SPATIO-TEMPORAL DYNAMICS OF SURFACE WETNESS CONDITIONS USING REMOTE SENSING DATA

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ABSTRACT:

Soil moisture is an important eco-hydrological variable that influences crop/forest productivity, drought, forest fire and insect outbreak among others. In this paper, our objective is to predict spatio-temporal dynamics over northern portion of the Canadian Province of Alberta. We implemented a remote sensing-based method, such as, temperature vegetation wetness index [TVWI: a function of potential surface temperature and normalized difference vegetation index (NDVI)] during the months of May-September in 2006. We used MODIS-based surface reflectance to calculate NDVI at 250 m and also surface temperature at 1 km in the formulation of TVWI. Our analysis revealed that a deviation between TVWI and ground-based measurements of volumetric soil moisture was within ±20% for significant amount of times (i.e., 75-85%).

1. INTRODUCTION

Soil moisture (SM) is an important eco-hydrological variable that influences crop/forest productivity, drought, forest fire and insect outbreak among others. A number of indirect methods (e.g., neutron scattering, time domain reflectometry, and frequency domain reflectormetry, among others) are traditionally used to measure SM. These methods are, in general, capable of producing accurate measurements. As these methods produce point type measurements, we need to employ other methods to address spatial variability. In this context, remote sensing-based methods can be effective in predicting both of the spatial and temporal dynamics of the SM (e.g., Hassan et al., 2007; Patel et al., 2009).

One of the most commonly used remote sensing-based methods is the integration of vegetation index [e.g., normalized difference vegetation index (NDVI)] and surface temperature (T_S) (Nemani and Running, 1989; Moran et al., 1994; Lambin and Ehrlich, 1996; Li et al., 2008; Tang et al., 2009; Petropoulos et al., 2010) in predicting surface moisture to infer SM. However, Carlson (2007) noted that this approach was not applicable over topographically variable terrain. To address this particular limitation, Hassan et al. (2007) proposed a modification in T_S to convert into potential surface temperature (θ_S) and then combined with NDVI. This method is termed as temperature vegetation wetness index (TVWI). In this paper, our objective is to: (i) implement the TVWI method to delineate surface wetness conditions in the topographically-variable Canadian Province of Alberta; and (ii) assess its' ability to capture ground-based measurements of SM.

2. METHODS

2.1 Study Area and Data Requirements

Figure 1 shows the extent of our study area, which is the northern portion of Alberta. This area is having a variable topography. Climatically, Alberta experiences temperature variations from -8°C in the south to -24°C in the north during January; and from 20°C in the south to 16°C in the north in July (Government of Alberta; http://alberta.ca/home/90.cfm, last visited April. 2010).

In this study, we used 8-day composite of surface reflectance for red (620–670 nm) and near infrared (NIR: 841–876 nm) spectral bands at 250 m spatial resolution and T_S images at 1 km spatial resolution during May-September period in 2006. These data were acquired by MODIS sensor of Terra satellite and freely available from NASA. Table 1 shows the epochs over which each of the 8-day averages data were collected. We also collected digital elevation model (DEM) at 250-m resolution generated from 3-arc second resolution height point-data from NASA Shuttle Radar Topography Mission archive. This DEM was used to eliminate the topographic influence on T_S. In order to establish relations between TVWI and SM, we acquired ground-based volumetric soil moisture (VSM) of 100 cm depth at 14 stations during the same period of satellite data (see Figure 1 for the location information). The ground-based SM measurements were acquired using Theta Probe type ML2x and made available to us by the Agriculture and Agri Food Canada.).

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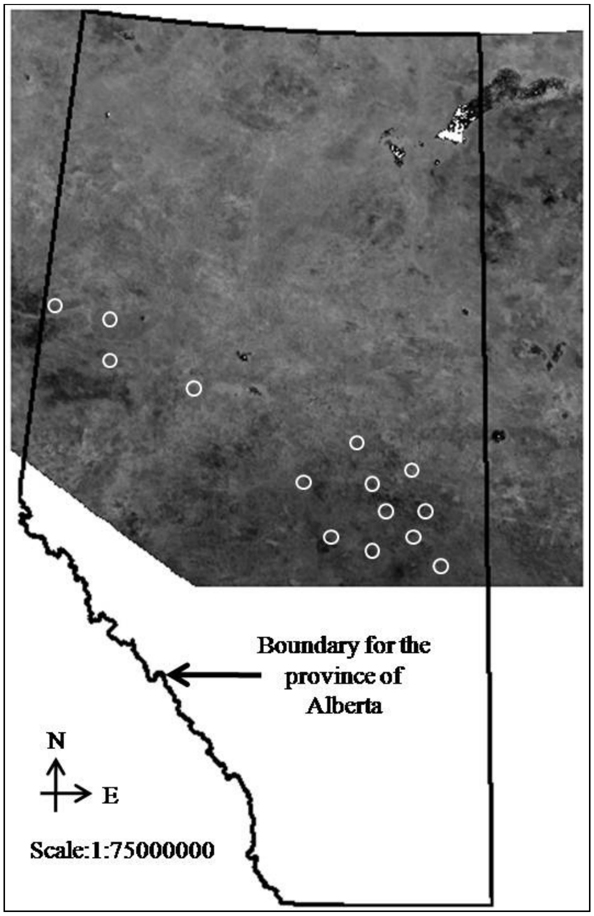

Figure 1: The extent of the study area with the gray satellite image in the background along with the boundary of the Province of Alberta. The white hollow circles are representing the locations where the ground-based soil moisture data were acquired.

2.2 Mathematical Models

We calculated NDVI as a function of red and NIR reflectance using the following equation:

$$NDVI = \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + \rho_{red}} \quad (1)$$

Where ρ = Surface reflectance values for the red and NIR bands.

The conversion of T_S into θ_S was performed in two steps [Hassan et al., 2007]: (i) atmospheric pressure at each pixel was calculated as a function of elevation; and (ii) θ_S then was calculated as a function of atmospheric pressure. The expressions are as follows:

$$p = 101.3\left[\frac{293 - 0.0065z}{293}\right]^{5.26} \quad (2)$$

$$\theta_s = T_s\left[\frac{p_o}{p}\right]^{R/C_p} \quad (3)$$

Where p (in kPa) = atmospheric pressure,
z (in m)= elevation,
T_S= surface temperature (in K),
p_o= average pressure at mean sea level (101.3 kPa),
R= gas constant (287 J kg-1 K-1),
c_p=specific heat capacity of air (~1004 J kg-1 K-1)
θ_S (in K)=Surface potential temperature

Epoch No.	Day of Year	Dates in 2006
1	121-128	01 May-08 May
2	129-136	09 May-16 May
3	137-144	17 May-24 May
4	145-152	25 May-01 Jun.
5	153-160	02 Jun-09 Jun
6	161-168	10 Jun-17 Jun.
7	169-176	18 Jun-25 Jun.
8	177-184	26 Jun-03 Jul
9	185-192	04 Jul-11 Jul
10	193-200	12 Jul-19 Jul
11	201-208	20 Jul-27 Jul.
12	209-216	28 Jul-04 Aug.
13	217-224	05 Aug-12 Aug
14	225-232	13 Aug-20 Aug.
15	233-240	21 Aug-28 Aug.
16	241-248	29 Aug.-05 Sep.
17	249-256	06 Sep-13 Sep.
18	257-264	14 Sep- 21 Sep.
19	265-272	22 Sep.- 29 Sep.
20	273-280	30 Sep.- 07 Oct.

Table 1: Description of time period when the MODIS-based data were acquired.

We then generated the scatter plots of θ_S-NDVI for each of the epoch as described in Table 1. In general, we observed trapezoidal shapes as shown in Figure 2. In Figure 2, the dry edge (θ_{dry}) would be the edge where θ_S would be highest in relation to NDVI; and reflect the unavailability of water for supporting evapotranspiration (i.e., TVWI=0). The wet edge (θwet), on the other hand, would be the edge where θ_S would be lowest in relation to NDVI; and reflect the unrestricted amount of water for supporting evapotranspiration (i.e., TVWI=1). Mathematically, TVWI was calculated as follows:

$$TVWI = \frac{\theta_{dry} - \theta_s}{\theta_{dry} - \theta_{wet}} \quad (4)$$

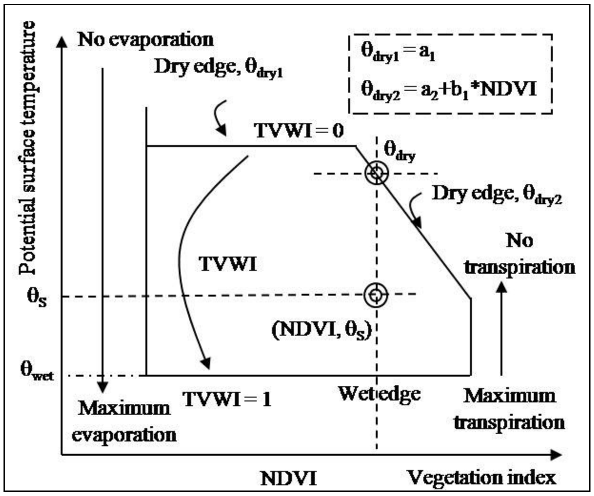

Figure 2: Schematic diagram illustrating the calculations of TVWI as a function of θ_S and NDVI (after Hassan et al., 2007).

2.3 Comparison between TVWI and SM Data

In this study, we generated 20 TVWI maps during 2006. Using these maps, we extracted temporal dynamics of TVWI at all of the 14 ground stations (see Figure 3 for locations). Then, we calculated an average TVWI values for each of the epoch. In a similar way, we averaged the ground-based measurement of VSM for the epoch of interest. Finally, we compared VSM values with the TVWI values in terms of deviations [i.e., (VSM-TVWI)*100/VSM].

3. RESULTS AND DISCUSSION

Figure 3 shows an example scatter plot between θ_S-NDVI for the epoch 5 (i.e., DOY in between 153-160). In this study, we considered a constant value of θ_{wet} (=275 K) like Hassan et al. (2007). Additionally, Table 2 shows the values of θ_{dry1}, θ_{dry2} (i.e., both the slope and intercept) for each of epoch.

Figure 4 shows the comparison between ground-based measurements of VSM and TVWI. It revealed that the deviation was within ±20% for 75% of the times (see Figure 4a). The ±20% deviation was acceptable in comparing environmental variables because of given variability within the natural systems (Hassan et al., 2010). Our analysis also revealed that one of the ground station data (i.e., Atmore) was causing relatively large deviation. Upon excluding this station, we observed that the deviation was within ±20% for 85% of the times (see Figure 4b).

We generated an average TVWI Map for the months May-September in 2006 (see Figure 5). Figure 5 also shows the relative frequency of the TVWI-values. It revealed that approximately 99.27% of the times TVWI-values fell within the range between 0.2-0.6. We observed that the TVWI had an increasing trend in the northward direction.

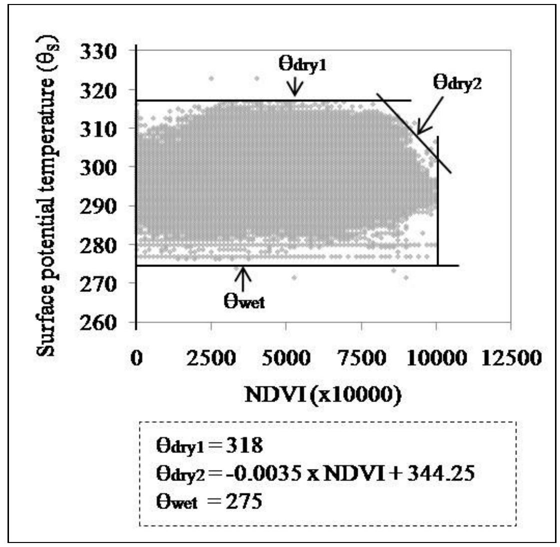

Figure 3: Example of scatter plot of θ_S vs. NDVI and the corresponding dry and wet edges during the epoch 5.

Epoch	θ_{dry1}	θ_{dry2}	
		Slope	Intercept
1	314.0	-0.0045	339.25
2	320.0	-0.0025	332.97
3	320.0	-0.0065	367.61
4	316.5	-0.0027	335.79
5	318.0	-0.0035	344.25
6	317.0	-0.0050	356.50
7	318.0	-0.0056	361.88
8	321.0	-0.0072	381.67
9	326.0	-0.0067	382.00
10	315.5	-0.0028	336.22
11	323.0	-0.0048	360.74
12	319.5	-0.0045	351.36
13	313.0	-0.0053	354.29
14	313.0	-0.0031	335.61
15	317.5	-0.0039	346.02
16	317.0	-0.0043	349.14
17	317.0	-0.0048	353.00
18	302.0	-0.0022	316.88
19	305.5	-0.0039	334.67
20	301.0	-0.0030	322.63

Table 2: Values of dryline1 (θ_{dry1}) and slope and intercept of the dryline2 (θ_{dry2}) over the study period.

4. CONCLUSION

In this paper, we demonstrated a remote sensing-based method to delineate spatio-temporal variability of surface wetness condition using TVWI. Our preliminary analysis revealed that TVWI would be effective in capturing SM. Thus, we need to analyse more data in order to enhance our confidence in using TVWI to predict SM.

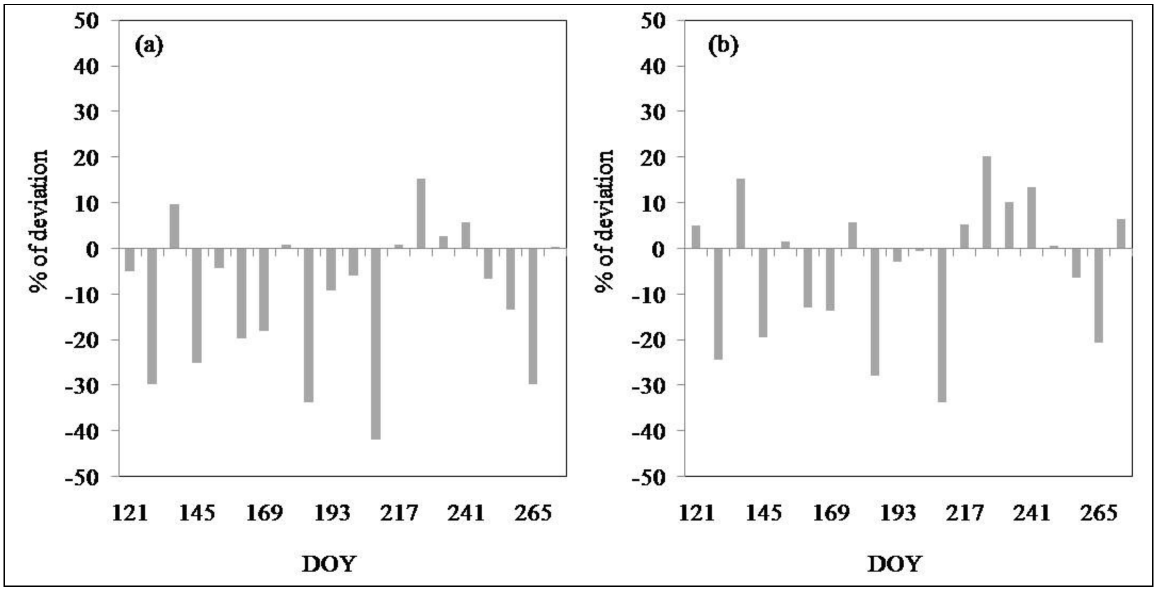

Figure 4: The deviation between the averaged ground-based measurements of VSM and TVWI at (a) 14 stations; (b) 13 stations. At each of the epoch, the average values of VSM and TVWI at all of the stations were compared.

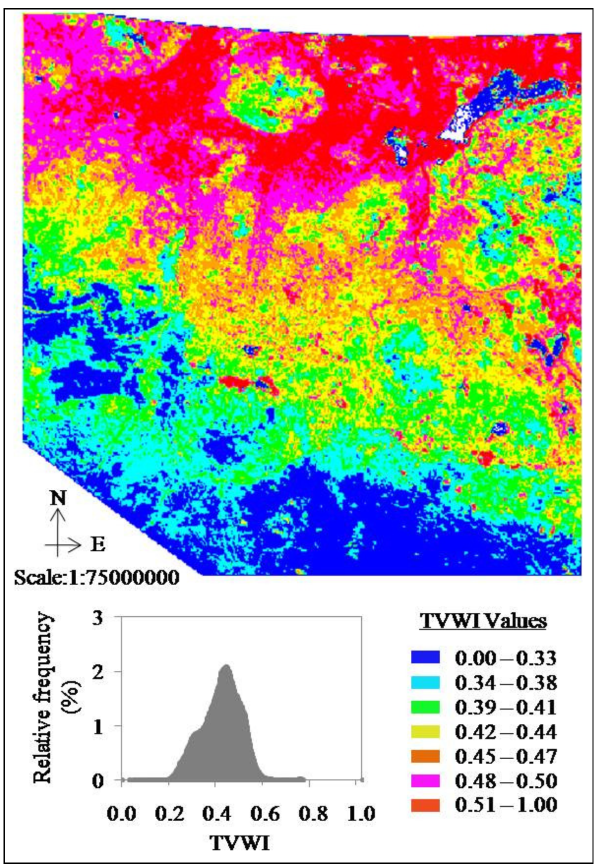

Figure 5: Spatial dynamics of averaged TVWI and its relative frequency distribution.

References

Carlson, T,, 2007. An overview of the "triangle method" for estimating surface evapotranspiration and soil moisture from satellite imagery. *Sensors,* 7, pp. 1612–1629.

Hassan, Q.K.; Bourque, C.P.-A; Meng, F.-R.; and Cox, R.M, 2007a. A wetness index using terrain-corrected surface temperature and normalized difference vegetation index derived from standard MODIS products: an evaluation of its use in a humid forest-dominated region of eastern Canada. *Sensors,* 7, pp. 2028–2048.

Hassan, Q.K.; and Bourque, C.P.-A; Meng., 2010. Spatial enhancement of MODIS-based images of leaf area index: application to the boreal forest region of northern Alberta, Canada. *Remote Sens,* 2, pp. 278-289.

Lambin, E.F.; Ehrlich, D, 1996. The surface temperature - vegetation index space for land cover and land-cover change analysis. *Int. J. Remote Sens,* 17, pp.463–487.

Li, Z.; Wang, Y.; Zhoub, Q.; Wu, J.; Peng, J.; Chang, H., 2008. Spatiotemporal variability of land surface moisture based on vegetation and temperature characteristics in northern Shaanxi Loess Plateau, China. *J. Arid Environ.,* 72, pp. 974–985.

Moran, M.S.; Peters-Lidard, C.D.; Watts, J.M.; and McElroy, J., 2004. Estimating soil moisture at the watershed scale with satellite-based radar and land surface models. *Can. J. Remote Sens.*, 30, pp. 805–826.

Nemani, R.; Running, S. 1989. Estimation of regional surface resistance to evapotranspiration from NDVI and thermal-IR AVHRR data. *J. Appl. Meteor.,* 28, pp. 276-284.

Patel, N. R.; Anapashsha, R.; Kumar, S.; Saha, S.K; Dadhwal, V.K., 2009. Assessing potential of MODIS derived temperature/vegetation condition index (TVDI) to infer soil moisture status. *Int. J. Remote Sen.,*, 30, pp. 23–39.

Petropoulos, G.; Carlson, T.N.; Wooster, M.J. and Islam, S., 2009. A review of Ts/VI remote sensing based methods for the retrieval of land surface energy fluxes and soil surface moisture. *Prog. Phys. Geography,* 33(2), pp. 224–250.

Tang, R.; Li, Z. L.; Tang, B., 2010. An application of the Ts–VI triangle method with enhanced edges determination for evapotranspiration estimation from MODIS data in arid and semi-arid regions: Implementation and validation. *Remote Sens. Environ.,* 114, pp. 540–551.

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