APPLICATION OF MODIS AND LANDSAT BASED EVAPOTRANSPIRATION FOR WESTERN STATES WATER MANAGEMENT

Masahiro Tasumi[1]
Richard G. Allen[2]
Ricardo Trezza[3]
Anthony Morse[4]
William Kramber[5]

ABSTRACT

The METRIC evapotranspiration (ET) estimation model was applied using MODIS (Moderate Resolution Imaging Spectroradiometer) satellite images in New Mexico to evaluate the applicability of MODIS images to ET estimation and water resources management. With the coarse resolution of MODIS (approximately 1km thermal resolution), MODIS was not found to be suitable for field-scale applications. In project and regional scale applications, MODIS has potential to contribute to ET estimation and water resources management. MODIS based ET maps for New Mexico were compared with Landsat based results for 12 dates. Average ET calculations using MODIS and Landsat applications were similar, indicating that MODIS images can be useful as an ET estimation tool in project and regional scale applications.

INTRODUCTION

Quantifying the consumption of water over large areas and within irrigated projects is important for water rights management, water resources planning and water regulation. Traditionally, ET from agricultural fields has been estimated by multiplying the weather-based reference ET by crop coefficients (K_c) determined according to the crop type and the crop growth stage (Doorenbos and Pruitt, 1977; Wright, 1981; Allen et al., 1998; ASCE-EWRI, 2005). However, there are typically some questions regarding whether the crops grown compare

[1]Associate Professor, University of Miyazaki, 1-1, Gakuen Kibanadai-Nishi, Miyazaki-shi, Miyazaki 889-2192, JAPAN; tasumi@kimberly.uidaho.edu.
[2]Professor, University of Idaho, 3793N, 3600E, Kimberly ID 83341; rallen@kimberly.uidaho.edu.
[3]Visiting Associate Professor, University of Idaho, 3793N, 3600E, Kimberly ID 83341; rtrezza@kimberly.uidaho.edu.
[4]Geospatial Technology Section Manager, Idaho Department of Water Resources (IDWR), P.O.Box 83720, Boise, ID 83720-0098; tony.morse@idwr.idaho.gov.
[5]Senior Remote-Sensing Analyst, Idaho Department of Water Resources (IDWR), P.O.Box 83720, Boise, ID 83720-0098; bill.kramber@idwr.idaho.gov.

with the conditions represented by the K_c values, especially in water short areas. In addition, it is difficult to estimate the correct crop growth stage dates for large populations of crops and fields. Recent developments in satellite remote sensing ET models have enabled accurate estimates of ET and K_c for large populations of fields and water users and quantification of ground-water pumpage in areas where water extraction from underground is not measured.

METRIC (Mapping Evapotranspiration at high Resolution and with Internalized Calibration; Allen et al., 2007a) is an image processing model comprised of multiple submodels for calculating ET as a residual of the surface energy balance. METRIC is a variant of SEBAL, an energy balance process developed by Bastiaanssen and his associates (1995, 1998a,b, 2000, 2005). METRIC was extended for application to mountainous terrain and to provide tighter integration with ground-based reference ET. METRIC has been applied with Landsat images in southern Idaho, southern California and New Mexico to estimate monthly and seasonal ET for water rights accounting and for operation of ground water models (Allen et al., 2007b). ET "maps" (i.e., images) via METRIC provide the means to quantify the temporal and spatial distribution of ET on a field by field basis.

Thermal information is essential for surface energy balance models. However, the future of satellite-based, field-scale thermal measurements is not bright. The Landsat program may terminate thermal measurement in the future. The ASTER satellite system has limited image availability. Under these circumstances, MODIS may be the default system to use with ET mapping in the near future, even though the pixel resolution is much larger than for Landsat or ASTER. This paper describes an application of MODIS and Landsat images with METRIC ET mapping model in New Mexico.

METRIC MODEL

In METRIC, ET is determined from satellite imagery by applying an energy balance at the surface, where energy consumed by the ET process is calculated as a residual of the surface energy balance equation:

$$LE = R_n - G - H \quad (1)$$

where LE is the latent energy consumed by ET, R_n is net radiation, G is sensible heat flux conducted into the ground, and H is sensible heat flux to the air.

R_n is computed by subtracting all outgoing radiant fluxes from all incoming radiant fluxes, including solar and thermal radiation:

$$R_n = R_{S\downarrow} - \alpha R_{S\downarrow} + R_{L\downarrow} - R_{L\uparrow} - (1-\tau_o)R_{L\downarrow} \quad (2)$$

where $R_{S\downarrow}$ is incoming shortwave radiation, α is surface albedo, $R_{L\downarrow}$ is incoming longwave radiation, $R_{L\uparrow}$ is outgoing longwave radiation, and τ_o is broad-band surface thermal emissivity.

Incoming shortwave radiation is calculated by analyzing the solar position and intensity of radiation (Allen et al., 2006). Surface albedo is calculated by integrating reflectivities from bands 1 – 5 and 7 of Landsat, or bands 1 – 7 of MODIS, and applying an operational atmospheric correction (Tasumi et al., 2007). Incoming longwave radiation is estimated using regionally calibrated equations, and outgoing longwave radiation is calculated by surface temperature (T_S) and emissivity.

In METRIC, soil heat flux is estimated as a function of R_n, T_S and a vegetation index. Sensible heat flux is estimated by analyzing the air-temperature gradient (dT) and aerodynamic resistance between two near surface heights (0.1 and 2 m above zero plane displacement), assuming dT varies linearly with radiometric T_S, and by taking two extreme "calibration pixels" from very dry and very wet agricultural surfaces (Allen et al., 2007a).

METRIC model has been tested with lysimeters (Tasumi et al., 2005) and applied in the western United States (Morse et al., 2000, 2001; Allen et al., 2005, 2007b). The calculated ET maps have been used for a number of purposes including water rights management, ground water pumpage monitoring, irrigation performance computation, developing regional crop coefficients, input to regional ground water models and for water rights transfer.

LANDSAT AND MODIS IMAGES

Landsat has been one of the primary operational earth observation satellites over the past three decades. With long-term historical image records and high spatial resolution of 30 m in the short wave bands and 60 to 120 m in the thermal band, Landsat images have been widely used for both research and non-research purposes. Landsat images provide ideal data for estimating ET from field scale to project/regional scale applications in arid and semi-arid regions.

MODIS, on board the Terra and Aqua satellites, has provided satellite images since 1998. Because MODIS produces highly automated, low cost images having more frequent coverage than Landsat, MODIS images have become widely used for earth observation at the moderate spatial resolution of 250 to 1000 meters. MODIS has several official "higher-level" image products, such as surface temperature, Leaf Area Index (LAI), and albedo (King et al., 2004; Wan, Z. 1999; Knyazikhin et al., 1999; Vermote and Vermeulen, 1999). These higher-level products are useful in some applications.

While some advantages are available, MODIS's two major disadvantages in ET mapping are the low spatial resolution and the difficulty of image quality controls. MODIS image resolution is 250m in the green and NIR bands, 500m for the five other visible and NIR bands, and 1000m for thermal. However, these resolutions are when the satellite view angle is near nadir. Although MOIDIS is purported to be a 'daily' satellite, near nadir images are available only each 3 to 5 days. The resolution degrades as the sensor view angle increases. Field-scale applications are not possible with the resolution of MODIS. Also, MODIS images do not have a convenient method to preview the data upon image order. In MODIS, a near-nadir cloud-free image is difficult to find since it is often blended into several other "lower quality" images (images having clouds and/or a larger sensor view angles). Also, MODIS images are not always in a usable condition due to hardware/software malfunctioning, and a careful evaluation by the user is required for a quality application. Table 1 briefly summarizes characteristics of MODIS and Landsat images for ET mapping.

Table 1. Characteristics of Landsat and MODIS Satellite Images

Satellite	Landsat 5	MODIS (Terra)
Resolution	30m/120m (shortwave/thermal)	250m-500m/1000m (shortwave/thermal)
Frequency	1image/16days	1 images/1day (2-4 near nadir images/16days)
Field scale application	Usable	Not usable
Regional scale application	Usable	Usable
Higher-level products	Not available	Available
Image previews	Available	Not available
Image quality control	Easy	Difficult

APPLICATION RESULTS AND DISCUSSIONS

In previous studies (Allen et al., 2007b), ET was calculated using Landsat in the western states of Idaho, Utah, California and New Mexico. In this study, 12 MODIS images were selected for application to the Middle Rio Grande region of New Mexico. All selected images were from MODIS Terra, and were near-nadir cloud-free images, and the image dates were chosen to match Landsat images processed during previous studies. Selected MODIS images were then processed and compared with the results of Landsat-based applications.

The largest technical difficulty in applying the METRIC model with MODIS images was the selection of calibration points. In general Landsat applications, the operator selects two extreme "calibration pixels" representing dry and wet agricultural surfaces. The energy balance is internally calibrated based on these calibration pixels by applying information contained in a reference ET calculation (based on the ASCE Penman-Monteith (ASCE-EWRI 2005)) and a FAO-56-based soil water balance-evaporation model (Allen et al., 1998). The

thermal resolution of MODIS is 1km, thus, calibration targets should ideally have at least 2km by 2km extent to insure containment of the pixel in the target area. Unfortunately, uniform dry and wet agricultural surfaces of this size are rarely available. In the MODIS application, dry pixels were found from surrounding desert areas, and relative ET for wet pixels was determined from an NDVI-based relationship that was previously established using Landsat-based ET.

Figure 1 shows Landsat (30-120m) and MODIS (500-1000km) based ET maps from a test run in Idaho during July 2003. The snapshot clearly demonstrates that MODIS based energy balance is not applicable for field-scale, while Landsat is applicable atr field-scale where agricultural field sizes are typically large (400m by 400m or more). The loss of clarity in MODIS images is quite apparent.

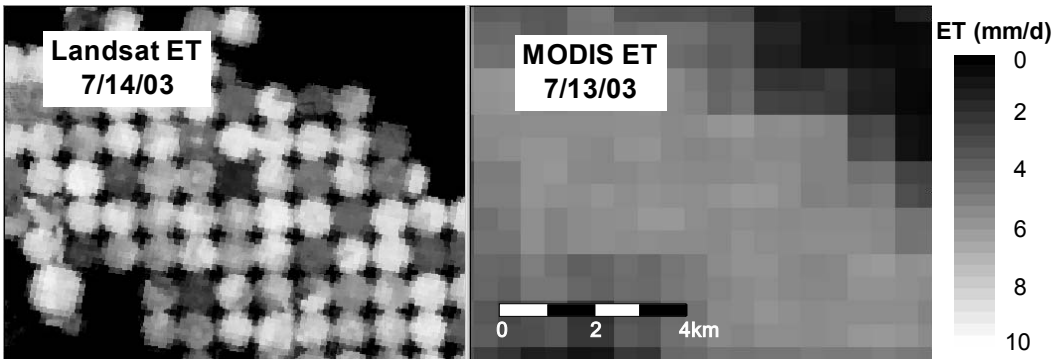

Figure 1. METRIC 24-hour ET by Landsat and by MODIS, for the Same Center-Pivot Irrigated Agricultural Area in Southern Idaho (42°23' 114°00')

MODIS ET estimation results were compared with Landsat results in the Middle Rio Grande area of New Mexico, as averages over an extended region and by vegetation group. ET values were compared in terms of alfalfa-referenced crop coefficient (K_c). The result of the comparison is shown in Figure 2 and the summary of the comparison is provided in Table 2. Both the Landsat and MODIS image resolutions were degraded to 2km, in order to avoid any impact of resolution difference on the comparison.

Based on the averages over 12 images, Landsat and MODIS applications calculated similar ET, with an absolute difference in K_c of 0.004. If limited to areas having NDVI 0.5 or higher (NDVI is a vegetation index computed from MODIS bands 1 and 2), the MODIS application slightly underestimated Landsat-based ET on most image dates, possibly because of the unsuccessful internal calibration for the "wet" condition. Results from both satellite applications were similar (0.003 K_c difference) for low vegetated pixels having NDVI 0.2 or lower. Standard deviation of differences between Landsat and MODIS results was about 0.04 in terms of K_c, which indicates that estimation differences for each individual image date were not large. However, discussing

estimation accuracy of MODIS application by Landsat for "satellite image dates" is difficult because METRIC applications with Landsat are expected to achieve less than 5 percent error in seasonal ET but may have large error in estimated ET for single dates (Tasumi et al., 2005). The general agreement between Landsat and MODIS indicates that MODIS images have potential for estimating regional ET.

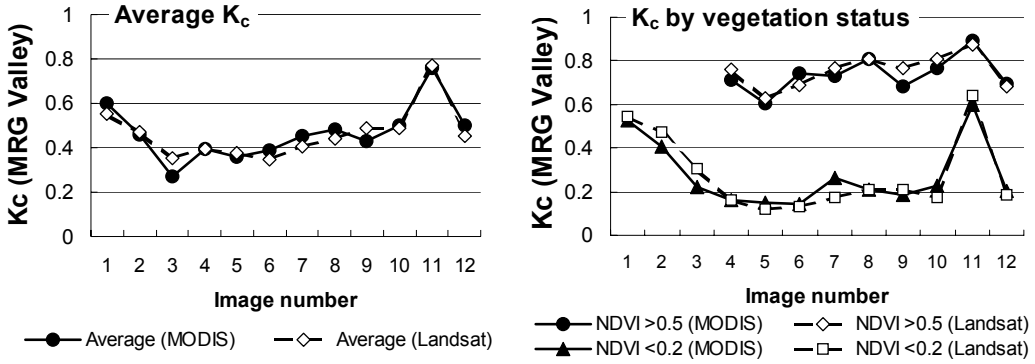

Figure 2. Crop Coefficient (K_c) Estimated by Landsat and MODIS Satellites Averaged over Large Areas of the Middle Rio Grande for 12 images in 2002

Table 2. Comparison of Calculated K_c between Landsat and MODIS.

Image #	Date	MRG valley whole area			MRG valley NDVI >= 0.5			MRG valley NDVI <= 0.2		
		MODIS	Landsat	Difference	MODIS	Landsat	Difference	MODIS	Landsat	Difference
1	1/ 14/ 02	0.598	0.555	0.043	-	-	-	0.528	0.543	- 0.015
2	3/ 3/ 02	0.460	0.470	- 0.009	-	-	-	0.409	0.471	- 0.061
3	4/ 4/ 02	0.272	0.351	- 0.079	-	-	-	0.220	0.305	- 0.085
4	5/ 6/ 02	0.393	0.391	0.001	0.712	0.759	- 0.047	0.162	0.162	0.000
5	5/ 22/ 02	0.357	0.375	- 0.018	0.603	0.627	- 0.023	0.147	0.120	0.027
6	6/ 7/ 02	0.388	0.349	0.038	0.740	0.686	0.054	0.142	0.133	0.010
7	6/ 15/ 02(L) 6/ 16/ 02(M)	0.452	0.407	0.046	0.729	0.767	- 0.039	0.262	0.174	0.088
8	7/ 25/ 02	0.480	0.440	0.040	0.808	0.808	0.000	0.211	0.208	0.003
9	8/ 10/ 02	0.428	0.485	- 0.057	0.685	0.764	- 0.079	0.187	0.211	- 0.024
10	8/ 26/ 02	0.499	0.487	0.012	0.767	0.808	- 0.041	0.225	0.176	0.049
11	9/ 20/ 02	0.757	0.768	- 0.011	0.895	0.876	0.019	0.600	0.643	- 0.044
12	11/ 6/ 02 (L) 11/ 7/ 02 (M)	0.499	0.451	0.049	0.695	0.685	0.010	0.203	0.187	0.016
Average	-	0.465	0.461	0.004	0.737	0.753	- 0.016	0.275	0.278	- 0.003
Standard Error	-	-	-	0.042	-	-	0.041	-	-	0.048

SUMMARY AND CONCLUSIONS

In this study, the METRIC ET estimation model was applied with MODIS imagery in New Mexico to evaluate its potential to be applied for ET estimation and water resources management. With the coarse resolution of MODIS (~ 1km thermal resolution), MODIS was found to be unsuitable for field-scale applications, unless some thermal pixel sharpening technique is developed. In project and regional scale applications, MODIS has good potential for ET estimation and water resources management.

MODIS based ET maps were compared with Landsat based results for 12 dates in New Mexico. Average ET between MODIS and Landsat applications were similar (0.004 difference of average Kc), which indicates that MODIS imagery, combined with METRIC, are useful as an ET estimation tool. Future study is required to improve calibration strategies for the energy balance with MODIS imagery.

REFERENCES

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. UN FAO, Irrig. Drain. Pap. 56. Rome, Italy. 300p.

Allen, R.G., Tasumi, M., Morse, A., and Trezza, R. 2005. A Landsat-based Energy Balance and Evapotranspiration Model in Western US Water Rights Regulation and Planning. J. Irrigation and Drainage Systems. 19:251-268.

Allen, R.G., Trezza, R., and Tasumi, M. 2006. Analytical integrated functions for daily solar radiation on slopes for use in energy balance and evapotranspiration studies. Agricultural and Forest Meteorology (accepted).

Allen, R.G., Tasumi, M., Trezza, R., 2007a. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC) – Model. J. Irrig. and Drain. Engineering, ASCE, (accepted).

Allen, R.G., Tasumi, M., Morse, A., Trezza, R., Kramber, W., Lorite, I., 2007b. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC) – Applications. J. Irrig. and Drain. Engineering, ASCE, (accepted).

ASCE – EWRI. 2005. The ASCE standardized reference evapotranspiration equation. Environmental and Water Resources Institute of the ASCE Standardization of Reference Evapotranspiration Task Committee. American Society of Civil Engineers, Reston, Virginia. 216p.

Bastiaanssen,W.G.M., 1995. Regionalization of surface flux densities and moisture indicators in composite terrain. Ph.D. Thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

Bastiaanssen,W.G.M., M.Menenti, R.A.Feddes, and A.A.M.Holtslag, 1998a. A remote sensing surface energy balance algorithm for land (SEBAL): 1. Formulation. J. of Hydr. 212-213:198-212.

Bastiaanssen,W.G.M., H.Pelgrum, J.Wang, Y.Ma, J.Moreno, G.J.Roerink and T. van der Wal, 1998b. The Surface Energy Balance Algorithm for Land (SEBAL): Part 2 validation. J. of Hydr. 212-213:213-229.

Bastiaanseen,W.G.M., 2000. SEBAL-based sensible and latent heat fluxes in the irrigated Gediz Basin, Turkey. J. of Hydr. 229:87-100.

Bastiaanssen, W. G. M., Noordman, E. J. M., Pelgrum, H., Davids, G. Thoreson, B. P., Allen, R. G., 2005. SEBAL model with remotely sensed data to improve water-resources management under actual field conditions. Journal of Irrigation and Drainage Engineering, ASCE, 131(1):85-93.

Doorenbos, J. Pruitt, W.O., 1977. Guidelines for predicting crop water requirements. Irrigation and Drainage Paper 24, Food and Agricultural Organization of the United Nations, Rome, 179p.

King, M. D., Closs, J., Wharton, S., & Myers, M. (Ed.) (2004). EOS Data Products Handbook Volume 1 (Revised 2004). EOS Project Science Office, NASA Goddard Space Flight Center, Greenbelt, MD.

Knyazikhin, Y., Glassy, J., Privette, J. L., Tian, Y., Lotsch, A., Zhang, Y., Wang, Y., Morisette, J. T., Votava, P., Myneni, R. B., Nemani, R. R., and Running, S. W. 1999. MODIS Leaf Area Index (LAI) and Fraction of Photosynthetically Active Radiation Absorbed by Vegetation (FPAR) Product (MOD15) Algorithm Theoretical Basis Document. http://eospso.gsfc.nasa.gov/atbd/modistables.html

Morse,A., M.Tasumi, R.G.Allen and W.J.Kramber, 2000. Application of the SEBAL Methodology for Estimating Consumptive Use of Water and Streamflow Depletion in the Bear River Basin of Idaho through Remote Sensing: Final Report. Idaho Department of Water Resources, ID.

Morse,A., R.G.Allen, M.Tasumi, W.J.Kramber, R.Trezza and J.L.Wright, 2001. Application of the SEBAL Methodology for Estimating Evapotranspiration and Consumptive Use of Water Through Remote Sensing: Final Report. Idaho Department of Water Resources, ID.

Tasumi, M., Trezza, R., Allen, R. G.., and Wright, J. L. (2005). “Operational aspects of satellite-based energy balance models for irrigated crops in the semi-arid U.S.” J. Irrigation and Drainage Systems. 19:355-376.

Tasumi, M., Allen, R.G., and Trezza, R., 2007. At-surface reflectance and albedo from satellite for operational calculation of land surface energy balance. J. Hydrol. Engr. ASCE. (submitted)

Vermote, E. F., and Vermeulen, A. (1999). “Atmospheric correction algorithm: spectral reflectances (MOD09).” MODIS Algorithm Theoretical Background Document, 107p. Document available on line at http://modis.gsfc.nasa.gov/data/atbd/atbd_mod08.pdf.

Wan, Z. 1999. MODIS Land-Surface Temperature Algorithm Theoretical Basis Document (LST ATBD) Version 3.3. Institute for Computational Earth System Science, University of California, Santa Barbara, CA.

Wright, J. L. 1981. Crop coefficients for estimates of daily crop evapotranspiration. Irrigation scheduling for water and energy conservation in the 80s, ASAE, Dec. St. Joseph, Mich.