Validation of MODIS Data for Localized Spatio-Temporal Evapotranspiration Mapping

M I Nadzri$^{1,3}$ and M Hashim$^{2}$

$^{1,2}$Institute of Geospatial Science & Technology (INSTeG)
Universiti Teknologi Malaysia
81310 UTM Johor Bahru, Malaysia

E-mail: izuanadzri@gmail.com

Abstract. Advancement in satellite remote sensing sensors allow evapo-transpiration (ET) from land surfaces to be derived from selected reflectance and emittance in visible and thermal infrared wavelengths, such as using Moderate Resolution Imaging Spectrometer (MODIS). In this paper, we report the validation of recent MODIS-generated higher-order global terrestrial ET product 16A2. The main focus of this paper is to devise the follow-up calibration for the localised region covering the entire Malaysia peninsular. The validation is carried out locally by dividing the study area into 3 distinct climatological regions based on the influence to monsoons, and using multi-temporal MODIS data acquired in 2000-2009. The result, evidently show the local effects still inherent in the MODIS 16A2 products; with varying $R^2$ within the 3 local climatological regions established (Northwest=0.49 South=0.47, and Southwest=0.52; all with $P < 0.001$). The accuracy each region validated is within $\pm$ RMSE 43mm for monthly ET. With $P$ value in acceptable range, the correction is useable for further usage.

1. Introduction

Water resources in condition of vapour, leaving the earth surface via atmosphere, namely evaporation (ET), is one of the important elements exists in the water balance after the precipitation. While some part of evapotranspiration may reach the atmosphere, the other part of it remain on the earth Planetary Boundary Layer (PBL) which in the lithosphere where most likely it intercept in the tree canopy. To measure the evapotranspiration, it requires an understanding on how the evapotranspiration is moved from the ground to the atmosphere which is the energy balance concept [1]. In small regional scale, the measurement was done in a point based situation, where the limitation is it doesn’t represent the value accurately in a wide scale. In tropic where the condition is dynamically change due to solar radiation is more intense [2] than other region, it is crucial to measure evapotranspiration in a better spatial-temporal means.

Using satellite remote sensing technique, it provides a better understanding how evapotranspiration is transported from one medium to another. The recent trend are high-level satellite data products, such as globally-scale ET-related; MODIS 16A2. This product is derived from is a hyper-spectral type sensor MODIS that have sets of sensitive spectral bands that enable global scale monitoring the

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$^{3}$ To whom any correspondence should be addressed.
earth’s environment. The satellite has a high revisiting time over the same place. Hence, it is possible to provide parameter input for evapotranspiration computation in a large spatio-temporal basis. With advancement of algorithm in retrieval of ET and potential ET, from MODIS raw data, these data products offers vast opportunities to derive a local-scale provided it is carefully validated and calibrated. Several global validations have been recently performed in America [3] and Asia continent [4], but such distribution in tropical is very small if ever existed, as none being reported. Consequently, this paper reports a study carried out to validate MODIS 16A2 for actual ET in peninsular Malaysia. The study concluded with the calibration parameters using long-term multi-temporal MODIS data against the corresponding in-situ gauges measurement.

2. Materials and Methods

2.1. Study area
Peninsular Malaysia (Figure 1) is located in south-east Asia, at latitude/longitude of 100°-105°E and 1°-6N°, respectively. Surrounded by Malacca Strait and South China Sea for the western and eastern coastlines, the climate is very much influenced by two main monsoon systems of the region; namely the southwest (SW) and northeast (NE) monsoons. Both SW (May-Sept) and NE (Nov-Mar) monsoon carries heavy rainfall to western and eastern coastlines, in respectively.

![Figure 1. Study area: (a) peninsular Malaysia; (b) the topographic features, and (c) main land cover types with 7 designated meteorological stations used in the study.](image)

The region also experiencing two inter-monsoons: warm inter-monsoon (Dec-Feb, Jun-Jul) and humid inter-monsoon (Apr-May, Sep-Nov). Located near the equator, the sun shines almost throughout the year except several events such as during heavy rainfall and cloudy monsoon seasons. The mean temperature fluctuates between 26 °C and 34 °C, with relative humidity varies from 51 to 95%.

2.2. Satellite ET Methods
The satellite-based ET used in this study is obtained from monthly MODIS 16A2 product acquired in 2000-2009 (120 month). It includes wet and moist soil evaporation that intercepted tree canopy before it reaches the ground and transpiration through stomata trees. The algorithm (eqn. $\Delta E = \frac{K_A \times C_P \times (e_{sat} - e)}{s + \gamma \times (1 + r_g/r_d)}$ (1) used to derive this data set is based on Penman-Monteith (P-M) equations [5], such that:
\[
\lambda E = \frac{s \times A \times C_p \times (E_{sat} - e) / r_a}{s + \gamma \times (1 + r_s / r_a)}
\]  
(1)

Where \(\lambda E\) is latent heat flux and \(\lambda\) is the latent heat of evaporation; \(s = d(e_{sat})/dt\), slope of the curve relating saturated water vapor pressure \((e_{sat})\) to temperature; \(A\) is available energy partitioned between sensible heat, latent heat and soil flux on land surface; \(\rho\) is air density, \(C_p\) is the specific heat capacity of air; and \(r_a\) is the aerodynamic resistance. The psychrometric constant \(\gamma = C_p \times P_a \times M_d / (\lambda \times M_w)\), where \(M_d\) and \(M_w\) are the molecular masses of dry and wet air respectively, and \(P_a\) is atmospheric pressure. The \(r_s\) is surface resistance where it is an effective resistance to evaporation from land and surface and transpiration from the plant canopy. An improved over the algorithm is including such as nighttime ET calculations, vegetation cover fraction, stomatal conductance and aerodynamic conductance. Further explanation can be found in [5].

2.3. Ground PET

Two types of ground PET were used in this study:

2.3.1. Penman-Monteith. The Penman-Monteith (P-M) method [6], include surface resistance and water vapour aerodynamic. In theory, it is among the complex method because it covers many

\[
ET_o = \frac{0.408 \times \Delta \times R_n - G + \gamma \times 900 + 273 \times e_s - e_a \times e_a}{\Delta + \gamma \times (1 + 0.34 \times u_2)}
\]  
(2)

Where, \(ET_o\) is the reference evapotranspiration (mm\text{day}^{-1}); \(\Delta\) is the slope vapour curve (kPa\text{°C}^{-1}); \(R_n\) is radiation of crop surface (MJ\text{m}^{-2}\text{day}^{-1}); \(T\) is air temperature at 2m height (°C); \(e_s\) is saturation vapour (kPa); \(e_a\) is actual vapour pressure, (kPa); and \(\gamma\) is psychrometric constant (kPa\text{°C}^{-1}).

2.3.2. Priestley-Taylor. The Priestley-Taylor (P-T) methods involve the finding that the actual evaporation is 1.26 times greater than the potential evaporation [7]. Thus, this finding takes place the aerodynamic condition in the equation with a constant (1.26) and it requires only temperature and long-wave radiation. The equation is written below (eqn. 

\[
ET_o = 1.26 \times \frac{\Delta}{\Delta + \gamma} \times (R_n - G) \times \frac{1}{\lambda}
\]  
(3)

Where, \(\Delta\) is slope vapour curve (kPa\text{°C}^{-1}); \(\gamma\) is psychrometric constant (kPa\text{°C}^{-1}); \(R_n\) is net radiation of vegetated surface (MJ\text{m}^{-2}\text{day}^{-1}); \(G\) is the soil heat flux density (MJ\text{m}^{-2}\text{day}^{-1}); and \(\lambda\) is latent heat vapour (MJkg^{-1}).

2.3.3. Hargreaves-Samani. The Hargreaves-Samani (H) equation [8] is generated through the understanding of temperature coefficient and relative humidity factor. The equation is as below (eqn. 

\[
ET_0 = 0.0023 \times (T_{max} - T_{min})^{0.5} \times (T_m - 17.8) \times R_a
\]  
(4)

Where, \(T_m\), \(T_{max}\), and \(T_{min}\) is mean, maximum and minimum temperature in Celsius (°C); and \(R_a\) is the extra-terrestrial radiation of vegetation surface (MJ\text{m}^{-2}\text{day}^{-1}).

2.3.4. Thornwaite. The Thornwaite (T) equation [9] is derived from relationship between ET and air temperature changes. The equation is as below (Eqn. 

\[
ET_0 = 0.0023 \times (T_{max} - T_{min})^{0.5} \times (T_m - 17.8) \times R_a
\]  
(4)
\( ET_0 = ET_{OSC} \times \left( \frac{N}{12} \right) \times \left( \frac{d_m}{30} \right) \)  
(5), \( ET_{OSC} = 16 \times \left( \frac{10 \times T_{med}}{t} \right)^\alpha \)  
(6), \( I = \sum_{i=1}^{12} \left( \frac{T_{med}}{5} \right)^{1.514} \)  
(7) and \( \alpha = 0.429 - 1792 \times 10^{-5} \times I \times -771 \times 10^{-7} \times I^2 \times +675 \times 10^{-9} \times I^3 \)  
(8):

\[
ET_0 = ET_{OSC} \times \left( \frac{N}{12} \right) \times \left( \frac{d_m}{30} \right) \\
ET_{OSC} = 16 \times \left( \frac{10 \times T_{med}}{t} \right)^\alpha \\
I = \sum_{i=1}^{12} \left( \frac{T_{med}}{5} \right)^{1.514} \\
\alpha = 0.429 - 1792 \times 10^{-5} \times I \times -771 \times 10^{-7} \times I^2 \times +675 \times 10^{-9} \times I^3
\]

Where, \( ET_{OSC} \) is gross evapotranspiration; \( N \) is maximum number of sunny hours in the month; \( d_m \) is mean temperature in Celsius (°C); \( I \) is monthly heat index; and \( \alpha \).

2.4. Validating and Calibration of MODIS 16A2 Satellite

The multi-temporal product sets are first been validated using all four method to find the best algorithm to further validate in term of monsoon and tropic condition. The calibration was done using linear approach in the monsoon section.

3. Results and discussion

3.1. Comparison of Satellite and Ground PET

The comparison is done to measure the reliability of satellite towards the ground method. Seven meteorological stations (Figure 1c) provide the input required from year 2000-2009. Throughout the comparison, P-M show high reliability and perform well compared to other method.
The P-M reported the highest correlation (0.3275) compared to P-T (0.2513), H (0.1133), M (0.0610) and (0.0509) in Table 1. In term of p-value, the P-M again shows highest value. The reason on why P-M perform well despite there are different landcover (Figure 1c), and using quite similar input is due to the comprehensiveness of all parameter that influence evapotranspiration such as wind, solar radiation, temperature, landcover, pressure, and humidity. For error, the RMSE for P-M again, show the least (-3) and supported by satellite to ground ratio (S/G) small differences (0.85). Furthermore, the inclusion of energy balance concept provides efficiency in water vapour to transfer from earth to atmosphere. In comparison for all four method (Figure 2), Penman-Monteith shown the best output [10] where it is been selected in for comparison on monsoon behaviour.

### 3.2. Effects of Monsoon On PET

The performance for the MODIS16A2 ET for each monsoon is analysed by using calculated P-M equation. Seven meteorological stations (Figure 1) provide the input required from year 2000-2009.

| TABLE 1. Accuracy method in root mean square error (RMSE) and satellite/round ratio (S/G ratio). |
|-----------------|-------------|-------------|-----------------|
| TYPE | RMSE | BIAS | S/G RATIO |
| P-M | 37.005 | -3.831 | 0.856 |
| P-T | 50.943 | -25.423 | 0.679 |
| H | 75.338 | -51.979 | 0.540 |
| T | 77.945 | -73.396 | 0.528 |

**Figure 2.** Regression and p-value for all method; a) Penman-Monteith, b) Priest-Taylor, c) Hargreaves, d) Thornwaite.
In Figure 3, the regression is small differences among all season. This situation occurs because during SE monsoon, the wind and rainfall come from the south hemisphere affect the magnitude and vector on south. However, the same event occurs during the NE monsoon in the opposite way.

Table 2. Accuracy root mean square error (RMSE), bias, satellite/round ratio (S/G ratio) and $R^2$ for each monsoon season.

| Type           | RMSE  | Bias  | S/G ratio | % R² Increased |
|----------------|-------|-------|-----------|----------------|
| Northeast Monsoon | 43.100 | 42.245 | 1.640     | 51.786         |
| Southwest Monsoon | 36.177 | 41.881 | 1.614     | 44.061         |
| Inter-monsoon   | 40.740 | 47.130 | 1.690     | 52.855         |

In detail (Table 2), the reason there are two distinct monsoons is because physical terrain range is from 0 km to 2174 km and the Peninsular were divided into two major sections which is the East and West region (Figure 1b). Thus, making the wind properties and rainfall distribution is localized to season monsoon characteristics. Here, the division through seasons increases the $R^2$ value (~±40%). Hence it is reasonable for RMSE and Bias, the value remains almost the same for all seasons.

4. Conclusion

This study investigate the potential of the satellite based ET of MODIS16A2 for localized spatio temporal distribution throughout Peninsular Malaysia. The result shows that the MODIS16A2 ET produced the best agreement with Penman-Monteith equation. The validation is then improved by applying for season basis. This homogenous situation generates almost similar range of value for input in estimating the ET. However, the value tends to overestimates but it is almost constant for all season. The relative adjustment is necessary to ensure the value in monsoon remains usable. It is recommended that the value to be calibrated so that it is operational for further wide spatio-temporal hydrological purposes.

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