Wetland Surface Temperature Estimation using EOS/MODIS Data

Agarwal, R. [1] **and Garg, J. K.,** [2]
University School of Environment Management, GGS IP University, Kashmere Gate, Delhi- 110404, India
Phone: +91-9313583845, E-mail: stat_reshu@yahoo.com[1], jkgarg@indiatimes.com[2]

Abstract
Moderate Resolution Imaging Spectroradiometer (MODIS) has established its usefulness in various global change studies due to its spectral and temporal resolution in various regions of electromagnetic spectrum. Its utility is not only restricted to land surface studies, but also to various hydrological, ecological and environmental investigations at regional/continental level. To support these studies, a range of MODIS data products are also available freely. One of the key factors of choosing MODIS data for global environmental studies is to gather data in the thermal region of electromagnetic spectrum. Thermal characteristics in the form of surface temperature of the targeted areas have proven their significance in observing the trend in land use, surface water etc. The paper describes a methodology to estimate the Wetland Surface Temperature (WST) using thermal bands of MODIS sensor onboard the Terra satellite. This technique introduces a factor incorporating the emitting characteristics of wetland surfaces in two thermal bands (10.78µm – 11.28µm and 11.77µm – 12.27µm). A study has also been carried out to compare the temperature derived from the proposed method with the temperature derived from constant emissivity method, conditional constant emissivity method and temperature of MODIS LST product. It has been found that for wet surfaces, our proposed method provides the temperature within ±2°C range of MODIS LST products.

1. Introduction

Surface temperature is an important phenomenon to determine the exchange of energy and matter between the earth's surface and atmosphere. It is a useful input for modeling energy balance components and is required for a wide variety of climate, hydrologic, ecological and biogeochemical studies. Since the earth's surface and atmosphere radiate thermal energy outward owing to heating by solar irradiation and by internal heat flow, sensors that measures this emitted radiation in parts of the thermal region of the spectrum can produce very informative data especially as images provide both distinctive signatures and indications of properties of materials that are diagnostic. Surface temperature using remotely sensed data have been estimated for various sensors using different algorithms. Singh (1988) derived a simple and accurate relations for converting Landsat-4 and Landsat-5 Thematic Mapper (TM) band 6 data into brightness temperature, which include the estimation of radiance for each digital number DN and calculation of temperature. This problem is a non-linear one and hence linear approximation need to be cautiously evaluated. In this method, numerical modeling of atmospheric radiative transfer has been done and the results are used to develop statistical inverse models for temperature estimation. It has been suggested that atmospheric and emissivity corrections are essential for accurate estimates of surface temperatures of different surfaces (Wan and Dozier, 1989).

1.1 Available Techniques for Surface Temperature Estimation

Once the atmospheric corrections are applied, solution of spectral emittance and temperature is needed. Since remotely sensed infrared radiance emitted by a surface is a function of its kinetic temperature and spectral emissivity with a nonlinear relationship, assumptions are usually made about the emissivity of earth's surface materials to allow their temperatures to be determined (Salisbury and Aria, 1992). The solution of the above relation is undetermined because for a single multispectral measurement there is always one more unknown than number of equations (1 temperature per channel + emissivity). There are several methods to solve such set of equations. A technique has been developed by (Kahle et al., 1980) in which a constant emissivity (say 0.95) has been assumed for all the features in one channel, and using Planck's law temperature has been estimated in other thermal channels. Later this method has been used for estimating temperature and thermal inertia derived from Thermal Infrared Multispectral Scanner (TIMS) data for Death Valley, California (Kahle, 1987). Kahle et al., (1992) have separated the temperature and emittance in remotely sensed radiance measurements by using constant emissivity method along with the downward and upward spectral radiance of the sensor. For any real material, the emitted radiance is given by:

$$L(\lambda(T) = \varepsilon_\lambda L_{bb}(\lambda\lambda T)$$

Equation 1

Where $L_{bb}(\lambda\lambda T)$ is black body radiance. But the radiated energy and the received energy by the sensor is different due to atmospheric attenuation and scattering. Resultantly, the modified radiance $L_s(\lambda\lambda T)$ is:

$$L_s(\lambda\lambda T) = \left[\varepsilon_\lambda L_{bb}(\lambda\lambda T) + (1-\varepsilon_\lambda)L_{A\downarrow}(\lambda\lambda\right]\tau_{A\lambda} + L_{A\uparrow}(\lambda\lambda$$

Equation 2

Where $L_{A\downarrow}(\lambda\lambda$ is the downward spectral radiance, $L_{A\downarrow}(\lambda\lambda$ is the upward spectral radiance from the atmosphere that reaches to the sensor and $\tau_{A\lambda}$ is the spectral atmospheric tranmissivity. By assuming constant emissivity in one channel (say 0.95) and using this value with the other parameters equation (2) can be solved for temperature. These temperatures can be used again to solve the equation (2) for emittance. Spectral ratio method and two temperatures method for measuring emissivity have been developed by (Watson, 1992a and Watson, 1992b). First one is based on the concept that although the spectral radiances are very sensitive to small changes in temperature the ratios are not; while the later one assumes that emissivity are temporal invariant. Spectral ratio method computes the spectral ratios of adjacent channels by estimating radiance ratios and is given as:

$$S_{i+1}/S_i = \{E_{i+1}/E_i\}\{H_{i+1}(T)/H_i(t)\} \;;\; i = 1, N-1$$

Equation 3

Where S_i is the radiance in i^{th} channel, E_i's are constants and $H_i(T)$ are the functions of blackbody radiances. From equation (3) $H_i(T)$ ratio has been computed by estimating the temperature. Subsequently, sensitivity ratio has been determined using Taylor's series expansion. This method provides greater precision in the emissivity ratio than in emissivity itself. Also, spectral emissivity can be determined from radiance measurements if the object can be observed at two different temperatures. Two temperatures method is based on this theory and assumes that emissivity is a temporal invariant. Here also, spectral ratio has been calculated like the previous method for two temperatures rather than the one temperature value. This method is valid for rocks and dry soil, but not well established for vegetation. It is also not true when changes in soil moisture occur between the measurements. Li et al., (1990) evaluated six methods to extract relative emissivity spectra from thermal infrared images. Becker and Li (1990) used Temperature independent spectral indices (TISI) method which is based on the power law approximation of the Planck's function whereas Reference Channel Method (REF) given by (Kahle et al., 1980) assumes the constant value of the emissivity for all pixels and then approximate surface temperature can be derived for each pixel, Emissivity Normalization Method (ENO) (Gillespie, 1985) assumes the constant emissivity in all (say N) channels for a given pixel which enables N temperatures to be calculated for each pixel. Maximum of these N temperatures is considered to be the land surface temperature and is used to derive emissivity values for the other channels as is done in the REF method. Emissivity Renormalization Method (ERNO) given by Stoll (1993) is same as two channels TISI (Temperature Independent Spectral Index) method. Alpha Emissivity (AE) Method is based on Wien's approximation of the Planck function. Peticolin and Vermote (2002) have given a method to retrieve surface reflectance, emissivity and temperature in the middle infrared (3-5µm) and thermal infrared (8-12µm) channels of MODIS data. This method first performs atmospheric corrections of the middle infrared radiances using National Centre for Environment Prediction (NCEP) humidity, pressure and temperature profile. Later on it constructs and uses the database of night emissivity ratio (TISI of emissivity) of the middle infrared reflectance (3-5µm) derived from day-time measurements and mean TISI values of emissivity. By hemispheric integration, it leads to middle infrared directional emissivity which when combined with TISI of emissivity, calculates thermal infrared emissivity and surface temperature.

1.2 Split Window Techniques

Two types of methods have been developed to estimate surface temperature from space: the single infrared channel method and the split window method. The single channel method requires good radiative transfer model and atmospheric profiles whereas split window method corrects for atmospheric effects based on the differential absorption in adjacent infrared bands (Price, 1984, Becker, 1987 and Becker and Li, 1990). Li and Becker (1993) have proposed a method to estimate both land surface emissivity and LST using pairs of day/ night co-registered AVHRR images. They have used a temperature independent spectral index (TISI) in thermal infrared bands and assumed the knowledge of surface TIR BRDF and atmospheric profiles. A generalized split window method for retrieving land surface temperature from AVHRR and MODIS data has been proposed by Wan and Dozier (1996). It has also been shown by accurate radiative transfer simulations that the coefficients in split window algorithm for LST must vary with the viewing angle. For viewing angle 46°, split window LST algorithm given by Becker and Li (1990) is:

$$T_s = A_0 + P\frac{T_4 + T_5}{2} + M\frac{T_4 - T_5}{2}$$

Equation 4

For NOAA AVHRR, the coefficients are (Li and Becker, 1993)

$$A_0 = 1.274$$

$$P = 1 + 0.15616\frac{1-\varepsilon}{\varepsilon} - 0.482\frac{\Delta\varepsilon}{\varepsilon^2}$$

$$M = 6.26 + 3.98\frac{1-\varepsilon}{\varepsilon} + 38.33\frac{\Delta\varepsilon}{\varepsilon^2}$$

Where, $\varepsilon = 0.5(\overline{\varepsilon_4} + \overline{\varepsilon_5})$ and $\Delta\varepsilon = \overline{\varepsilon_4} - \overline{\varepsilon_5}$

$\overline{\varepsilon_4}$ and $\overline{\varepsilon_5}$ are the band emissivities based on field measurements. These coefficients have been obtained from regression analysis of radiative transfer simulations. It has been suggested that atmospheric lower boundary temperature values retrieved from HIRIS/2 or MODIS atmospheric sounding channels can be used to determine the range for the optimum coefficients of split window method. Physics based LST algorithm for simultaneously retrieving surface band averaged emissivities and temperatures from day/night pairs of MODIS data in seven infrared bands has been reported. The set of 14 nonlinear equations in the algorithm have been solved with the statistical regression method and the least squares fit method. This algorithm has been tested with simulated MODIS data for 80 sets of band-averaged emissivities (Wan and Dozier, 1996). Thus, several algorithms have been developed to estimate the temperature of various land features. Present study takes wet areas into consideration and proposes an algorithm for Wet Surface Temperature (WST) estimation using the thermal channels 31 (10.78 – 11.28μm) and 32 (11.77 – 12.27μm) of MODIS data. This methodology deploys a factor incorporating the thermal properties of wet surfaces in these two bands.

2. Prepossessing

MODIS uses a whiskbroom scanner to achieve over 2000 km wide swath with a maximum scan angle of ± 55^0 on either side of the orbital path. Very large scan angle results in the instantaneous field of view (IFOV) of 1x1 km (8-36 bands) at nadir to almost 2x5 km at maximum scan angle. This increase in IFOV produces an overlap of adjacent scan angle (bowtie effect), which causes a repetition of features at every 10^{th} scan line. To rectify the impact of this effect, bowtie correction has been applied on MODIS image. Subsequently, data acquired over the area of Gujarat has been georeferenced using Geographic Lat-Long projection with WGS 84 datum.

3. Methodologies

MODIS thermal bands 31 (10.78 – 11.28μm) and 32 (11.77 – 12.27μm) have been used for estimating temperature of wet surfaces which include water, mud, aquatic vegetation etc. The temperature is given the name Wetland Surface Temperature (WST) like LST (Land Surface Temperature). The schematic of methodology is given in Figure 1. As is well known that sensor acquires data in digital form and each pixel contains a digital value called Digital Number (DN). These pixel values have been converted into radiance using band scale factor (BSF) and offset values and then used for further analysis. Digital image is an array of n rows and m columns, it can be represented in $n \times m$ matrix form. If x_{ij} and y_{ij} are the DN values for pixel in i^{th} row and j^{th} column for band 31 and band 32 ($\forall$ i = 1, 2…m; j = 1, 2…n) respectively and $R31_{ij}$ and $R32_{ij}$ are radiance for pixel in i^{th} row and j^{th} column for band 31 and band 32. According to Constant Emissivity Method (CEM) emissivity is considered constant (say ε =0.93) for all land cover types and is used to calculate temperature in band 31 ($T31_{ij}$) for all $R31_{ij}$ (i = 1, 2…m; j = 1, 2…n) using Planck's law given by equation (6)

$$T31_{ij} = \frac{C_2}{\lambda_{31}\left[\log\left\{\left(\frac{\varepsilon \times C_1}{R31_{ij} \times \lambda_{31}^5}\right) + 1\right\}\right]}$$

Equation 5

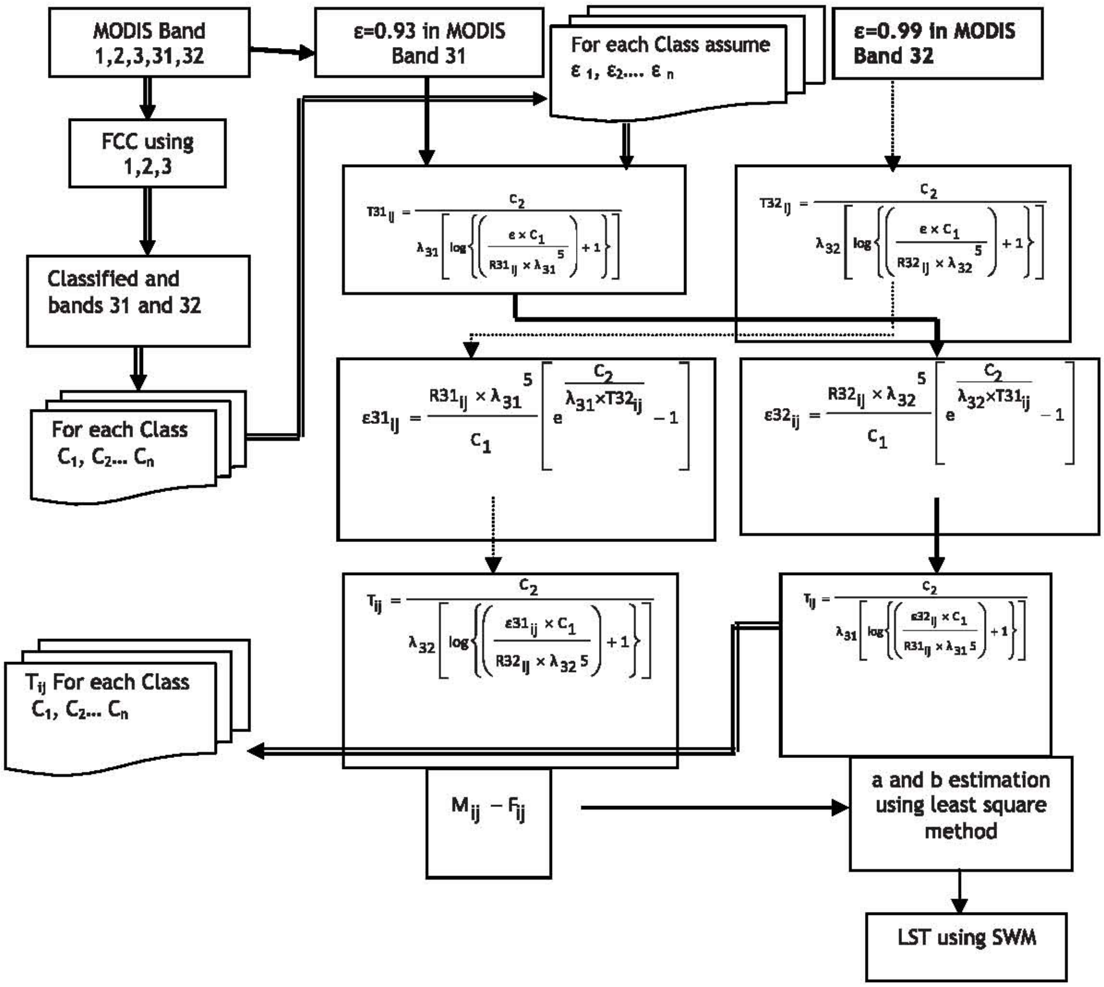

Figure 1: Schematic of the methodologies

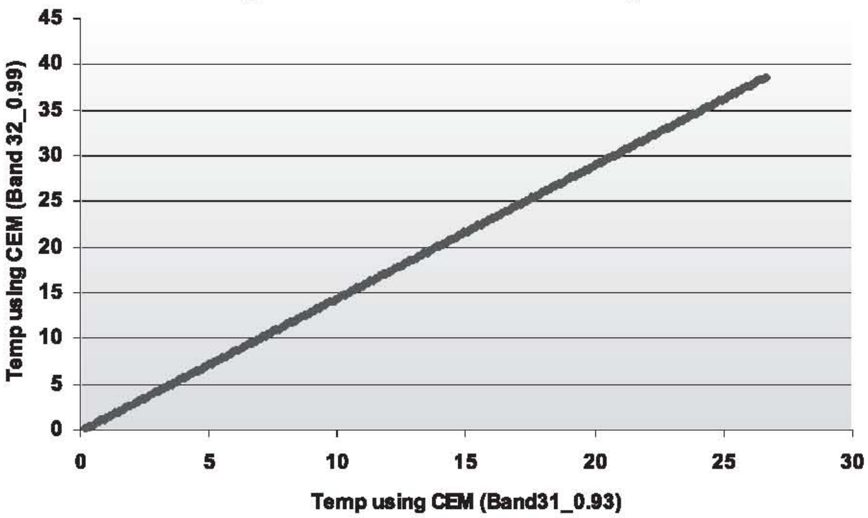

Figure 2: Relation between LST using CEM from band 31 and band 32 of MODIS data

where, $T31_{ij}$ = Temperature of pixel in i^{th} row and j^{th} column for band 31 for $\varepsilon = 0.93$, $C_1 = 2\pi hc^2 = 3.74183 \times 10^{-16}\ Wm^2$, $C_2 = 1.4388 \times 10^{-2}\ mK$, λ_{31} = 11.03µm = Mean of the wavelength in band 31. Making use of $T31_{ij}$, emissivities in band 32 have been calculated using equation (6)

$$\varepsilon 32_{ij} = \frac{R32_{ij} \times \lambda_{32}^5}{C_1}\left[e^{\frac{C_2}{\lambda_{32} \times T31_{ij}}} - 1\right]$$

Equation 6

where, $\varepsilon 32_{ij}$ = emissivity for pixel in i^{th} row and j^{th} column for band 32, $R32_{ij}$ = Radiance for pixel in i^{th} row and j^{th} column for band 32, λ_{32} = 12.02µm = Mean of the wavelength in band 32, Calculated emissivities for band 32 ($\varepsilon 32_{ij}$) are then used to rectify the temperature in band 31 using equation (7)

$$T_{ij} = \frac{C_2}{\lambda_{31}\left[\log\left\{\left(\frac{\varepsilon 32_{ij} \times C_1}{R31_{ij} \times \lambda_{31}^5}\right) + 1\right\}\right]}$$

Equation 7

Where, T_{ij} = LST for pixel in i^{th} row and j^{th} column using constant emissivity method. Conditional Constant Emissivity Method (CCEM) estimates temperature using CEM for different classes after assigning emissivity to each class in band 31. The proposed method for surface temperature estimation uses the emissivity range (0.93-0.99), since emissivity of most of the land cover features varies between 0.93-0.99. It is assumed that in band 31 all land cover features have same emissivity (0.93). Using constant emissivity method $\left[T1_{ij}\right]_{m\times n}$ has been calculated (using equation 3). Similarly for band 32 it is assumed that all land cover types have emissivity 0.99. Applying the same procedure $\left[T2_{ij}\right]_{m\times n}$ has been estimated. A linear correlation has been observed between both the temperatures (Figure 2). On the basis of linear relationship $\left[T2_{ij}\right]_{m\times n}$ is a linear function of $\left[T1_{ij}\right]_{m\times n}$ and is given by equation (8).

$$\left[T2_{ij}\right]_{m\times n} = a\left[T1_{ij}\right]_{m\times n} + b$$

Equation 8

According to the principal of least squares, a and b has to be determined so that:

$$E = \sum_{i=1}^{m}\sum_{j}^{n}\left(\left[T2_{ij}\right]_{m\times n} - a\left[T1_{ij}\right]_{m\times n} - b\right)^2$$

Equation 9

is minimum. From the principle of maxima and minima, the partial derivatives of E with respect to a and b should vanish separately, i.e.

$$\frac{\partial E}{\partial a} = 0 = -2\sum_{i=1}^{m}\sum_{j=1}^{n}\left[T1_{ij}\right]_{m\times n}\left(\left[T2_{ij}\right]_{m\times n} - a\left[T1_{ij}\right]_{m\times n} - b\right)$$

Equation 10

And $$\frac{\partial E}{\partial b} = 0 = -2\sum_{i=1}^{m}\sum_{j=1}^{n}\left(\left[T2_{ij}\right]_{m\times n} - a\left[T1_{ij}\right]_{m\times n} - b\right)$$

Equation 11

Equation (10) and (11) gives:

$$\sum_{i=1}^{m}\sum_{j=1}^{n}\left[T1_{ij}\right]_{m\times n}\left[T2_{ij}\right]_{m\times n} = a\sum_{i=1}^{m}\sum_{j=1}^{n}\left[T1_{ij}\right]^2_{m\times n} + b\sum_{i=1}^{m}\sum_{j=1}^{n}\left[T1_{ij}\right]_{m\times n}$$

Equation 12

$$\sum_{i=1}^{m}\sum_{j=1}^{n}\left[T2_{ij}\right]_{m\times n} = a\sum_{i=1}^{m}\sum_{j=1}^{n}\left[T1_{ij}\right]_{m\times n} + mnb$$

Equation 13

These equations are called normal equations. Solving normal equations 12 and 13, a and b are calculated by using following formulas:

$$a = \frac{\left(\sum_{i=1}^{m}\sum_{j=1}^{n}\left[T1_{ij}\right]_{m\times n}\sum_{i=1}^{m}\sum_{j=1}^{n}\left[T2_{ij}\right]_{m\times n}\right) - mn\sum_{i=1}^{m}\sum_{j=1}^{n}\left[T1_{ij}\right]_{m\times n}\left[T2_{ij}\right]_{m\times n}}{\left(\sum_{i=1}^{m}\sum_{j=1}^{n}\left[T1_{ij}\right]_{m\times n}\right)^2 - mn\sum_{i=1}^{m}\sum_{j=1}^{n}\left[T1_{ij}\right]^2_{m\times n}}$$

Equation 14

$$b = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left[T2_{ij}\right]_{mean} - a\sum_{i=1}^{m}\sum_{j=1}^{n}\left[T1_{ij}\right]_{mean}}{mn}$$

Equation 15

Now, we assume the functions M_{ij} and F_{ij} such that:

$$M_{ij} = \frac{T1_{ij} + T2_{ij}}{2} \; 8 \quad \forall \; i = 1,2....m, \; j = 1,2....n$$

Equation 16

And $$F_{ij} = \frac{T2_{ij}}{T1_{ij}} \times 10 \quad \forall \; i = 1,2.....m, \; j = 1,2.....n$$

Equation 17

After estimating a and b, it is assumed that Wetland Surface Temperature (T_{ij}) and $(M_{ij} - F_{ij})$ are linearly related by the equation:

$$T_{ij} = a(M_{ij} - F_{ij}) + b \; 8 \; \forall \; i = 1,2.....m, \; j = 1,2.....n$$

Equation 18

Using equation (18) WST can be calculated.

4. Results and Discussion

MODIS data acquired on October 6, 2005 covering Gujarat was georeferenced with geographic (Lat/Lon) projection, WGS 84 datum, latitude (25°86', 20°57') and longitude (67°23', 73°93'). Georeferenced data has then been used for WST estimation and for comparative study of WST with MODIS LST product. For the assessment of temperature using conditional constant emissivity method, classified image has been used and for each class emissivities have been assigned (Table 1). Land surface temperature of selected area using constant emissivity method, conditional constant emissivity and proposed method for WST estimation are shown in Figure 3.

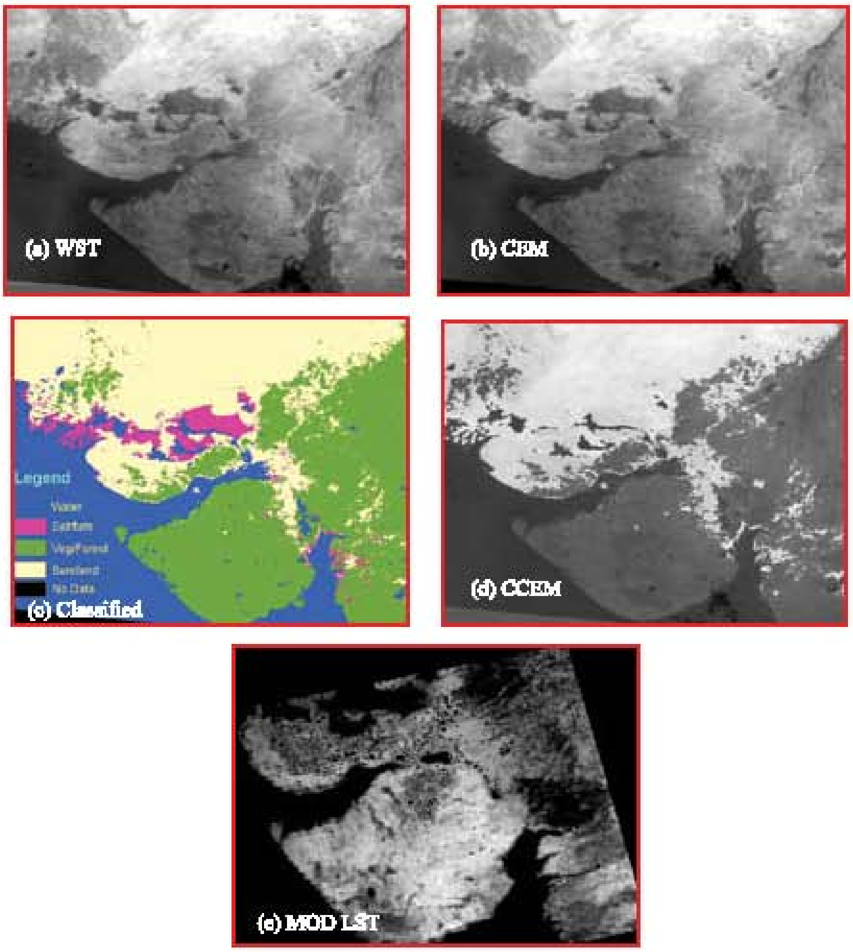

Figure 3: Surface Temperature images derived using various methods (a) WST (b) CEM (c) Classified (d) CCEM (e) MODIS LST

Table 1: Assigned emissivities for estimating LST using CCEM

Class	Assigned Emissivity
Water	0.99
Moist Salt Flats	0.88
Veg/ Forest	0.98
Barren Land	0.90

The main emphasis of the present study is to estimate the temperature of wet surfaces. These areas have comparatively low temperature than that of barren land and other non-wetland areas. A comparison has been made between the temperatures of wet surfaces (i.e. water bodies, mud flats, aquatic vegetation and moist salt flats etc.) derived using CEM, CCEM and WST methods and temperature of MODIS LST product. Output images derived from WST, CEM and CCEM methods are shown in Figure 3. Results show that for features with low temperatures (water bodies, mud flats, aquatic vegetation and moist salt flats), WST and CEM methods give close values to the LST product (Figure 4). However, for non-wet features these techniques are not comparable. The third method CCEM shows a lot of difference in temperature values for both wet and non-wet features.

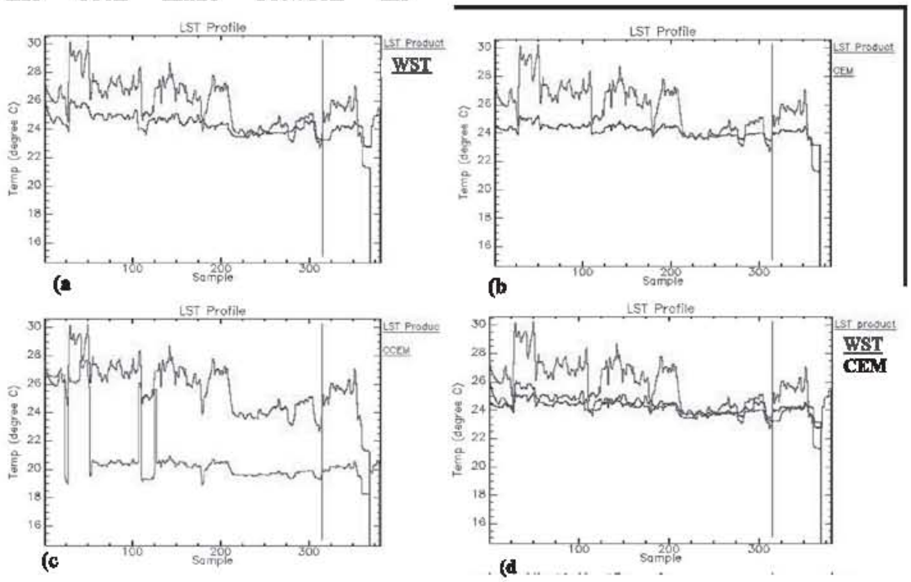

Figure 4: Comparison of Surface Temperature profile generated using (a) WST (b) CEM (c) CCEM, (d) WST and CEM with LST product

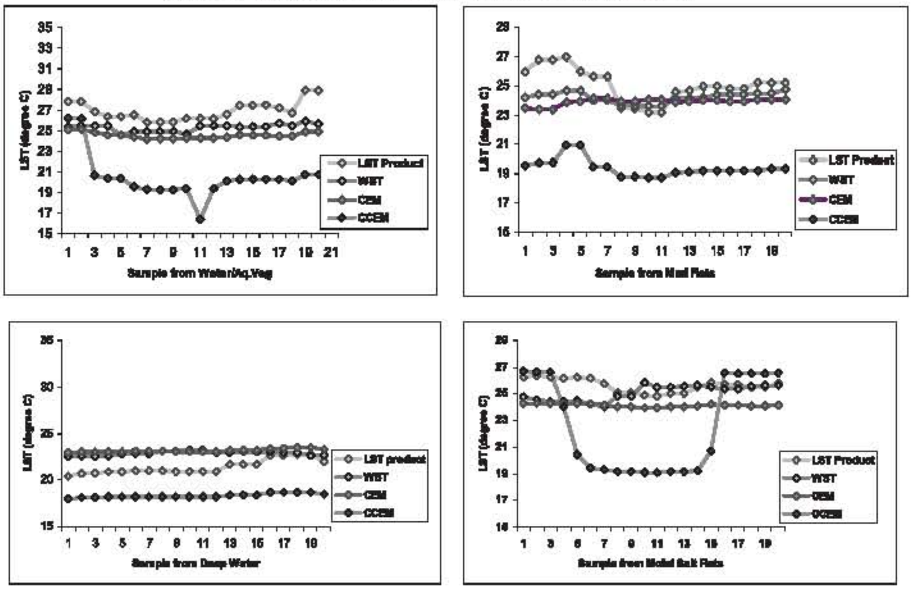

Figure 5: Comparison of Temperature of Wetland Surfaces estimated using WST, SEM and CCEM with MOD LST product

To illustrate the difference between the temperature values derived using CEM and WST, samples have been taken for each wet feature and are plotted (Figure 5). This plot elucidates the pattern of temperature for water, aquatic vegetation, mud flats and moist salt flats. It is observed that though for water and aquatic vegetation WST and CEM give the same temperature range, however, individual samples from these classes show that WST provide surface temperature closer with LST product. For remaining classes (mud flats and moist salt flats), WST performs better. It has also been observed that for wet surfaces, proposed method provides the temperature within ±2°C range of MODIS LST products. The main reason of the better performance of WST is the inclusion of the range of emissivity and establishment of the relation between the emissivities of features in two thermal bands.

5. Conclusion

The paper describes a methodology for Wetland Surface Temperature (WST) estimation using MODIS data which makes use the information collected in thermal bands (band 31 and 32) and using the complete emissivity range for wetland surfaces. Surface temperature of wetland surfaces like water, aquatic vegetation, mud flats and moist salt flats, estimated using the proposed method have been compared with that of constant emissivity method, conditional emissivity method and MODIS LST product. It has been observed that in general the new method gives better results.

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