2020
Turkish Journal of Remote Sensing and GIS

Turkish Journal of Remote Sensing and GIS
Türk Uzaktan Algılama ve CBS Dergisi

Turk J Remote Sens GIS, March 2021, 2(1): 11-20
Journal homepage: http://www.dergipark.org.tr/en/pub/rsgis

A Study of the Impact of Aerosols on The Estimation of Land Surface Temperature from Space Using Simulation of Satellite Data

Uydu Verilerinin Simülasyonunu Kullanılarak Aerosollerin Uzaydan Yer Yüzey Sıcaklığının Tahmini Üzerindeki Etkisine İlişkin Bir Çalışma

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ORIGINAL PAPER

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doi: 10.48123/rsgis.839293

Article history:
Received: 11.12.2020
Accepted: 02.02.2021
Published: 13.03.2021

Abstract

Accurate estimation of land surface temperature (LST) is strongly required for many applications such as environmental studies. However, there are several algorithms in the literature for estimating LST from satellite those do not take into account the effect of the aerosols. Actually, these aerosols can exert an important influence on the estimation of LST from satellite thermal infrared data. Therefore, in this paper we presented a theoretical study and a simple methodology to show the impact of the aerosols on the estimation of LST from satellite in the thermal infrared region. For this, the simulation by the radiative transfer code Modtran3.5 has been carried out. The results showed that, the impact of aerosols on the estimation of LST depends on the Viewing angle, atmospheric situation, type of aerosols and surface emissivity. The results showed also that, the difference between LST estimated when the aerosol model is considered with respect to atmosphere without aerosol content varies increasingly with the viewing angle and is very sensitive to the situation of the atmosphere and varies decreasingly with the visibility and varies increasingly with the surface emissivity. This work shows that, for the lowest values of the visibility, the impact of aerosols is important and correction is needed for estimating LST. Discussion about this is given in this work.

Keywords: *Aerosols, Land surface temperature, Satellite data, Thermal infrared region, Radiative transfer equation*

Özet

Birçok çevre araştırması için yer yüzey sıcaklığının (LST) doğru tahmin edilmesi büyük ölçüde gereklidir. Literatürde uydu verilerinden yer yüzey sıcaklığını tahmin etmek için önerilen birçok algoritma aerosollerin etkisini dikkate almaz. Oysaki bu aerosoller, uydu termal kızılötesi verilerinden yapılan yer yüzey sıcaklığı tahminleri üzerinde önemli bir etki yaratabilmektedir. Bu nedenle, bu çalışma, aerosollerin termal kızılötesi bölgede yer yüzey sıcaklığı tahmini üzerindeki etkisini göstermek için teorik bir araştırma ve basit bir metodoloji sunmaktadır. Bu amaçla, ışınımsal transfer kodu Modtran3.5 ile simülasyon gerçekleştirilmiştir. Elde edilen sonuçlar, aerosollerin yer yüzey sıcaklığı tahmini üzerindeki etkisinin görüş açısına, atmosferik duruma, aerosol tipine ve yüzey emisyonuna bağlı olduğunu göstermektedir. Ayrıca, aerosol modelinin dikkate alındığında ve alınmadığında oluşan yer yüzey sıcaklığı farklarının atmosferin durumuna duyarlı olduğunu, görüş açısına bağlı olarak arttığını, görünürlüğe bağlı olarak azaldığını ve yüzey yayılımına bağlı olarak azaldığını göstermektedir. Bu çalışma, aerosollerin etkisinin görünürlüğün en düşük değerleri için önemli olduğunu ve yer yüzey sıcaklığını tahmin etmek için düzeltmeye ihtiyaç duyulduğunu göstermektedir. Bununla ilgili tartışma bu çalışmada verilmektedir.

Anahtar kelimeler: *Aerosoller, Yer yüzey sıcaklığı, Uydu görüntüsü, Termal kızılötesi bölge, Radyoaktif transfer denklemi*

1. Introduction

The knowledge of land surface temperature (LST) and its spatio-temporal distribution at large scale is possible from thermal infrared data using satellite observations (Labbi and Mokhnache, 2015). The knowledge of LST also is crucial because LST is key input parameter in climatic, evapotranspiration, hydrological, and ecological models. However, the impact of aerosols on the satellite thermal infrared data is widely acknowledged as one of the most significant and uncertain aspects of land surface temperature estimation.

Previous studies show that, LST can be estimated from the thermal infrared radiation emitted from Earth surfaces by using many methods. Therefore, different algorithms for estimating LST from satellite thermal infrared data has been realized (Becker and Li, 1990; Dash et al. 2002; François and Ottlé, 1996; Jiang and Li, 2008; Labbi and Mokhnache, 2015; Qin and Karnieli, 2001; Sobrino and Romaguera, 2004). These algorithms include the split-window methods and the mono-window methods. However, each of these algorithms do not take into account the effect of the aerosols that can exert an important influence on the estimation of LST from satellite and is not always negligible (Jiménez-munoz and Sobrino, 2006; Gao et al. 2015). In reality, the thermal infrared radiation emitted from Earth surfaces is perturbed by the aerosols (solid or liquid particles suspended in the atmosphere) and by the atmospheric water vapor content before reaching a sensor (Malkevich and Gorodetsky, 1988; Gao et al. 2015).

For the sensitivity/uncertainty analyses of LST retrieval from satellite observations, Jiménez-munoz and Sobrino (2006) show that for view angles lower than 25°, the error on LST is lower than 1 K and for a view angle of 55°, the error on LST is higher than 7 K, and this for the following conditions: Mid-Latitude Summer atmosphere, LST equals 300 K, emissivity equals 0.98 and channels 10–12 µm. Also, Gao et al. (2017) indicate that the total LST uncertainty caused by the standard error of the algorithm, the uncertainties of land surface emissivity and the atmospheric water vapor content, and the instrument noise would be 1.22 K and 0.94 K for dry and wet atmosphere, respectively.

Several studies show that, in the thermal infrared region the satellite-measured radiance over desert decreased in the presence of aerosols (De Paepeet al. 2008; Zhao et al. 2020). Gao et al. (2015) show that the root mean square error (RMSE) can decreases to approximately 2.3 K for estimating LST from satellite when the viewing angle equals 60° and the visibility equals 3 km; and RMSE would be increased by approximately 1.0 K when visibility varies from 3 km to 23 km. Therefore, the atmospheric correction from the aerosols effects is necessary for estimating LST from satellite data.

The main goal of this paper is to study the aerosols effects on the estimation of LST from satellite thermal infrared data (10.5-12.5µm). Therefore, the paper is organized as follow: firstly, we presented the radiative transfer equation. Secondly, we explained the methodology for estimating land surface temperature with and without aerosols contents using the Modtran3.5 (Abreu and Anderson, 1996) radiative transfer code. Then, we studied in detail the impact of aerosols on the estimation of LST from satellite in the thermal infrared region. Finally, we presented the main conclusion of this paper.

2. Methodology

In this work, we have used an iterative method for retrieving LST. We can explain this methodology as follow:

2.1 Brightness temperature retrieval

The brightness temperature (T_b) observed by satellite is obtained by applying the inverse of the Planck function to the measured at-sensor radiation. For a cloud-free atmosphere under local thermodynamic equilibrium, this at-sensor radiance can be written as follow (Gao et al., 2015; Qin and Karnieli, 2001):

$$L_\lambda^{sat} = B_\lambda(T_b) = \tau_\lambda(\theta)\left\{\varepsilon_\lambda(\theta)B_\lambda(T_s) + [1-\varepsilon_\lambda(\theta)]L_\lambda^{atm\downarrow}\right\} + L_\lambda^{atm\uparrow} \tag{1}$$

where $\tau_\lambda(\theta)$ is the total atmospheric directional transmission (dimensionless), $\varepsilon_\lambda(\theta)$ is the land surface directional emissivity (dimensionless), $B_\lambda(T_s)$ is the radiance emitted by a black body ($W\, m^{-2} sr^{-1} \mu m^{-1}$) at land surface temperature T_s in K, $L_\lambda^{atm\uparrow}$ is the upwelling atmospheric radiance in $W\, m^{-2} sr^{-1} \mu m^{-1}$, $L_\lambda^{atm\downarrow}$ is the downwelling atmospheric radiance in $W\, m^{-2} sr^{-1} \mu m^{-1}$, and L_λ^{sat} is the at-sensor radiance in $W\, m^{-2} sr^{-1} \mu m^{-1}$.

The upwelling and downwelling atmospheric radiances can be calculated respectively as follow (Li, 1990; Qin and Karnieli, 2001):

$$L_\lambda^{atm\uparrow} = \int_0^h B_\lambda(T_z)\frac{\partial \tau_\lambda(\theta, z)}{\partial z} dz \tag{2}$$

$$L_{\lambda}^{atm\downarrow} = \frac{1}{\pi}\int_{0}^{2\pi}\int_{0}^{\frac{\pi}{2}}\int_{\infty}^{0} B_{\lambda}(T_z)\frac{\partial \tau_{i,\lambda}(\theta_i, z)}{\partial z} dz\, sin(\theta_i)\, cos(\theta_i)\, d\theta_i d\phi_i \quad (3)$$

where θ_i is the downwelling direction of atmospheric radiance (dimensionless), $\tau_{i,\lambda}(\theta_i, z)$ is the downwelling atmospheric directional transmittance from altitude z to the ground surface (dimensionless), $B_{\lambda}(T_z)$ is the radiance emitted by a black body ($W\ m^{-2}sr^{-1}\mu m^{-1}$) at atmospheric temperature T_z (in K) and z is the atmospheric altitude (m), and h represents the altitude at the top of the atmosphere (m).

2.2 Land surface temperature retrieval

For retrieving LST, we have firstly calculated the brightness temperature from LST without the aerosols effect using the equation (1) and the Modtran3.5 (Abreu and Anderson, 1996) radiative transfer code. Secondly, we have calculated the same brightness temperature from LST with the aerosols effect (it is necessary to get the same brightness temperature in the two case). Finally, we have made a comparison between the LST estimated without the aerosols effect and the LST estimated with the aerosols effect. Figure 1 shows the flowchart overview of the methodology used in the study.

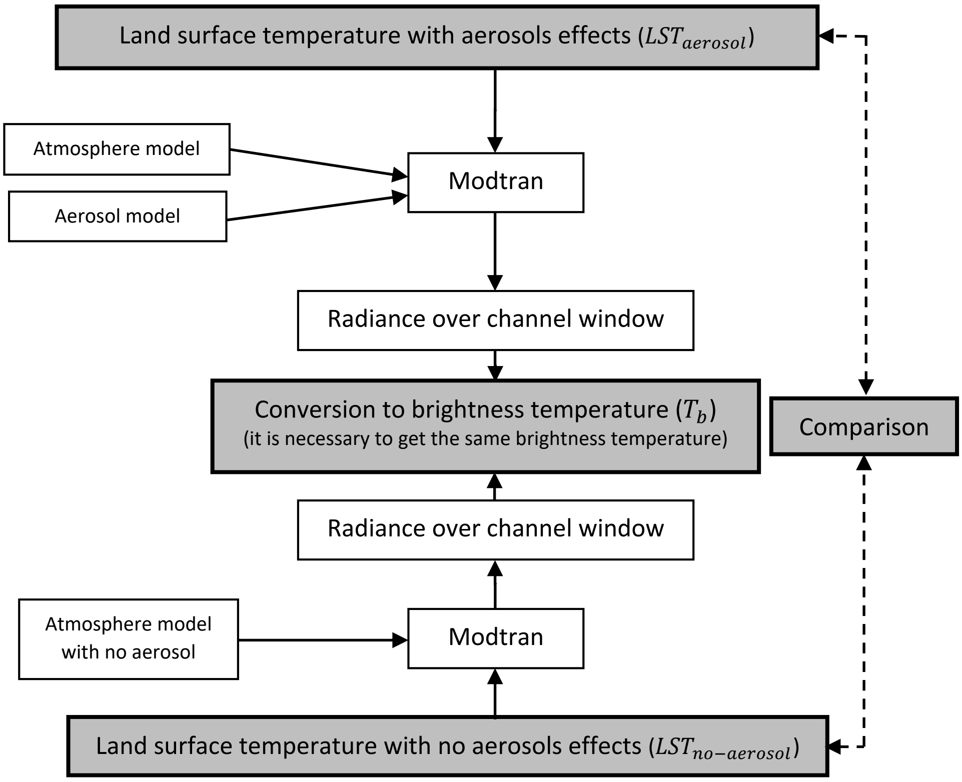

Figure 1. Flowchart overview of the methodology used in the study

3. Results and discussion

In all the following, a simulation using the Modtran3.5 radiative transfer code (in Lowtran7 mode) for the channel window 10.5-12.5µm (square filter), and for a surface elevation equals 500 m above sea level has been carried out.

3.1 Angular effects

In order to study the impact of the viewing angle on the determination of LST under aerosols conditions, we have used Modtran3.5 code for seven view angles, from 0° to 60° by steps of 10°. The following assumptions were also used: 1) the aerosol model is Radiative fog extinction (visibility = 0.5 km); 2) the atmospheric model used is Mid-Latitude Summer; 3) the surface emissivity equals 1.

Figure 2 shows the angular effects on the difference between LST estimated when the aerosol model is considered with respect to atmosphere without aerosol content (δT_s) for different values of LST estimated without considering aerosol content. The results obtained show that the difference δT_s varies increasingly with the viewing angle; this is due to the increase in the optical thickness of aerosols. Indeed, we found that the angular effects can provide a variation of δT_s equals 3.17*K*. Therefore, we can conclude that the estimation of LST from satellite when the aerosol is considered is very sensitive and requires real value of the viewing angle. We can also conclude that the angular effects disappear in case of the LST estimated, when the aerosol is considered, equals the LST estimated without considering aerosol content (δT_s=0).

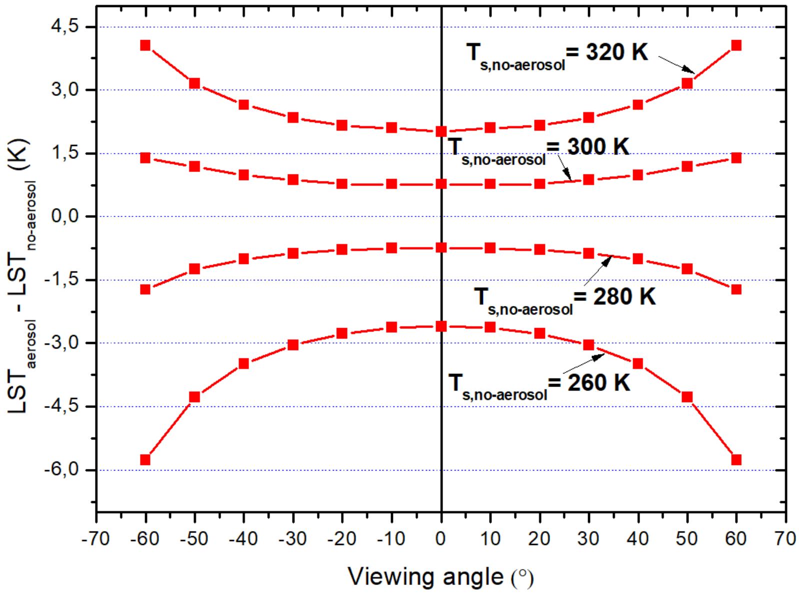

Figure 2. Effect of the viewing angle on the difference between LST when the aerosol model is considered with respect to atmosphere without aerosol content

3.2 Study of the effect of atmospheric situation

In this study, we want to study the impact of the atmospheric situation on the determination of LST for aerosols conditions. Therefore, we have used the Modtran3.5 radiative transfer code for six different atmosphere models (1: Tropical, 2: Mid-Latitude Summer, 3: Mid-Latitude Winter, 4: Sub-Arctic Summer, 5: Sub-Arctic Winter, and 6: 1976 U. S. Standard). In the same simulation, we have used also five aerosol models (Rural extinction: visibility = 5*km*, Maritime extinction: visibility = 23 km, Urban extinction: visibility = 5 km, Radiative fog extinction: visibility = 10 km, Desert extinction: visibility = 10 km and wind speed = 5m/s). The following assumptions were also used: 1) the LST estimated without considering aerosol content equals 300*K*; 2) the viewing angle equals 0°; and 3) the surface emissivity equals 1

Figure 3 shows the difference δT_s for six different atmosphere models and for five aerosol models as previously described. The results show that the difference δT_s is very sensitive to the atmospheric situation and depends also to the aerosol model. Indeed, we found that the variation in the atmospheric situation can provide a variation of δT_s equals 5.1*K* (this for aerosol model Radiative fog extinction). Therefore, we can conclude that the estimation of LST from satellite when the aerosol is considered is very sensitive and requires the real situation of the atmosphere.

We have shown in Figure 4 differences between LST when the Rural extinction (visibility = 5km) is considered with respect to atmosphere without aerosol content depending on the LST estimated without considering aerosol for six different atmosphere models (1: Tropical, 2: Mid-Latitude Summer, 3: Mid-Latitude Winter, 4: Sub-Arctic Summer, 5: Sub-Arctic Winter, and 6: 1976 U. S. Standard). The results show that for the six different atmosphere models described previously, the difference δT_s is negative for the lowest values of temperature and positive for the greatest values of temperature. Indeed, according to same figure we found that the variation in the LST estimated without considering aerosol can provides a variation on δT_s. Therefore, we can conclude that the estimation of LST from satellite, when the aerosol is considered, depends also on the LST.

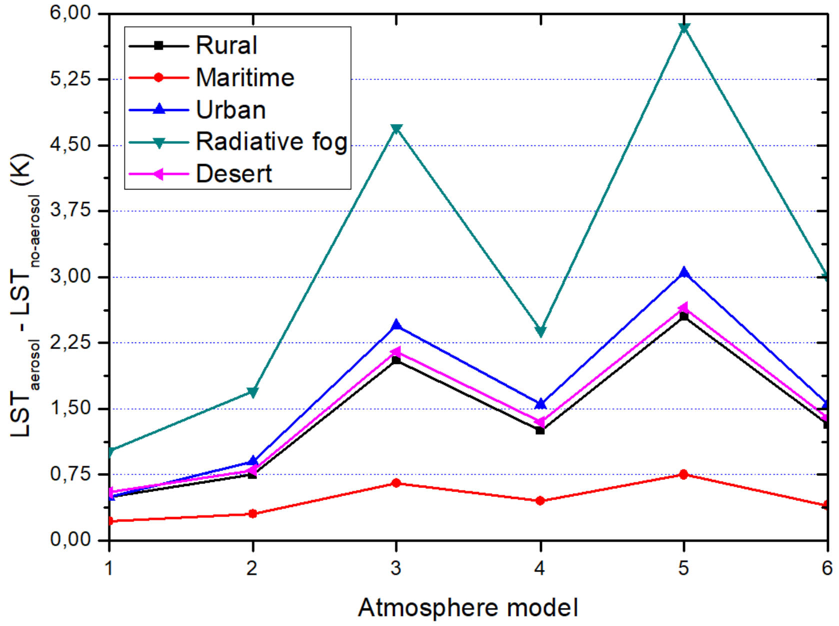

Figure 3. Differences between LST when the aerosol model is considered with respect to atmosphere without aerosol content for six different atmosphere models (1: Tropical, 2: Mid-Latitude Summer, 3: Mid-Latitude Winter, 4: Sub-Arctic Summer, 5: Sub-Arctic Winter, and 6: 1976 U. S. Standard)

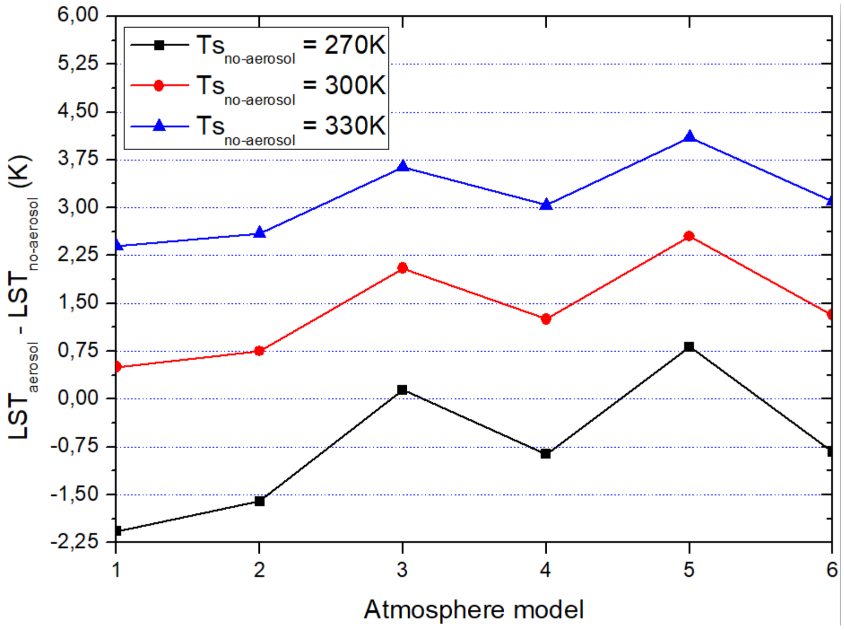

Figure 4. Differences between LST when the Rural extinction (visibility = 5km) is considered with respect to atmosphere without aerosol content depending on the LST estimated without considering aerosol for six different atmosphere models (1: Tropical, 2: Mid-Latitude Summer, 3: Mid-Latitude Winter, 4: Sub-Arctic Summer, 5: Sub-Arctic Winter, and 6: 1976 U. S. Standard)

3.3 Study of the effect of different type of aerosols

To study the effect of different types of aerosols on the determination of the LST, we have made a simulation with Modtran3.5 radiative transfer code for five different aerosol models (Rural extinction: visibility = 5km, Maritime extinction: visibility = 23 km, Urban extinction: visibility = 5 km, Radiative fog extinction: visibility = 10 km, Desert extinction: visibility = 10 km and wind speed = 5m/s). The following assumptions were also used: 1) the atmospheric model used is Mid-Latitude Summer; 2) the viewing angle equals 0°; 3) the surface emissivity equals 1.

Figure 5 shows the differences between atmospheric transmissivity without including the aerosols effect and considering different types of aerosols extinction. The results show that the lowest difference in transmissivity is 1.5%, which corresponds to the Maritime extinction with a default visibility of 23 km. In this case, the impact of aerosols is negligible and correction is not needed. However, there are great differences between the transmissivity for an atmosphere without aerosol content and an atmosphere with fog extinction and a visibility of 10 km. In Figure 6 we have shown the evolution of δT_s depending on the LST without including the aerosols effect. The results show that the lowest values of δT_s correspond also to the Maritime extinction with a default visibility of 23 km and the great values of δT_s correspond to the fog extinction with a visibility of 10 km. Therefore, from these results, we can conclude that the aerosols effect for fog extinction with a visibility of 10 km is important and correction is very required.

In Figure 7 we have shown the evolution of δT_s for different values of the visibility (in which the LST without including the aerosols effect equals 300K). The results show that the difference δT_s varies decreasingly with the visibility; this is due to the decrease in the optical thickness of aerosols. The results show also that the great values of δT_s correspond to the fog extinction.

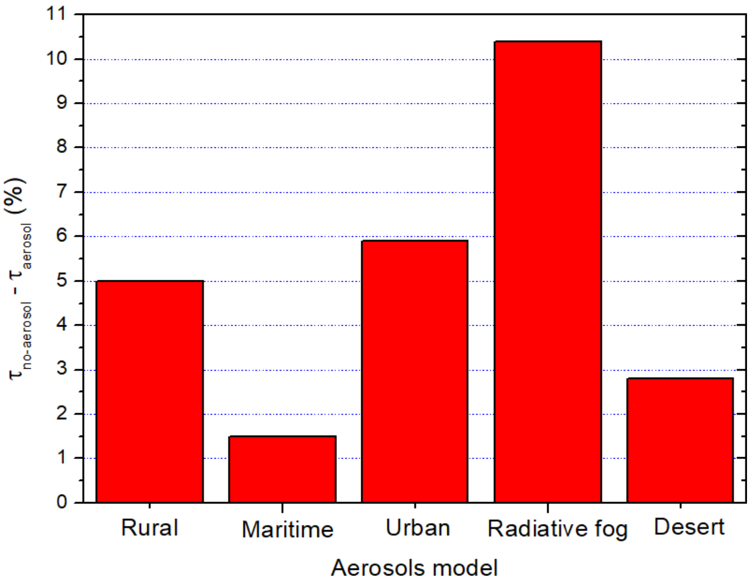

Figure 5. Differences between atmospheric transmissivity without including the aerosols effect and considering different types of aerosols extinction

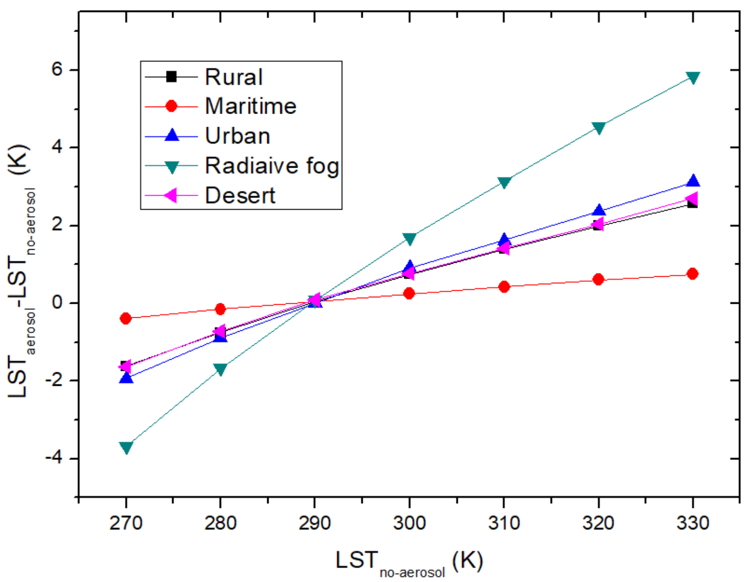

Figure 6. Differences between LST without including the aerosols effect and considering different types of aerosols extinction

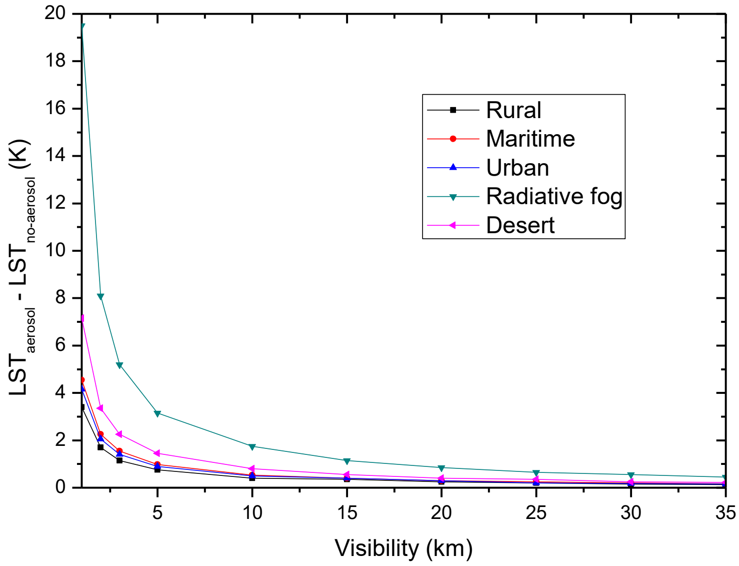

Figure 7. Differences between LST without including the aerosols effect and considering different types of aerosols extinction for different values of visibility

3.4 Study of the effect of desert-aerosol extinction

The Sahara and its borders constitute the main source of mineral dust, yielding over 50% of global production (Vergé-Dépré et al. 2006). In order to study the impact of the desert-aerosol extinction on the determination of the LST, we have used Modtran3.5 code for different values of visibility and wind speed. The following assumptions were used: 1) the atmospheric model used is Mid-Latitude Summer; 2) the viewing angle equals 0°; 3) the LST without including the aerosols effect equals 300*K*; and 6) the surface emissivity equals 1.

Figures 8 shows the differences between LST estimated without including the aerosols effect and considering desert-aerosol extinction depending on the wind speed and for different values of visibility. The results show that the lowest difference in LST corresponds to the lowest values of wind speed and corresponds to the greatest values of the visibility. In this case, the impact of aerosols is negligible and correction is not needed. It is clear that in the case of lowest values of visibility and for the greatest values of wind speed (~20 m/s) the acquisition of satellite data for estimating LST has no sense. Therefore, from these results, we can conclude that the desert-aerosol extinction in normal conditions is important and correction is very required.

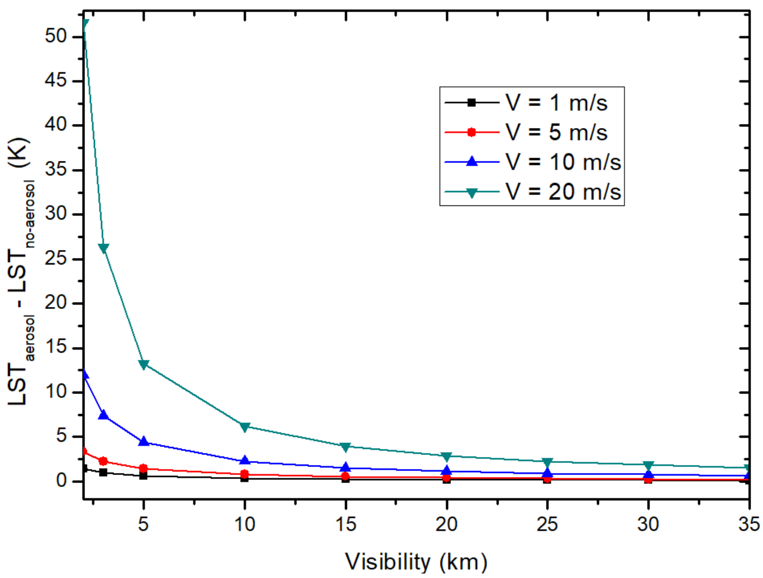

Figure 8. Differences between LST without including the aerosols effect and considering desert-aerosol extinction depending on the wind speed and for different values of visibility

3.5 Study of the effect of surface emissivity

The emissivity of surface has also an impact on the values of δT_s. Therefore, in order to show the impact of the surface emissivity, we have used Modtran3.5 code for different values of the surface emissivity. The following assumptions were used: 1) the atmospheric model used is Mid-Latitude Summer; 2) the viewing angle equals 0°; and 3) the aerosol model is Rural (visibility = 5 km).

In Figure 9 we have shown the difference between LST without including the aerosols effect and considering rural aerosol extinction depending on the LST without including the aerosols effect for different values of surface emissivity. The results show that the difference δT_s varies increasingly with the surface emissivity and with the LST without including the aerosols effect. Indeed, we found that the variation on surface emissivity can provides a variation on δT_s equals 0.74*K*. Therefore, we can conclude that the estimation of LST from satellite when the aerosol is considered depend also on the surface emissivity.

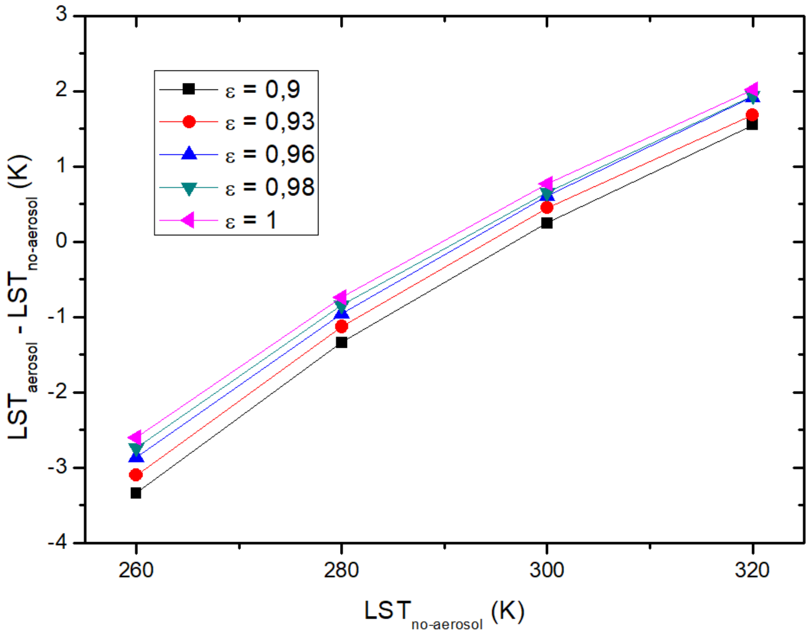

Figure 9. Differences between LST without including the aerosols effect and considering rural aerosol extinction depending on the LST without including the aerosols effect for different values of surface emissivity

4. Conclusion

An overall study for the impact of the aerosols on the estimation of land surface temperature from satellite thermal infrared data was presented. It includes:

- **Angular effects: :** The effects of the viewing angle on the difference (δT_s) between LST estimated when the aerosol model is considered with respect to atmosphere without aerosol content has been investigated. The results obtained showed that the difference δT_s varies increasingly with the viewing angle. We have concluded that the estimation of LST from satellite when the aerosol is considered is very sensitive and requires real value of the viewing angle.
- **Study of the effect of atmospheric situation:** We have concluded that the estimation of LST from satellite when the aerosol is considered is very sensitive and requires the real situation of the atmosphere. We have concluded also that the estimation of LST from satellite when the aerosol is considered depends also on the LST estimated without aerosols effect.
- **Study of the effect of different type of aerosols:** The results showed that the lowest values of difference δT_s corresponds to the Maritime extinction with a default visibility of 23 *km* and the great values of difference δT_s corresponds to the fog extinction with a visibility of 10*km*. The results showed that δT_s varies decreasingly with the visibility; this is due to the decrease in the optical thickness of aerosols.
- **Study of the effect of desert-aerosol extinction:** For the desert –aerosol extinction, the results showed that the lowest values of δT_s corresponds to the lowest values of wind speed and corresponds to the greatest values of the visibility. In this case, the impact of aerosols is negligible and correction is not needed.

The results showed also that the great values of δT_s corresponds to the greatest values of wind speed and corresponds to the lowest values of the visibility. Therefore, we have concluded that the desert-aerosol extinction in normal conditions is important and correction is very required.

- **Study of the effect of surface emissivity:** The results showed that the difference δT_s varies increasingly with the surface emissivity and with the LST without including the aerosols effect.

The overall result in this paper is that the difference δT_s depends on the following parameters: 1) the viewing angle, 2) the atmospheric situation, 3) the surface emissivity, 4) the values of the land surface temperature without aerosols effect itself, 5) the visibility of the atmosphere, and 6) the wind speed for the desert-aerosol extinction.

Therefore, for the enhancement of the estimation of LST from satellite, it is necessary to take into account the effects of the aerosol in the atmosphere.

Acknowledgments

The author would like to thank the three reviewers for their comments on our paper.

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