Application of MODIS LST Data for Calculation of Evapotranspiration in the State of Espírito Santo, Brazil

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Abstract. The areas susceptible to desertification in Brazil include the areas of Semiarid Climate and Dry Sub-humid Climate, as well as the surrounding areas, located in the Nordeste e Sudoeste do Brasil (the Northeast and Southeast Zones), occupying approximately 1,340 km² in all, and directly affecting 30 million people. Of the total area, 180,000 km² are already found to be in an advanced or very advanced process of desertification. The United Nations definition of aridity is based on methodology developed by Thornthwaite (1941) and adjusted by Penman (1953), in which the aridity index (AI) is the ratio between precipitation and evapotranspiration. The objective of this work is to analyse the correlation of monthly surface temperature data, obtained through use of the Moderate Resolution Imaging Spectrometer (MODIS), (MOD11), with the ambient air temperature, measured at seven meteorological stations in the state of Espirito Santo. These measurements are averaged over monthly periods, aiming to realize an adjustment of the MODIS land surface temperature (LST) data to mathematical models, enabling the estimation of air temperature over wide areas, permitting the calculation of evapotranspiration and the aridity index for such areas.

Keywords. MODIS LST, evapotranspiration, desertification, Brazil.

1. Introduction

The areas susceptible to desertification in Brazil, are the areas of dry subhumid and semiarid climates and areas immediately surrounding, occupy about 1.340.000 km^2 and directly affect 30 million people. Of the total area, 180 thousand square kilometers, located in the Northeast and Southwest of Brazil [1], already are in serious threat of desertification.

The State of Espirito Santo has twenty-four municipalities which are considered as Areas Susceptible to Desertification (ASD) enrolled in the Plan of National Action (PAN-Brazil). They occupy an area of 16.680 km^2, equivalent to approximately 36% of the state´s territory. These areas are in an increasing condition of environmental degradation and have few data that can evaluate and be used to assist in monitoring this process.

The measurement of seasonal variation in evapotranspiration, when analyzed together with other climatological phenomena, including the impact of anthropic action on the soil, allows diagnosis of the water deficit of a region, enabling identification of areas in a process of degradation, such as those of desertification, or as being susceptible to the same. The aridity definition adopted by the United Nations is based on the methodology developed by [2] and adjusted by [3], in which the aridity index (IA) is represented by the ratio between precipitation and evapotranspiration.

The *Moderate Resolution Imaging Spectroradiometer* (MODIS) on board the satellite Land EOS-1, provides daily coverage of the entire globe recording land surface temperature (LST) data, which is available free of charge, in resolutions of 250 m, 1-km and 5-km [4]. LST data have been used for evapotranspiration calculation mostly because of its wide coverage and low cost. Some research has been performed correlating LST data with data measured at land surface points. [5] made evapotranspiration forecasts with MODIS and meteorological data in the New Mexico area, USA. [6] performed a revision of various methods for evapotranspiration estimation at the earth´s surface. [7] developed a computational framework to generate maps of daily temperatures using MODIS LST data and data from meteorological stations.

The objective of this work is to analyse the correlation of data from MODIS LST with temperature data measured at meteorological stations in the State of Espírito Santo, utilizing MODIS LST data for the calculation of evapotranspiration in the Areas Susceptible to Desertification (ASD).

2. Methods

The area of study encompassed the State of Espírito Santo, located in Brazil's Southeast (Figure 1), which is characterized by a hot tropical climate over most of its territory, being hot superhumid along the north and central coastal regions and becoming mesothermal bland in the mountainous region. The thermal averages are superior to 18ºC over the greater part of the territory, during every month of the year and the thermal amplitude between the hot and cold seasons does not exceed 6°C in the coastal region, increasing towards the interior [8], [9].

Figure 1: Location map of the study area.

Fortyeight images, a 30 day compilation, from MODIS LST were used (product MOD11C3). They were acquired from the division Land Processes Distributed Active Archive Center (LPDAAC) of the United States Geological Survey (USGS). The temperature data of the study area were obtained from seven automatic meteorological stations of Meteorology National Institute (INMET).

The MODIS LST images were processed in the Modis Reprojection Tools (MRT) software, developed by NASA, for (i) conversion of the images from HDF format to GeoTIFF format, (ii) modification of the sinusoidal projection to WGS84 and (iii) cropping the images to within the limits of the State of Espírito Santo .

Using the ENVI software, the LST images were multiplied by the factor 0.02 for temperature conversion to Kelvin and afterward 273.15 was subtracted for conversion to degrees Celsius.

Then, an arithmetic average of the nine LST image pixels was taken. These nine pixels represent the area influencing the station data, the central pixel being where the station is located and the eight neighbouring pixels (Figure 2). This average was performed to minimize local factors that might influence data if only the pixel where the station is located was considered.

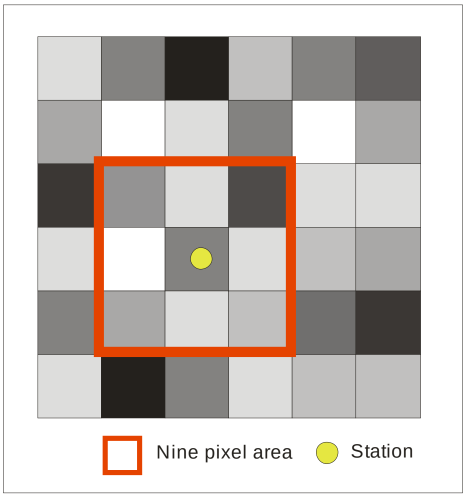


Figure 2: Demonstrating the location of the nine pixel area around the meteorological stations.

LST's average values for the nine pixels of each station were correlated with the temperature data measured at the meteorological stations. The data were adjusted using four mathematical functions: Linear, logarithmic, exponential and second degree polynomial, for the identification of the curve that presented the largest coefficient of determination value (R^2).

A seasonal analysis of the LST data was performed with the temperature data from the meteorological stations, to observe the behaviour of these data (Figure 3). Following, an average value of the differences between temperatures was calculated and the temperature differences average value (5.03 °C) was subtracted from the LST temperature.

Then, evapotranspiration was calculated by adjusting LST, LST and station data from the seven stations in the field using Thornthwaite's Method [2], per equation 1:

$$EP = 16.2\,(10 \times T/I)^a \qquad (1)$$

where: *EP* is for potential evapotranspiration (mm/month); *T* is the monthly average temperature (°C); *I* is the annual heat index, the resultant of the sum of 12 monthly indices *I* (equation 2):

$$I = \Sigma \boldsymbol{ij} \quad \text{(with } j \text{ from 1 to 12)} \qquad (2)$$

where:

$$i_j = [t_j/5]^{1.514}$$

$$a = 675 \cdot (I \cdot 10^{-3})^3 - 77.1 \cdot (I \cdot 10^{-3})^2 + 1{,}792 \cdot (I \cdot 10^{-5}) + 0.49329$$

The evapotranspiration data obtained with the LST data and the adjusted LST data were correlated with the evapotranspiration calculated with data from the stations and adjusted for the four mathematical functions (linear, logarithmic, exponential and second degree polynomial), in order to identify the curve that presented the largest coefficient of determination value (R^2).

With the evapotranspirations calculated, the aridity index (IA), which is the ratio between precipitation (P) and potential evapotranspiration (EP), was calculated (equation 3):

$$IA = P/EP \tag{3}$$

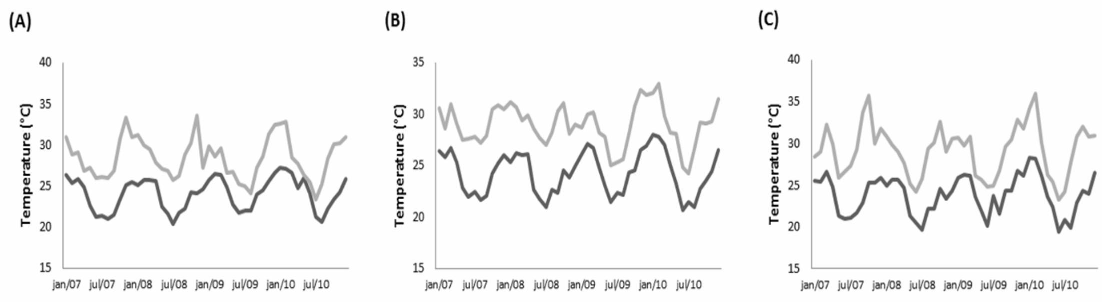
3. Results

The correlation of MODIS LST data and the meteorological stations temperature values (Table 1) presented values of moderate to strong correlation, as defined in the literature, where correlation values of R^2 between 0.3 and 0.6 are considered moderate and values of R^2 between 0.6 and 0.9 strong.

Table 1. Coefficient of determination value (R^2) between MODIS LST data and temperature recorded in meteorological station.

Functions / Stations	linear	exponential	logarithmic	second degree polynomial
São Mateus	0.467	0.469	0.478	0.502
Vitória	0.669	0.673	0.664	0.671
Alegre	0.568	0.566	0.577	0.583
Linhares	0.636	0.638	0.641	0.646
Alfredo Chaves	0.724	0.729	0.711	0.733
Serra dos Aimorés	0.391	0.394	0.424	0.515
Campos	0.501	0.505	0.503	0.503

The seasonal analysis of MODIS LST data with temperature data from the meteorological stations demonstrated that data from both presented similar variations, with the temperature differential in the range of 5°C (Figure 3), demonstrates the similarity between these data. Another seasonal analysis, between the adjusted MODIS LST data and the temperature data from the meteorological stations (Figure 4), also demonstrated a good agreement between them. MODIS LST data closely approximates data collected in the field.



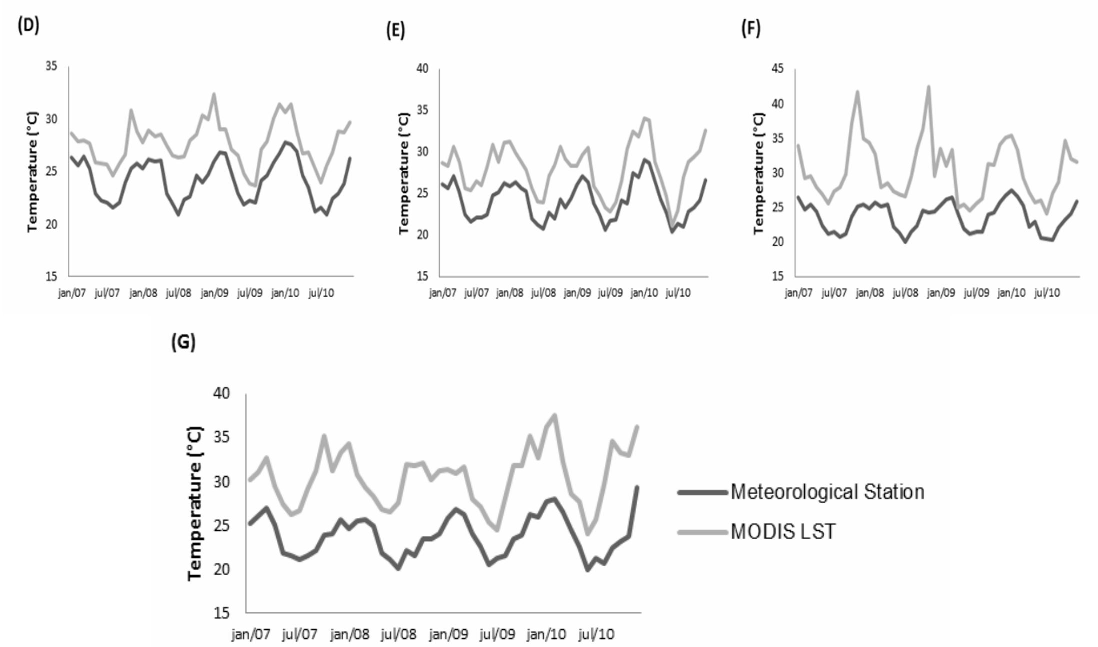


Figure 3: Seasonal analysis of the MODIS LST data and the temperatures registered in seven meteorological stations. (A) São Mateus; (B) Vitória; (C) Alegre; (D) Linhares; (E) Alfredo Chaves; (F) Serra dos Aimorés; (G) Campos.

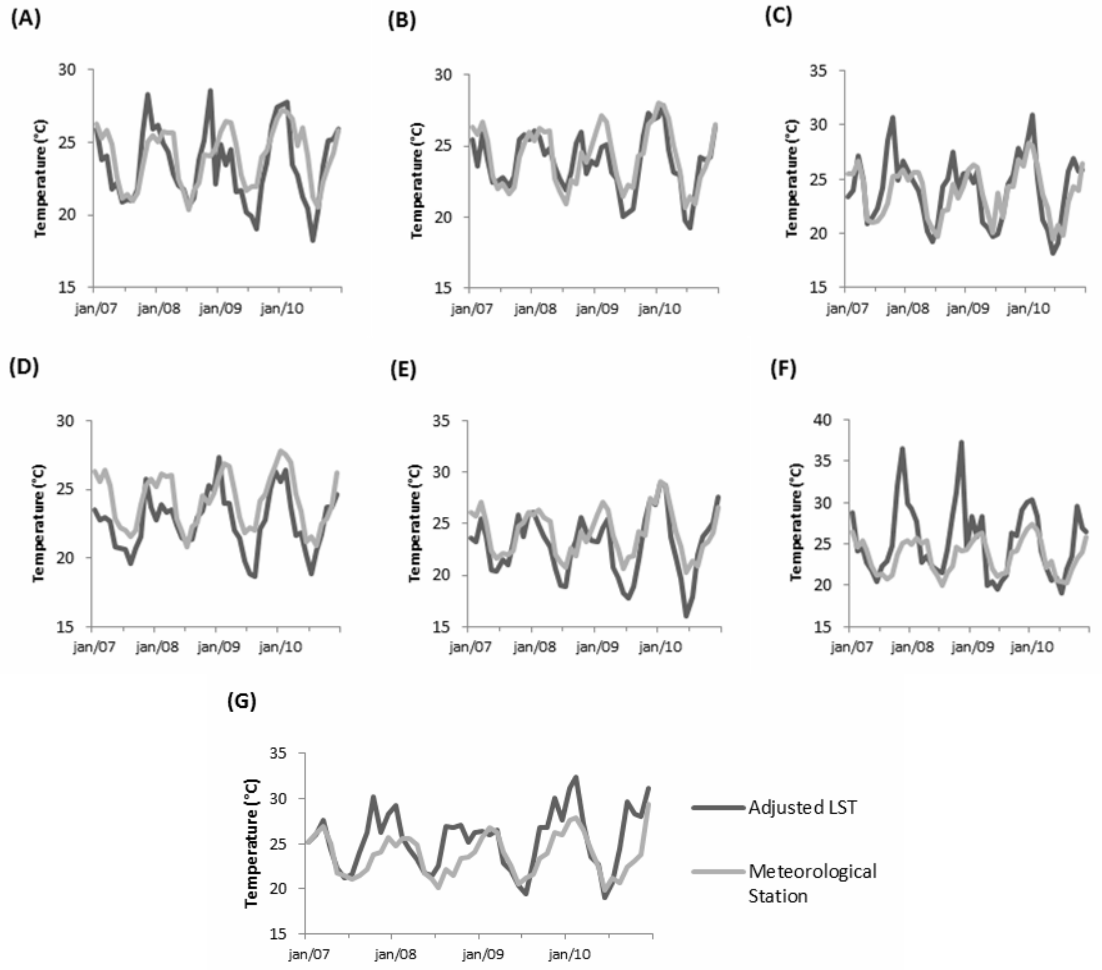


Figure 4: Seasonal analysis of the adjusted MODIS LST temperatures with the temperatures registered at the meteorological stations. (A) São Mateus; (B) Vitória; (C) Alegre; (D) Linhares; (E) Alfredo Chaves; (F) Serra dos Aimorés; (G) Campos.

The evapotranspirations calculated with adjusted MODIS LST data showed strong agreement with data registered by the meteorological stations (Figure 5). This means that MODIS LST data can be used, once adjusted, for evapotranspiration calculation in areas with scant meteorological station coverage.

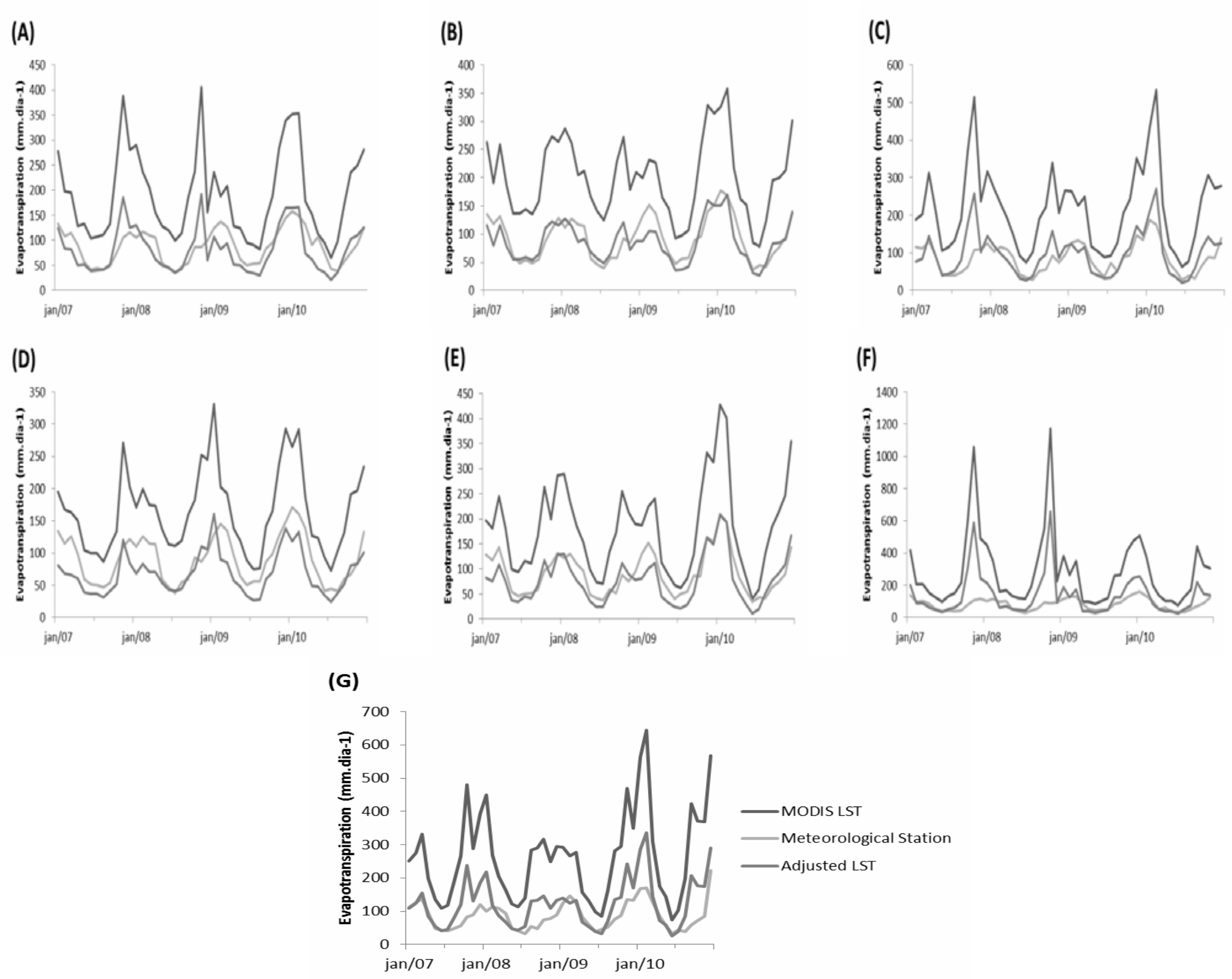
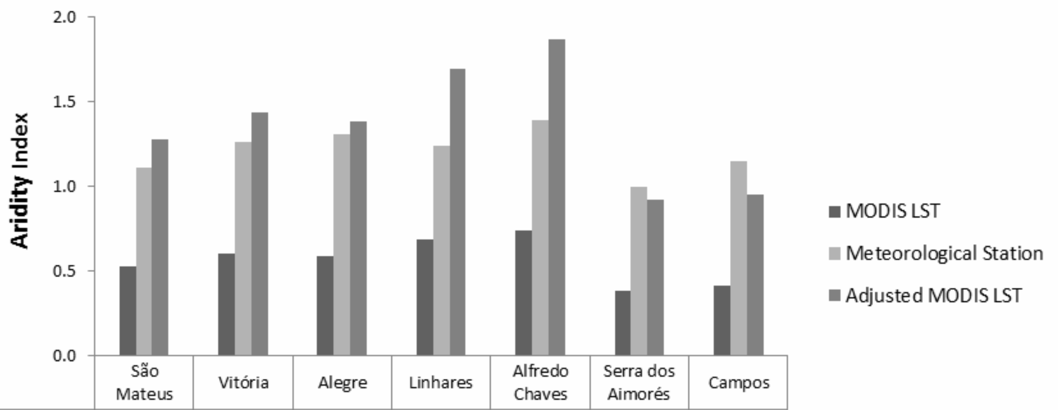


Figure 5: Evapotranspiration calculated with data from: MODIS LST, adjusted MODIS LST and the meteorological station measurements.

According to [10], the aridity index (IA) is correlated with susceptibility to desertification. Susceptibility to desertification is being considered very high for regions with an aridity index between 0.05 and 0.20; high for regions with an aridity index between 0.21 and 0.50 (semiarid); and moderate for regions with an aridity index between 0.51 and 0.65 (dry subhumid).

The Aridity Indices when calculated with the adjusted MODIS LST data remained in the subhumid and humid climate range (IA > 0.65), in the same way that they did when calculated with the data from the meteorological stations, as seen in Figure 6. This indicates that adjusted MODIS LST data, when used for the aridity index calculation, is adequate for regional classification.



	São Mateus	Vitória	Alegre	Linhares	Alfredo Chaves	Serra dos Aimorés	Campos
MODIS LST	0.526	0.605	0.586	0.690	0.743	0.387	0.412
Meteorological Station	1.112	1.265	1.309	1.243	1.397	0.999	1.153
Adjusted MODIS LST	1.280	1.439	1.389	1.699	1.870	0.923	0.957

Figure 6: Aridity index to adjusted LST, MODIS LST and meteorological station.

4. Conclusions

The moderate and strong correlations found between MODIS LST data and temperature data measured at the meteorological stations indicates that MODIS LST data can be used in place of the temperature data registered by meteorological stations, when properly adjusted. The strong agreement of evapotranspiration calculated with adjusted MODIS LST data and with data from the meteorological stations indicates the possible use of MODIS LST data for evapotranspiration prediction, for areas with few temperature monitoring stations, principally because of its broad coverage as well as the low cost of acquisition and processing.

The methodology suggested for the aridity index calculation by the United Nations, when used with adjusted MODIS LST data, maintained the same aridity index range as when calculated with data from the meteorological stations. This observation reinforces the possibility of using MODIS LST data for the calculation and monitoring of the aridity index over widespread territorial areas or for those areas with few meteorological stations.

Acknowledgements

This research was supported by the Foundation for Research Support of the Espírito Santo (FAPES), Process number 47806435/2010, concession number 009/2010.

References

[1] Santana, M. O., 2007. *Atlas das áreas susceptíveis à desertificação do Brasil*. MMA, Secretaria de Recursos Hídricos, Universidade Federal da Paraíba, Brasília: MMA, 134 pp.

[2] Thornthwaite, C. W., 1941. *Atlas of climatic types in the United States*. Mixed Publication, 421, U.S. Department of Agriculture, Forest Service.

[3] Penman, H. L., 1953. *The physical bases of irrigation control*. In: Hort. Congr., 2, London, Royal Horticultural Society, p.913-924.

[4] Wan, Z., Zhang, Y., Zhang, Q. and Li, Z., 2004. Quality assessment and validation of the MODIS global lend surface temperature. *International Journal of Remote Sensing*, 25, pp. 261-274.

[5] Nagler, P. L., Cleverly, J., Glenn, E., Lampkin, D., Huete, A. and Wan, Z., 2005. Predicting riparian evapotranspiration from MODIS vegetation indices and meteorological data. *Remote Sensing of Environment*, 94, pp. 17-30.

[6] Kalma, J. D., McVicar, T. R. and McCabe, M. F., 2008. Estimating Land Surface Evaporation: A Review of Methods Using Remotely Sensed Surface Temperature Data. *Surv Geophys* 29: pp. 421–469.

[7] Hengl, T., Heuvelink, G. B. M., Tadic, M. P. and Pebesma, E. J., 2012. Spatio-temporal prediction of daily temperatures using time-series of MODIS LST images. *Theor Appl Climatol* 107: pp. 265–277.

[8] IBGE. Mapa de clima do Brasil 2002. Available at : http://www.ibge.gov.br/home/geociencias/default_prod.shtm.

[9] Moraes, C., 2004. *Geografia do Espírito Santo*. Instituto Histórico e Geográfico do Espírito Santo.

[10] Matallo, H., 1999. *Proposta de um Sistema Básico de Indicadores para Identificação e Monitoramento dos Processos de Desertificação na América Latina e Caribe.* In: SCHENKEL; MATALLO. Desertificação. Unesco, Brasília.