer (MOD16) using flux tower data (mm/8d) in Panjin in growing season of 2005

Table 1 Validation of MOD16 products using flux tower based evapotranspiration (ET) from the Panjin eddy flux tower

Season	R^2	*RMSE* (mm/8d)	*Bias* (mm/8d)	*PBias* (%)	*N*
Spring	0.39	2.09	−2.27	−40.58	12
Summer	0.34	6.14	1.77	7.82	12
Fall	0.58	2.09	−3.53	−49.13	8
Growing Season	0.67	5.47	−1.07	−8.62	32

Notes: Spring includes March, April and May. Summer includes June, July and August. Fall includes September and October. *N* means numbers of measurements

influenced by surface air temperature, a finding that was also identified by Zhou et al. (2010). Further analysis of the relationship between wind speed and results from the flux tower, as well as MOD16 modelled ET for 8-days and monthly data, are shown in Table 2. Eight-day and monthly comparisons between wind speed and flux tower measured ET recorded R^2 values of 0.14 and 0.42, respectively. By contrast, 8-day and monthly comparisons between wind speed and flux tower measured ET were 0.14 and 0.24, respectively. In general, a significant relationship between wind speed and ET existed.

4 Discussion

Our investigation focused on the evaluation of the MOD16 modelled ET product in Panjin coastal wetland using flux tower measured ET. Discrepancies between MOD16 ET and flux tower ET can originate from a number of factors (the majority of which were identified by Mu et al. (2007; 2011)), including flux tower footprint vs. MODIS pixel size, flux tower measurement error, parameterization (input data) of the Penman-Monteith model and limitations of the algorithm (Ramoelo et al., 2014).

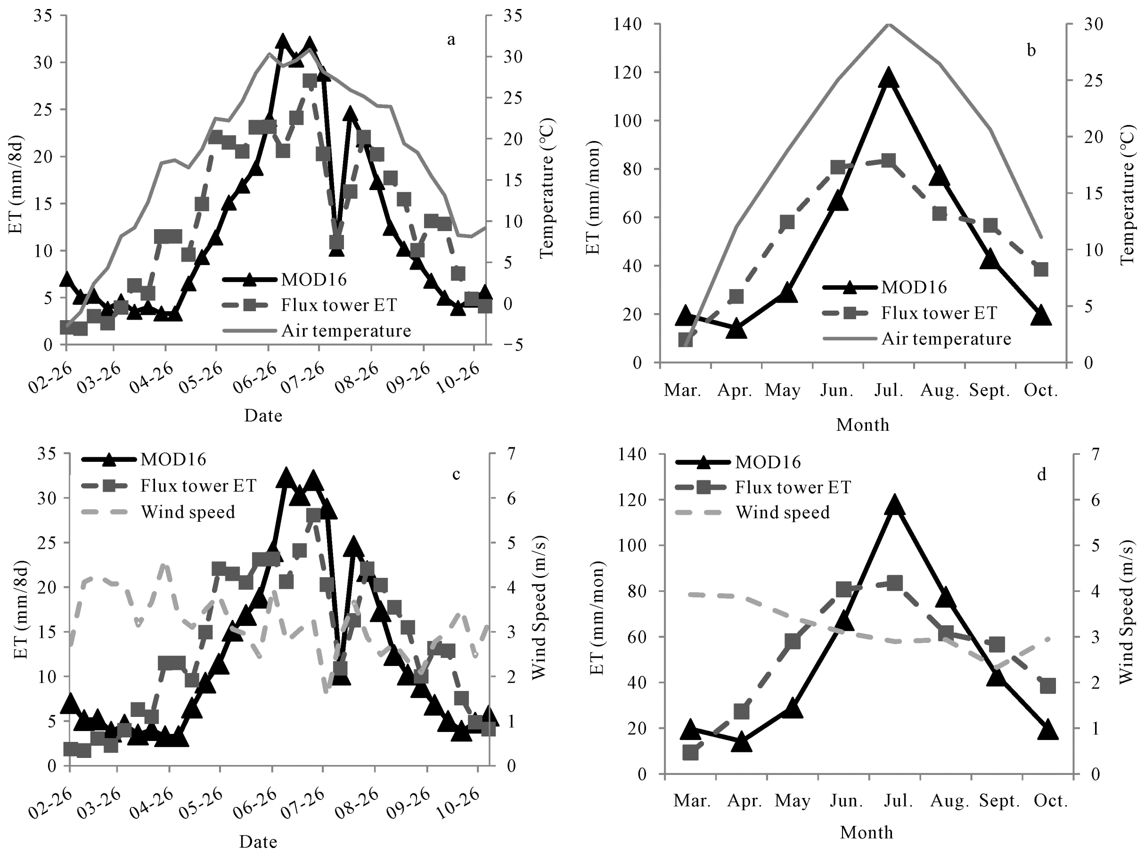

Fig. 3 Different time series comparison of evapotranspiration (ET) product from the Moderate Resolution Imaging Spectrometer (MOD16), ET relevant parameters (a. surface air temperature in 8-day interval, b. surface air temperature in a month interval, c. wind speed in 8 days interval, d. wind speed in a month interval) and Panjin flux tower derived ET in growing season of 2005

Table 2 Comparison analysis among ET, surface air temperature and wind speed

Relations	Types	Duration	R^2	*RMSE* (mm/8d)
ET and surface air temperature	Flux tower	8-day	0.84	3.14
		Month	0.92	8.04
	MOD16	8-day	0.60	5.81
		Month	0.73	20.36
ET and wind speed	Flux tower	8-day	0.14	7.55
		Month	0.42	21.09
	MOD16	8-day	0.14	9.02
		Month	0.24	34.28

The main input data for the MODIS ET model includes MODIS derived global products such as land cover (Friedl et al., 2002), albedo, leaf area index (LAI), fraction of photosynthetic absorbed radiation (FPAR) and meteorological data. These input parameters, which are generally poor or not validated for coastal wetlands, are coarse scale products which are likely to generate significant ET prediction errors (Ramoelo et al., 2014). An example of the coarse nature of this produce can be highlighted with reference to the MODIS global land cover (MOD12Q1) which, using a relatively coarse product (500 m), inadequately captures the heterogeneity of coastal wetland ecosystems. MODIS-FPAR is derived from MODIS-LAI/FPAR algorithm (a complex three-dimensional radiative transfer model with LOOKUP table inversions per biome type (Liu et al., 2013; Ramoelo et al., 2014)), differing form the early method of empirical relationships between values of

LAI/FPAR and NDVI, but MODIS-FPAR is linearly proportional to NDVI (Liu et al., 2013). Like NDVI, MODIS-FPAR is sensitive to canopy background variations and saturates in areas with dense canopy, while enhanced vegetation index (EVI) is developed to optimize the canopy background information with improved sensitivity in high biomass areas and improved vegetation monitoring through a decoupling of the canopy background signal and a reduction in atmosphere influences (Liu et al., 2013). Therefore, it is crucial that input data, such as land cover, FPAR and LAI, are also assessed and validated in a local context and improved when required (Ramoelo et al., 2014). Our investigation will help determine and document error propagation within the MOD16 algorithm and support the development of local parameterization of models for an integrated water management system. Sensitivity analyses are required to identify the variables which have the most influence on ET output and to document the level of agreement between input and output errors (Ramoelo et al., 2014).

It is also possible that uncertainties associated with the flux tower measurements could have influenced the results gained from this investigation. Aubinet et al. (1999) highlighted that flux towers can have an energy balance closure problem due to the sum of net radiation and ground heat flux sometimes being greater than the sum of the turbulent fluxes of latent and sensible heat. Flux tower measurements are also largely influenced by weather conditions; during rainy and stormy days flux tower sensors either record abnormal values or simply do not record any data. Therefore, missing flux tower measurements will have affected the cumulative 8-day ET (Ramoelo et al., 2014).

Spatial discrepancy may still exist between the footprint of the flux tower measurements and the MODIS pixels. The height of the sensors on a flux tower (Burba and Anderson, 2010), wind direction or velocity, atmospheric stability and underlying surface conditions influence the size of the eddy covariance source area (Liu et al., 2013). In addition, the layout of a 3 × 3 1-km pixel may not directly match the flux tower footprint. Although footprint modeling is a means to reduce the spatial discrepancy between flux tower measurements and MODIS pixels (Jia et al., 2012), this was beyond the scope of this study.

Shortcomings associated with the algorithm itself could also have influenced the differences between flux tower and MOD16 ET (Ramoelo et al., 2014). Mu et al. (2011) argued that several physical factors, such as micro-climate, plant biophysics for site specific species and landscape heterogeneity, influence soil surface evaporation and plant transpiration processes, factors which potentially affect the accuracy of MOD16 ET estimation. MOD16 ET also does not account for disturbance history or species composition and stand age (Mu et al., 2007; 2011), thus adding further uncertainty to the results. Finally, the algorithm makes the assumption that stomata close during the night, an assumption which contradicts previous findings (for example Musselman and Minnick, 2000) which have shown that stomata can be open during the night. This error will therefore induce underestimation of daily ET due to bias imposed by night-time vegetation transpiration (Mu et al., 2011).

5 Conclusions

Our investigation evaluated the quality of the MOD16 ET global products and compared MOD16 ET with ET results obtained from a flux tower in the Panjin coastal wetland, Northeast China. This study is important as data from MOD16 is generally poor and its accuracy is not consistent over a period of time for coastal wetlands. In general, results from Panjin showed that there was an underestimation of MOD16 ET in the spring and fall, with *Biases* of –2.27 and –3.53 mm/8d, respectively (–40.58% and –49.13% of the observed mean). Results for *Bias* during the summer had a range of 1.77 mm/8d (7.82% of the observed mean), indicating an overestimation of MOD16 ET. According to the *RMSE*, summer (6.14 mm/8d) achieved the lowest value, indicating low accuracy of the MOD16 ET product. However, *RMSE* (2.09 mm/8d) in spring was the same as that in the fall. We have also evaluated the MOD16 product in this investigation and quantified errors for a coastal wetland. Although both surface air temperature and wind speed were found to influence ET distribution, surface air temperature was found to be the most influential. Several factors could have influenced the inconsistency between MOD16 and flux tower derived ET, including parameterization of the model, scaling from flux tower measurement to a pixel, and limitations associated with the algorithm used. For further evaluation of MOD16, footprint modeling for the eddy covariance source area should be undertaken to ensure spatial representativeness or to reduce errors associated with scaling from flux tower measurements to a pixel. In addition, the energy balance closure problem should be analyzed, provided that there is reliable soil heat flux data. In future, there is a need to develop locally parameterized models for consistent estimation and mapping of ET in coastal wetlands and it is important to understand existing ET estimation methods in order to improve ET estimation for coastal wetland environments. In addition, future activities should also focus on the improvement of the estimation accuracy of other remote sensing derived input variables, such as LAI, albedo and land cover. Accurate and consistent estimation and mapping of ET is crucial for understanding plant or crop water-use, an important component of integrated water resource management.

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