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High-resolution Surface Relative Humidity Computation Using MODIS Image in Peninsular Malaysia

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Abstract: Forest fire is a serious disaster all over the world. The Fire Weather Index (FWI) System can be used in applied forestry as a tool to investigate and manage all types of fire. Relative humidity (*RH*) is a very important parameter to calculate FWI. However, *RH* interpolated from meteorological data may not be able to provide precise and confident values for areas between far separated stations. The principal objective of this study is to provide high-resolution *RH* for FWI using MODIS data. The precipitable water vapor (*PW*) can be retrieved from MODIS using split window techniques. Four-year-time-series (2000−2003) of 8-day mean *PW* and specific humidity (*Q*) of Peninsular Malaysia were analyzed and the statistic expression between *PW* and *Q* was developed. The root-mean-square-error (RMSE) of Q estimated by *PW* is generally less than 0.0004 and the correlation coefficient is 0.90. Based on the experiential formula between *PW* and *Q*, surface *RH* can be computed with combination of auxiliary data such as DEM and air temperature (T_a). The mean absolute errors of the estimated *RH* in Peninsular Malaysia are less than 5% compared to the measured *RH* and the correlation coefficient is 0.8219. It is proven to be a simple and feasible model to compute high-resolution *RH* using remote sensing data.
Keywords: relative humidity; precipitable water vapor; specific humidity; MODIS

1 Introduction

The Canadian Fire Weather Index (FWI) System can be used in applied forestry as a tool to investigate and manage all types of fire management (Chrosciewicz, 1978; McRae, 1980; Fyles et al., 1991; McRae et al., 1994). The development of the FWI system (Van Wagner, 1987; 1990) over the last two decades allows the routine prediction of fire behavior from weather data (Fyles et al., 1991). The FWI is calculated from point measurements of air temperature, relative humidity, wind velocity, and precipitation. Nevertheless, the measurement stations are sparse especially in mountainous regions. When one station is isolated more than 20km from an adjacent station, interpolation method may not be able to provide precise and confident values for areas between the stations (Han et al., 2003). For this reason, remote sensing data may be very useful, because it provides the mapping capability at a regular spatial resolution for every point in a region.

In fact, the application of satellite data to FWI calculation is more difficult than that of meteorological data since using satellite data does not directly estimate the meteorological parameters required in the FWI calculation. However, several methods have been proposed to estimate air temperature using remote sensing data (Viau et al., 1996; Vogt et al., 1997). Lavoie (1997) has applied these methods by using remotely sensed air temperature to calculating the components of the FWI system. Han et al. (2003) used Geostationary Operational Environmental Satellite (GEOS) and National Oceanic and Atmospheric Administration (NOAA) data to estimate relative humidity and air temperature. It was the first to estimate relative humidity from satellite data and increased the contribution of satellite data to the calculation of the FWI from 25% to 50%.

At present, two Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on board the National Aeronautics and Space Administration (NASA) Terra and Aqua Spacecraft platforms are operational for global remote sensing of the land, ocean, and atmosphere. The objective of this study is to estimate surface relative humidity using MODIS data.

2 Method

2.1 Study area

Most forest fire occurred between July and September in Peninsular Malaysia (Ivan et al., 1999). Peninsular Malaysia lies in 1.29°–6.82°N and 99.73°–104.28°E. This area has a warm and humid climate. The relative humidity is about 80% all year round and temperatures range

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from 21°C to 32°C. The climate is affected by the northeast and southwest monsoons, tropical winds that alternate during the course of the year. Most of Peninsular Malaysia are mountainous region. Gunung Tahan is the highest peak which rises 2190m above the central spine of the Titiwangsa Mountain range in Peninsular Malaysia. About four-fifths of Peninsular Malaysia are covered by tropical rainforest.

2.2 Data sources

Relative humidity (*RH*) is a very important parameter to calculate FWI value. *RH* reflects the amount of moisture in the atmosphere. If *RH* is low, it will contribute to the drying of fuels; conversely, if *RH* is high, the fuels will absorb moisture from the atmosphere. To estimate surface *RH* in Peninsular Malaysia using MODIS data, some meteorological parameters were obtained from ground-based measurements recorded at 24 automatic meteorological stations. MODIS Level-1 data were processed to calculate precipitable water vapor (*PW*), MOD07 of MODIS Level-2 atmospheric profile products were used to extract surface air temperature in the clear sky. MODIS Level-1 data were provided by Malaysian Centre for Remote Sensing (MACRES) and MOD07 data were downloaded from NASA official website.

2.3 Calculation method

RH is the ratio of vapor pressure (e) and saturation vapor pressure (e_s). Vapor pressure (e) depends on air pressure (P_a) and specify humidity (Q), while saturation vapor pressure (e_s) depends on air temperature (T_a). Their relationship can be described as equations (1), (2) and (3) (Wang, 1987):

$$RH = e/e_s \quad (1)$$

$$e_s = 611\exp\left(\frac{17.27T_a}{237.3+T_a}\right)RH \quad (2)$$

$$e = Q \times P_a/0.622 \quad (3)$$

where 0.622 is the ratio of the mole weight of water vapor and dry air.

There is no direct method to estimate *RH* from remote sensing data. However, some simple statistical relationships were found (Smith, 1966; Liu ,1984; Yang and Qiu, 1996). Yang and Qiu (1996) derived the empirical expressions of the relation between the precipitable water vapor (*PW*) and ground vapor pressure (e) based on radiosonde data at 20 stations in China. The mean relative errors were less than 15%. Liu (1984) analyzed 9-year monthly mean precipitable water vapor (*PW*) and specific humidity (Q) of temperate, subtropical and tropical zones.

Several quadratic regressions were produced and the mean relative errors were less than 6.6%. Since precipitable water vapor (*PW*) can be retrieved successfully by MODIS data, it is possible to estimate RH using MODIS data.

3 Results

3.1 Precipitable water vapor (PW)

Descriptions of techniques for water vapor remote sensing using near-IR (NIR) channels were previously reported (Reagan, 1987; Frouin et al., 1990; Gao and Goetz, 1990; Gao and Kaufman, 2003; Kaufman and Gao, 1992; Kaufman et al., 1997). In order to improve the accuracy of the water content estimation in the atmosphere, Chesters et al. (1983), Fraser and Kaufman (1985), Kaufman and Gao (1992), King et al. (1992) and Gao and Kaufman (2003) have performed many studies for the retrieval of water content of atmosphere using the NIR method. Among the 36 bands of MODIS, five of them are NIR bands: 2 (0.865μm), 5 (1.24μm), 17 (0.905μm), 18 (0.936μm) and 19 (0.940μm).

Kaufman and Gao (1992) concluded that the retrieval of water content by channel ratio is feasible. Five bands in MODIS are devised to retrieve water content according to this principle. Bands 17, 18 and 19 are three absorption bands, but bands 2 and 5 are atmosphere window bands. The three and two band ratio approaches are used to retrieve the water content of the atmosphere. The equations are as follows:

$$T_{obs}(0.940\mu m) = \rho^*(0.940\mu m)/[C_1\rho^*(0.865\mu m) + C_2(1.24\mu m)] \quad (4)$$

$$T_{obs}(0.936\mu m) = \rho^*(0.936\mu m)/\rho^*(0.865\mu m) \quad (5)$$

$$T_{obs}(0.905\mu m) = \rho^*(0.905\mu m)/\rho^*(0.865\mu m) \quad (6)$$

where T_{obs} is observed transmittance, ρ^* is the computed apparent reflectance at the top of the atmosphere for the specified channel, C_1 is equal to 0.8, and C_2 is equal to 0.2.

For the relationship of water content and transmittance of atmosphere, we can utilize the models LOWTRAN, MODTRAN, etc. to simulate and secure the statistical expression. Kaufman and Gao (1992) gave the expression as Equation (7):

$$T_{obs} = \exp(\alpha - \beta\sqrt{PW}) \quad (7)$$

where *PW* is total precipitable water vapor. We do many experiments and get the coefficients of α and β for Malaysia. For T_{obs} (0.940μm), α=0.12 and β=0.651; for T_{obs} (0.936μm), α=0.056 and β=0.60; for T_{obs} (0.905μm), α=0.025 and β=0.3.

T_{obs} can be computed from the MODIS, hence we can compute the water content of the atmosphere through Equation (8):

$$PW = \left(\frac{\alpha - \ln(T_{obs})}{\beta}\right)^2 \quad (8)$$

Atmospheric water vapor has very different absorption coefficients over the band passes of MODIS channels centered near 0.936, 0.940, and 0.905μm. As a result, the three channels have different water vapor sensitivities under the same atmospheric condition. The strong absorption channel at 0.936μm is most sensitive under dry conditions, while the weak absorption channel at 0.905μm is most sensitive under humid conditions. Under a given atmospheric condition, the derived water vapor values from the three channels are different. A mean water vapor value (PW) is obtained according to the following equation:

$$W = f_1 PW_1 + f_2 PW_2 + f_3 PW_3 \quad (9)$$

where PW_1, PW_2 and PW_3 are water vapor values derived from the 0.936μm, 0.940μm, and 0.905μm channels respectively, and f_1, f_2, and f_3 are the corresponding weights. In Malaysia, f_1=0.24, f_2=0.40 and f_3=0.36.

Kaufman and Gao (1992) have performed a lot of experiments and analyses on the retrieval of precipitable water vapor (PW) from MODIS for different conditions and concluded that the accuracy of the retrieved PW is about 87% in the cloud-free conditions. We utilize the results retrieved by the parameters to compare with the MODIS PW product. The average PW and the distribution of PW are almost the same and the average PW error is less 0.016g/cm^2.

3.2 Specific humidity (*Q*)

We analyzed of 8-day mean precipitable water vapor (PW) and specific humidity (Q) of Peninsular Malaysia from 2000 to 2003 and produced the scatter plots of Q versus PW (Fig. 1). The curve is a quadratic regression and the bar represents 0.0004，corresponding to 10W/m^2 in latent heat flux for typical conditions. The scatter root-mean-square-error (RMSE) between the measured values and those predicted by the regression is generally less than 0.0004 and the correlation coefficient is 0.90. The specific humidity (Q) can be calculated from precipitable water vapor (PW) according to the following experiential Equation (10):

$$Q=0.001\times(-0.0762PW^2 + 1.753\, PW + 12.405) \quad (10)$$

The measured specific humidity (Q_1) of 2004 was used to validate this experiential equation. A comparison between the estimated specific humidity (Q_2) and measured specific humidity (Q_1) is presented in Fig. 2. The correlation coefficient is 0.922 and RMSE is less than 0.00032.

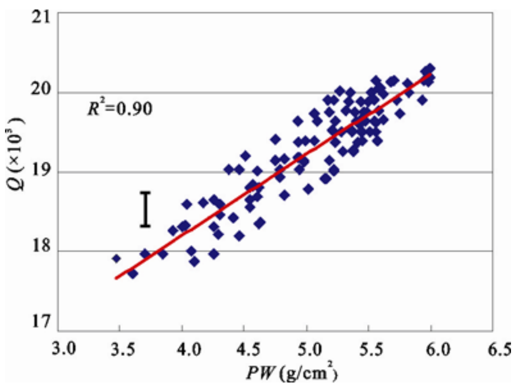

Fig. 1 Scatter plot of Q versus PW

3.3 Air pressure (P_a)

Air pressure (P_a) can be obtained from MOD07 of MODIS atmospheric profiles products in the clear sky. Due to clouds, some air pressure data are not available. However, it can be estimated by using elevation that is derived from DEM. Air pressure will decrease with the increment of elevation. Fig. 3 shows the corresponding relationship of air pressure (P_a) with elevation (H). Air pressure (P_a) can be calculated from elevation (H) according to the following experiential Equation (11):

$$P_a = 1013.3 - 0.1038H \quad (11)$$

The variety of air pressure with time is small, which is less than 8hpa. Therefore the air pressure estimated with experiential eqution is very close to the actual value, the average error is about 12hpa.

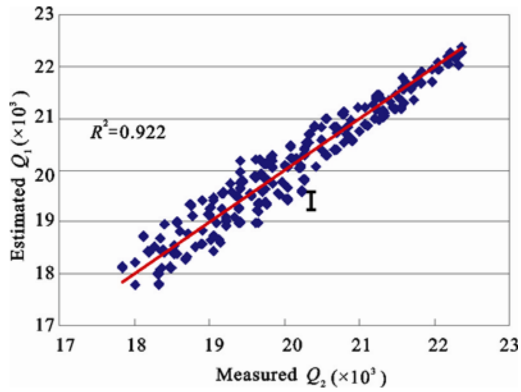

Fig. 2 Scatter plot of measured Q_1 versus estimated Q_2

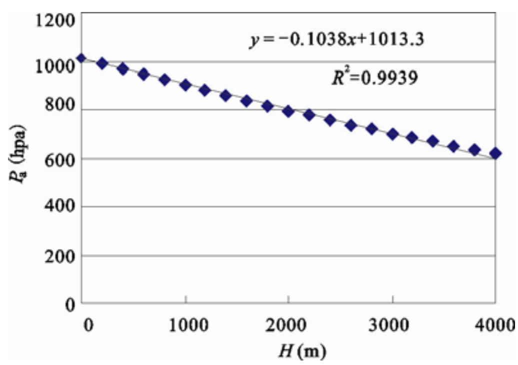

Fig. 3 Scatter plot of P_a versus H

3.4 Air temperature (T_a)

Air temperature (T_a) can be obtained from meteorological data and MOD07 of MODIS atmospheric profile products in the clear sky. The air temperature interpolated from meteorological data is not ideal especially in the mountainous area, for air temperature is much lower than that of plain area due to the higher elevation. Air temperature will decrease with the increment of elevation. Fig. 4 shows the corresponding relationship of air temperature (T_a) with elevation (H). According to the experience, in the area where the elevation is higher than 400m, the elevation must be used to correct the air temperature. Air temperature of MODIS product is pixel-based, which can describe air temperature in detail, but the accuracy of the computed air temperature near the meteorological station is not as good as that of meteorological data. Based on these analyses, Interactive Data Language (IDL) program can be used to optimize the result of air temperature combining the meteorological data, MODIS atmospheric profiles products and DEM.

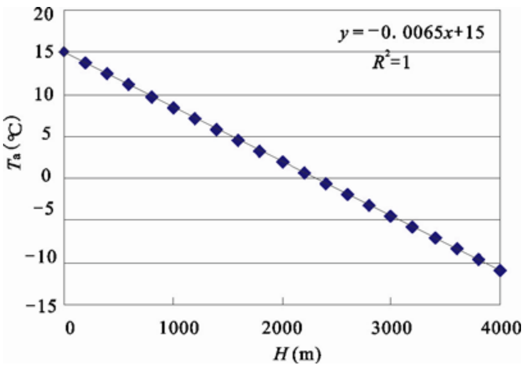

Fig. 4 Scatter plot of T_a versus H

3.5 Relative humidity (*RH*)

Once all the parameters such as specific humidity (Q), air pressure (P_a), air temperature (T_a) were obtained, the relative humidity (RH) can be calculated using equations (1)–(3). Table 1 shows the comparison of relative humidity at 10 meteorological stations of Peninsular Malaysia in the clear sky at 11:00 A.M. on August 12, 2004. From Fig. 5, we can see the two relative humidity curves are close, the absolute errors are less than 4.8% and their mean absolute error is about 2.9%.

4 Validation

The relative humidity measured from meteorological stations at 11:00 A.M. at the same time of Terra overpass is used to compare with that from MODIS in the clear sky. These contrastive pairs of 30 days in August, 2004 have been analyzed and the scatter plot is got (Fig. 6). The mean absolute error between measured *RH* from meteorological data and estimated *RH* from MODIS is less then 5% and the correlation coefficient is 0.8219. It is feasible to measure the surface relative humidity using MODIS image based on the relationship between specific humidity (Q) and precipitable water vapor (PW).

5 Conclusion and Discussion

This paper used MODIS data to compute surface relative humidity based on the empirical expressions of the relationship between the precipitable water vapor and specific humidity. It presented a simple and feasible method to estimate relative humidity by remote sensing data and facilitated to get RH parameter for FWI values computation in forest fire management. Compared to interpolation methods, the surface relative humidity computed from MODIS data improved the spatial resolution and provided more precise and confident values for areas between meteorological stations.

It will be more effective to use MODIS data to retrieve surface relative humidity in the area where there is less

Table 1 Measured *RH* and estimated *RH* of meteorological stations

Station	Latitude (°N)	Longitude (°E)	Elevation (m)	Measured *RH* (%)	Estimated *RH* (%)	Error (%)
Kuala krai	5.533	102.200	68	77.6	82.3	4.71
Lubuk merbau	4.800	100.900	78	80.2	83.9	3.67
Cameron	4.467	101.367	1545	89.1	92.9	3.80
Muadzam shah	3.050	103.083	33	75.6	76.5	0.88
Klia sepang	2.733	101.700	16	76.1	74.1	–1.97
Temerloh	3.467	102.383	39	77.9	81.4	3.53
Kuantan	3.783	103.217	15	77.9	79.3	1.38
Batu pahat	1.867	102.983	6	81.7	86.3	4.64
Kluang	2.017	103.317	88	77.4	81.1	3.71
Senai	1.633	103.667	38	78.1	77.4	–0.66

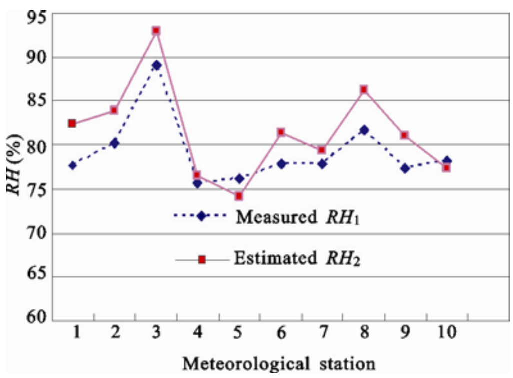

Fig. 5 Measured RH_1 and estimated RH_2

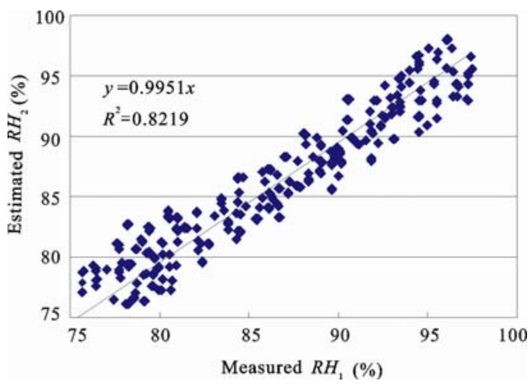

Fig. 6 Scatter plot of measured RH_1 versus estimated RH_2

cloud. MODIS MOD07 products supply precipitable water vapor, air temperature and air pressure data, and based on these data, relative humidity can be computed. Therefore MODIS can provide relative humidity as well as air temperature and increase the contribution of satellite data to the calculation of the FWI.

FWI values are calculated from air temperature, relative humidity, wind velocity, and precipitation. In future study, the relative humidity computed from this method and air temperature obtained from the combination of MODIS MOD07 product and meteorological data will be used to calculate FWI. The comparison will be carried out on the produced results.

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