University of Tehran Press

Journal of the Earth and Space Physics

Homepage: https://jesphys.ut.ac.ir

Vol. 48, No. 4, Winter 2023, P. 161-172
(Research Article)

The Comparison of MODIS Land Surface Temperature with Meteorological Stations Measurements in Iran

Moradi, M.[1] | Salahi, B.[2]

1. Department of Zrebar Lake Environmental Research, Kurdistan Studies Institute, University of Kurdistan, Sanandaj, Iran. E-mail: moradimasood@ymail.com
2. **Corresponding Author**, Department of Physical Geography, Faculty of Social Science, University of Mohaghegh Ardabili, Ardabil, Iran. E-mail: bromand416@yahoo.com

(Received: 8 June 2022, Revised: 6 Nov 2022, Accepted: 10 Jan 2023, Published online: 5 March 2023)

Abstract

Land surface temperature (LST) plays a key role in the transfer of heat to the atmosphere and to the subsurface layers of soil. This study aims at examining the determination coefficient of MODIS LST on air temperature and soil temperature at different depths of Iran. A new method was employed to create a time consistent LST from Terra and Aqua MODIS products, to eliminate the observation differences in local solar time. Preceding the production of time consistent MODIS LST for 12:30 PM, a comparison was carried out with temperature measurements of meteorological stations. The correlation of MODIS LST and Meteorological Station Measurement (hereafter MSM) demonstrate high values, especially for air temperature and 5cm-deep subsurface soil temperature (R^2>0.95). The lowest value was obtained for 100cm-deep soil temperature (R^2=0.83). The results of intra annual analysis revealed significant relationship between MODIS LST and MSM temperatures. In the comparison of MODIS LST with subsurface soil temperatures, the scatter plot changes from 1:1 to fusiform due to the delay in heat transfer from surface to the subsurface of soil layers. This result postulates that MODIS LST is consonant with MSM temperatures in arid and semiarid regions of Iran. Spatial variation of correlation is higher for 100cm-deep soil temperature (16%). On the contrary, for air temperature and 5cm-deep soil temperature showing the highest correlation, the spatial variation is negligible throughout Iran (6.2%). However, Root Mean Square Error (RMSE) analysis revealed LST differences from 2.43 to 24.88 ˚C throughout Iran rather than MSM temperatures.

Keywords: Land Surface Temperature, MODIS, Time Consistent, Heat Transfer.

1. Introduction

Remote sensing is a beneficial method in surveying spatial and temporal changes on land surface that can monitor variant non-sustainable characteristics of land from local to global scales. Depending on satellite type (geostationary or polar orbiting), remote sensing can provide high resolution (temporal or spatial) coverage that is essential for maintainable development studies (Mendelson et al., 2007; Liu et al., 2021). Remote sensing data produce homogeneous surface temperature estimates on a global scale (Wang et al., 2005). LST plays a vital role in the interaction between the Earth surface and the atmosphere (Jimenez et al., 2012). Temporal and spatial variations of LST reflect the behavior of climatic factors and ground surface characteristics (Xu et al., 2013; Yu et al., 2021) and is the most effective method to drive the energy balance on a regional basis (Bhattacharya, 2005). The scarcity of meteorological stations in remote areas and complex mountainous terrains lead to the inaccurate estimation of temperature (Zeng et al., 2015). Climate variability in inhomogeneous terrains is strong, and factors like topography, land use, and soil humidity are the most effective factor in climate variation (Alfieri et al., 2013; Peng et al., 2020). Several researchers have studied remotely sensed temperatures in relation to the ground measurement. In some studies, satellite LST was compared to meteorological station temperature records (Benali et al., 2012; Diaz, 2013; Mostovoy et al., 2006; Zhu et al., 2019; Barbosa & Scotto, 2022); while, other studies have validated remotely sensed temperature using in situ radiometric measurements (Faysash et al.,

Cite this article: Moradi, M., & Salahi, B. (2023). The Comparison of MODIS Land Surface Temperature with Meteorological Stations Measurements in Iran. *Journal of the Earth and Space Physics*, 48(4), 161-172. DOI: http//doi.org/10.22059/jesphys.2023.343651.1007433

Publisher: University of Tehran Press.
DOI: http//doi.org/10.22059/jesphys.2023.343651.1007433

Print ISSN: 2538-371X
Online ISSN: 2538-3906

1999; Lei et al., 2010). In validation studies, the radiation from homogeneous sites like rice fields (Coll et al., 2009; Galve et al., 2007), lakes (Wan & Li, 2008; Wan et al., 2002), silt playa (Snyder et al., 1997), and dense vegetation (Wan & Li, 2008) was compared with the remotely sensed LST. In a different method, Lipton (1992) first estimated LST based on the slope and aspect of the mountains of Colorado and then compared it with satellite observations. In a comparative method, Colombi et al. (2007) employed MODIS LST to estimate the air temperature in snow-covered and bare ground surfaces at high altitudes of Alpine region. Comparison of the urban heat island resulted from LST and air temperature shows the coordination of the results. However, the intensity of urban heat island resulted from the LST is usually higher (Yang et al., 2020; Nascimento et al., 2022).

On the other hand, time differences between remotely sensed data and ground measurements are a major problem in comparing these two data sets. Estimation of diurnal temperature cycle from remotely sensed LST have been done based on physical or statistical methods that result in an estimation of the diurnal cycle of LST (Aires et al., 2004; Ignatov & Gutman, 1998; Jin & Dickinson, 1999; Quan et al., 2014). A distinct method is the estimation of time consistent LST from remotely sensed data to produce LST for a specific time (Duan et al., 2014). Several studies have been devoted to study the relationship between air temperature and soil depth temperature in different time scales (Smerdon et al., 2006; Mackiewicz, 2012), and still it has been employed for the prediction of temperature trend (Chudinova et al., 2006; Zhan et al., 2019).

In this study, we aim to calculate a time consistent LST from MODIS Terra and Aqua daytime LST in order to resolve the problem of time observation difference of pixels and make remotely sensed data consistent with MSM. Finally, a correlation is made between MODIS LST and MSM (air temperature, and subsurface soil temperature at a depth of 5 to 100 cm) in Iran. Hence, the purpose of this study is to examine the coefficient of determination of MODIS LST on air temperature and soil temperature at different depths. The goal is to study the relationship between MODIS LST and temperature of air and soil depths in order to examine whether the use of remotely sensed temperature data show a logical relationship between these two data sets 2002 to 2010 throughout Iran.

2. Materials and Methods

Terra and Aqua daily MODIS LST products were downloaded from NASA earth data website https://search.earthdata.nasa.gov/search. In this research, MODIS LST product was used. Atmospheric and radiometric corrections have been made for these data. Furthermore, the pixels containing clouds cover, which have affected the quality of the LST, have been removed from the data. The selected time series started in July 8, 2002 (date from which MODIS Aqua is available) and ended in December 31, 2010 (the last available time series of MSM temperatures data in this research).

Terra and Aqua daytime overpasses are from 10 to 12 AM and 12 to 14 PM local time, respectively. Due to the basic properties of scanning in MODIS sensor onboard the polar-orbiting satellites, the local solar time is different for pixels along a given scan line in a day, or for a pixel on different days in one revisit duration (Duan et al., 2014). Regarding this problem and to provide the LST time series that can be consistent with the observation time at ground stations (12:30 PM), the following procedure was adopted.

$$SLP = \frac{Dlst}{Dt} \qquad Dlst = lstad - lsttd$$
$$Dt = tad - ttd \tag{1}$$

where *SLP* is the ratio of LST difference to the local time difference for Terra and Aqua, daytime observations calculated in Kelvin/hour, *Dlst* is the difference between Aqua day LST (*lstad*) and Terra day LST (*lsttd*) in Kelvin, and *Dt* is the difference between Aqua day local time (*tad*) and Terra day local time (*ttd*) in terms of hours. The calculated *SLP* was used to produce land surface temperature at 12:30 PM local time for every pixel using Equation (2).

$$LST_{12:30} = lstad - SLP * (tad - 12.5) \tag{2}$$

Air and soil temperature parameters are measured in meteorological stations in 8 and

3 times per day respectively. Here, we apply temperature parameters including the air temperature at a height of 2 meter (T-air), and soil temperature in subsurface levels of 5, 10, 20, 30, 50, and 100 cm (T-soil05, T-soil10, T-soil20, T-soil30, T-soil50 and Tsoil100). All of these parameters were obtained from Iran Meteorological Organization (IRIMO) in 294 meteorological stations throughout the country. The stations are located in various land cover types and different climate regions such as arid and desert regions, shorelines, dense vegetation covers, and mountainous regions with sparse to dense vegetation cover. Temperature measurements were selected at 12:30 PM local time (9 GMT) for comparison with time consistent MODIS LST data. MODIS scientific dataset (Wan, 2007) are used for quality control of LST data. In this way, only good quality pixels (code=00: not affected by cloud cover or other reasons) are selected for LST analysis. There is no recommendation for the examination of quality assurance for these pixels in the user guide report of MODIS LST product.

Following the identification of pixel locations and the meteorological stations located in it, the LST values in the time series were recalled from MODIS LST pixels. Coefficient of determination was calculated between MODIS LST observation and every seven parameters of MSM temperatures (T-air, and Tsoil05–Tsoil100). Mean temperature time series was calculated from all 294 MSM and compared with their mean LST values. Long term mean temperature calculated for every day of the year using the time series of data and then Intra annual correlation between MODIS LST and MSM temperatures was examined, using daily long term mean temperature. The R^2 values were used to demonstrate the correlation of MODIS LST with MSM temperatures.

Spatial variation of the relationship between MODIS LST and MSM temperatures was examined by utilizing their coefficient of determination and finally, the values of R^2 statistic were mapped for every 294 MSM to reveal the spatial variation of LST/MSM correlation in Iran. Nearest neighborhood interpolation was applied for mapping of the R^2 values.

In order to check the difference between MODIS LST and MSM temperatures, root mean square error (RMSE) was calculated. The RMSE values obtained for each of the MSM temperatures have been clustered using hierarchical cluster analysis and Ward method. Then, the average RMSE values in each of the determined clusters were calculated and the spatial distribution was checked for the clusters.

3. Results and Discussion

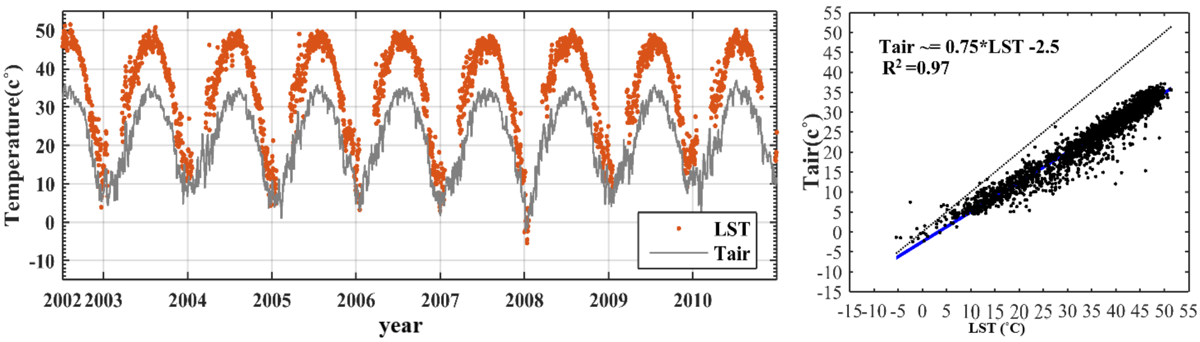
3-1. Correlation coefficient

Daily time series of MODIS LST and T-air demonstrates a high coefficient of determination ($R^2 = 0.97$). LST is higher than T-air in most time of the year. The difference between LST and T-air increases in warm seasons and is in line with an increase in air temperature. On the contrary, the difference decreases and LST values are very close to T-air measurements in cold seasons. In early 2003, 2006, and 2008, LST was generally lower than T-air (Figure 1A). The high coefficient of determination can be used to resolve the air temperature using satellite data (Kloog et al., 2017). T-soil05 shows the smallest difference to LST, because the land surface receives direct solar radiation and experiences higher temperature, but for air and soil temperature, heat conductivity controls the transition of heat from surface to the depth, hence it controls the soil temperature variations.

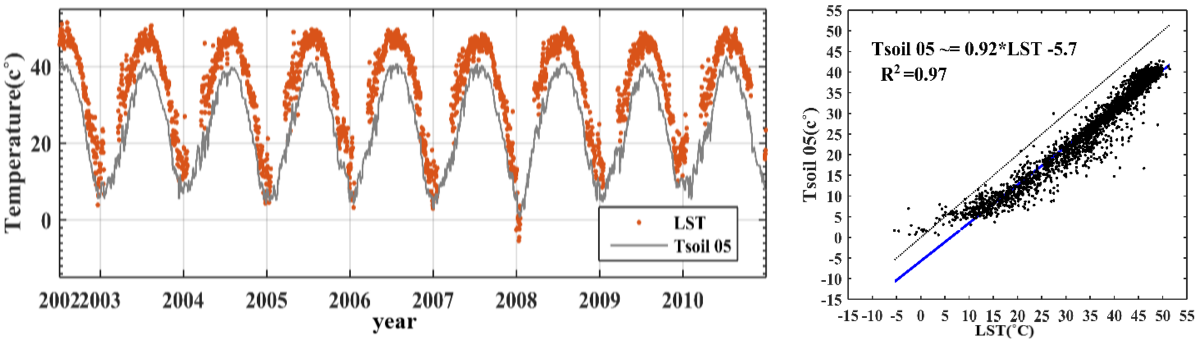
The surface heat transfer to 5cm-deep soil occurs sooner than deeper soils. Consequently, it shows the highest coefficient of determination to LST ($R^2 = 0.97$ $\beta = 0.92$). The difference between LST and T-soil increases with an increase in soil depth, due to the distribution of energy in greater soil mass. In other words, heat conductivity and the density of soil, controls the distribution of the energy in the soil and determine the relationship between LST and T-soil in various depths. When the soil temperature varies close to the freezing point, this relationship becomes more complex. In such cases, the energy transfer is minimized and the difference between LST and soil temperature is maximized. Therefore, despite a decrease in LST values, the subsurface temperatures remain constant because heat transfer between the surface and the depth has been reduced (Figures 1B to 1D, and

Figure 2). The more complex behavior of the relationship between satellite-derived LST and the soil temperature close to the freezing point might also be explained by the relatively high energy required to thaw or freeze water. In a wet soil layer, consumption or release of latent heat leads to thawing or freezing processes. This mechanism affects thermal regimes in cold seasons of the year.

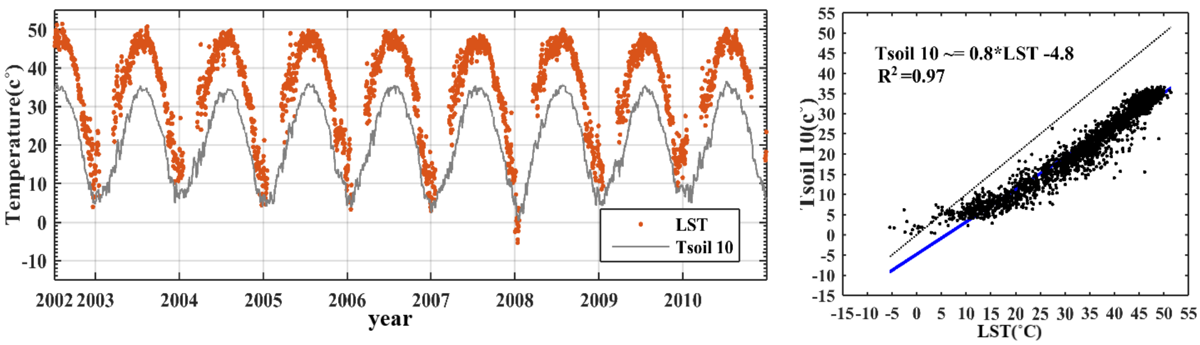
Analysis of daily time series of MODIS LST and MSM temperatures show an annual cycle that is repeated every year with a small inter annual variation (Figures 1 and 2). Daily long-term mean temperatures can provide more details of intra annual temperature variations. Due to the delay in heat transfer to deeper soil layers, the T-soil of various depths shows different intra annual variation in comparison to LST. In warm seasons, LST is higher than all T-soil, while LST are lower than T-soil in cold seasons, especially at a depth of 50 and 100 cm (Figures 2B and 2C). Therefore, in subsurface layers from 5 to 100 cm, the correlation between LST and T-soil changes from 1:1 linear relationship to fusiform pattern that is wide in the middle and taper at both ends (Figures 3F and 3G). Scatter plots for LST and T-soil in 10, 20, and 30 cm show asymmetric fusiform (Figures 3C to 3E). It implies that the soil temperature in deeper layers is higher (lower) than the surface temperature in cold (warm) seasons (Figure 2). In other words, the relationship between LST and T-soil follows nonlinear in cold and warm seasons.



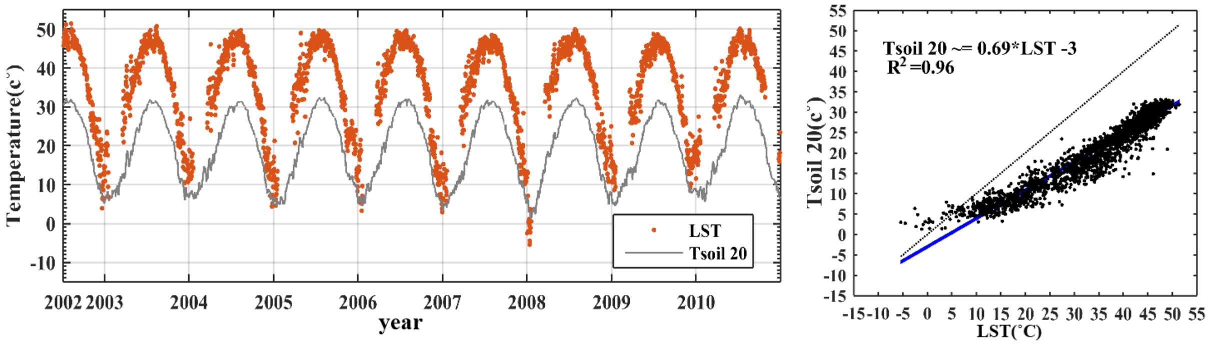
(a)



(b)

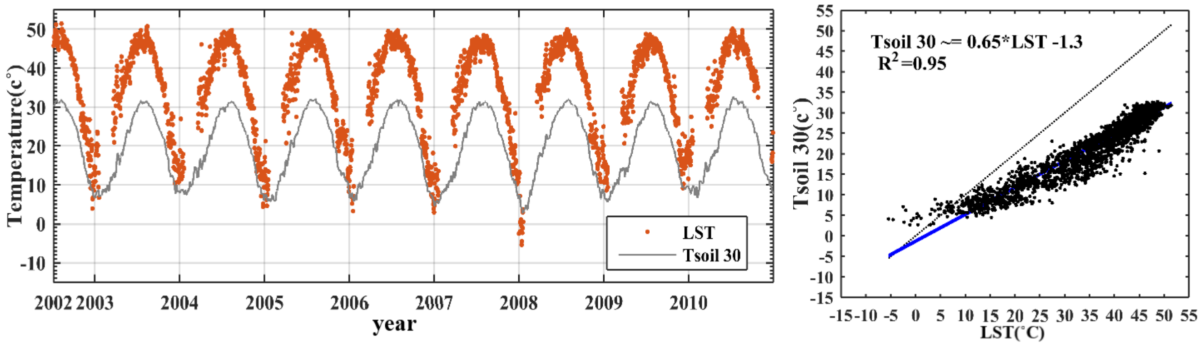


(c)

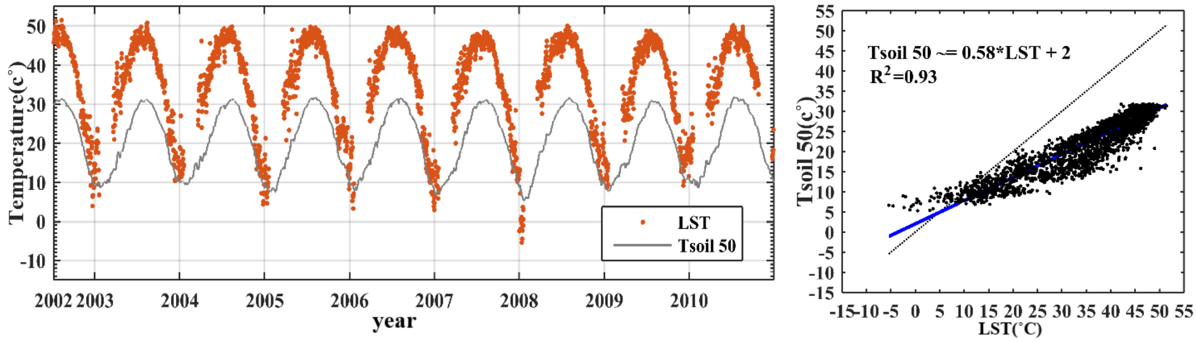


(d)

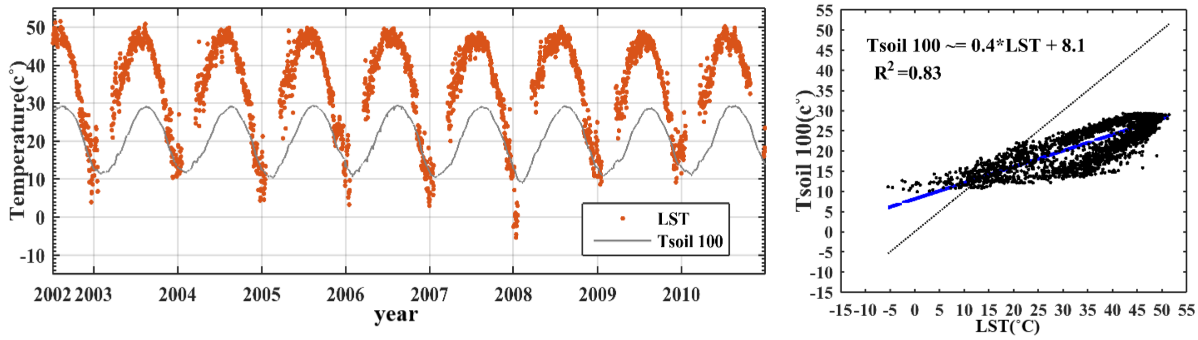
Figure 1. Daily time series of MODIS LST and MSM temperatures includes air temperature (a), and soil temperatures at a depth of 5 cm (b), 10 cm (c), and 20 cm (d) on the left side, and the best fit line on the right side. The time series is the average of 294 MODIS LSTs and MSM temperatures.



(a)



(b)



(c)

Figure 2. Daily time series of MODIS LST and MSM temperatures include soil temperature in 30 cm (a), 50 cm (b), and 100 cm (c) depths in the left side, and the best fit line (right side). The time series is the average of 294 MODIS LSTs and MSM temperatures.

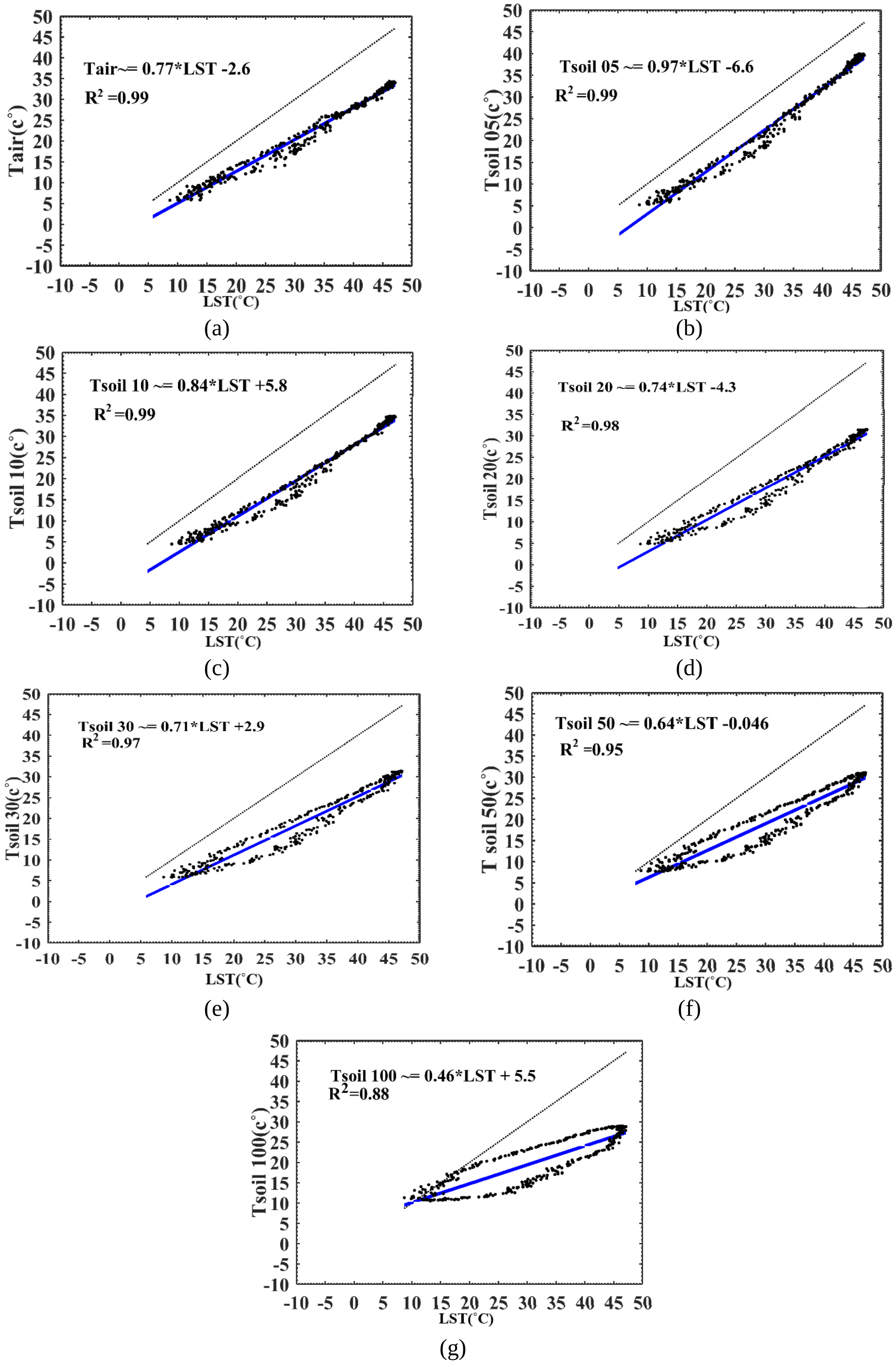


Figure 3. Best-fit line between MODIS LST and MSM temperature includes T-air (a), and T-soil in 5 to 100 cm soil depths (b-g) for daily mean of selected time series.

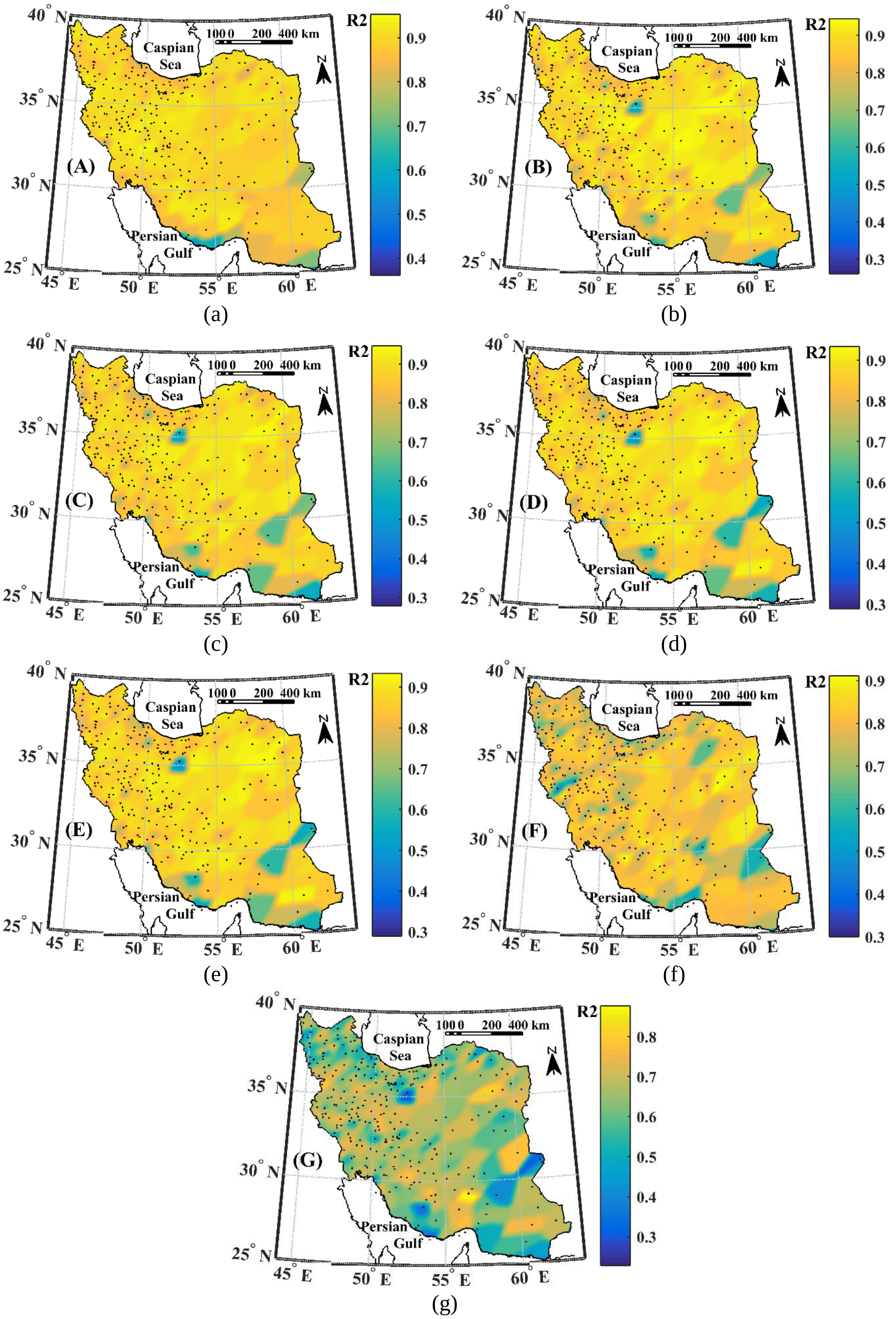


Figure 4. Spatial variation of R^2 values between MODIS LST and MSM temperatures includes T-air (a), and T-soil in 5, 10, 20, 30, 50, and 100 cm soil depths (b-g) respectively.

3-2. Spatial analysis of correlation coefficient

In order to detect the spatial consistency of MODIS LST correlation with MSM temperatures, the coefficient of determination were mapped. There are strong correlations between MODIS LST and T-air in most parts of Iran with negligible spatial variations (Figure 4A). Consequently, we can say that MODIS LST is a good estimator for air temperature in different parts of the country. With regards to sparse and disordered MSMs, particularly in deserts and at high altitudes, using MODIS LST data with much higher resolution than that of MSM is highly recommended in studying spatial behavior of temperature. High coefficient of determination with low spatial variations was also obtained for soil depth of 5 to 30 cm (Figures 4B to 4E). For T-soil under 30 cm, coefficient of determination have been weakened in most regions. By a decrease in correlation, the spatial variations increase particularly for Tsoil100 (Figure 4G). Interpolation of R^2 values in Iran shows that some stations, generally on the southern coast or the islands close to it, are lower than other regions.

The mean of correlation between LST and each of the MSM temperatures alongside the coefficient of variation of the correlation are given in Table 1. As expected, the mean of MSM air temperature correlation with MODIS LST in Iran enjoyed the most value and its coefficient of variation was also the least. On the contrary, the Tsoil100 demonstrated the higher coefficient of variation of R^2 with the least mean of correlation throughout Iran.

3-3. Accuracy assessment with RMSE

The clustering of RMSE between MSM temperatures and MODIS LST in Iran shows a significant variation throughout MSM temperatures. However, spatial distribution analysis shows that some clusters are located in specific regions with homogeneous environmental and climatological characteristics. For example, in all the RMSE values, the stations located in the Caspian Sea coastal region, and some stations of the southern coast are located in one cluster (Figure 5) and show a lower RMSE values. The significant reduction of RMSE values in this cluster (1.7 to 2.7) compared to other clusters indicates the low difference between the MSM temperatures and the MODIS LST in humid coastal areas (clusters 5 and 6 in Table 2). Another cluster that shows a specific spatial distribution especially in the difference of T-air and LST (cluster 4) includes the stations of arid central region and the eastern part of Zagros mountain range (Figure 5). Unlike the coastal areas, the RMSE values in this cluster have recorded the largest difference, which can be related to the mostly arid climate of these stations and its effect on the increase of RMSE (Table 2). On the other hand, Tsoil05 has the lowest difference ($3.01<RMSE<9.33$) and air temperature has the highest correlation with MODIS surface temperature ($R^2<0.91<0.85$). The results in this regions are more consonant with other researches done in tropical (Diaz, 2013) and Mediterranean (Benali et al., 2012) climates. However, arid and semiarid regions show higher RMSE values (up to 12 ˚C) despite that of high correlations ($R^2>0.9$).

Table 1. Mean coefficient of determination between LST and MSM temperatures, and the R^2 coefficient of variation (CV) in Iran.

MSM temperatures	Mean R^2 with LST	CV (%)
T-air	0.89	6.15
T-soil05	0.86	9.45
T-soil10	0.86	9.49
T-soil20	0.85	9.94
T-soil30	0.85	9.94
T-soil50	0.78	13.35
T-soil100	0.64	16.00

Table 2. Average of Clustered RMSE and corresponding R2 values.

Clusters / Temperature	1		2		3		4		5		6	
	R2	RMSE	R2	RMSE	R2	RMSE	R2	RMSE	R2	RMSE	R2	RMSE
T-air	0.89	7.56	0.91	9.87	0.87	4.77	0.90	12.21	0.85	1.77	-	-
Tsoil05	0.87	6.63	0.88	4.88	0.84	3.01	0.88	9.33	-	-	-	-
Tsoil10	0.87	8.37	0.89	11.58	0.83	3.17	0.87	5.91	-	-	-	-
Tsoil20	0.86	10.23	0.84	8.37	0.82	5.99	0.88	12.01	0.88	14.24	0.81	2.68
Tsoil30	0.87	10.72	0.85	8.61	0.87	13.14	0.82	5.72	0.81	2.62	-	-
Tsoil50	0.81	11.35	0.80	9.69	0.78	7.87	0.80	13.88	0.75	4.03	-	-
Tsoil100	0.66	12.62	0.68	11.17	0.63	8.05	0.67	14.66	0.63	2.43	0.59	5.34

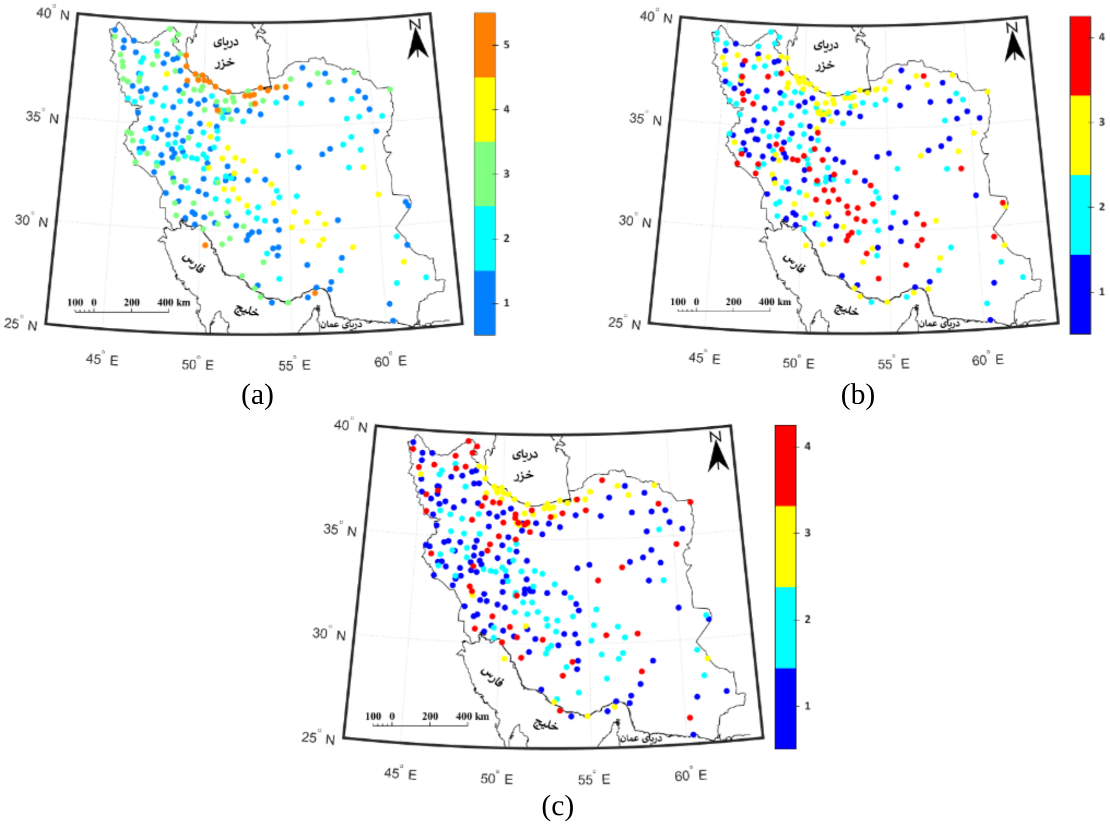


Figure 5. RMSE clusters throughout Iran for T-air/LST (a), Tsoil05/LST (b), and Tsoil10/LST (c)

4. Conclusion

MODIS LST was compared with seven MSM temperature parameters in Iran. The highest coefficient of determination and lowest RMSE (1.77 and 3.01 ˚C in coastal humid regions) were obtained for MODIS LST in comparison to the air temperature and Tsoil05 respectively. MODIS LST was found to be higher than MSM temperatures in the warm seasons, but it was close to MSM in cold seasons. Inter and intra annual variations of MODIS LST in comparison to MSM temperatures demonstrated coordinate changes that exhibited the effect of surface temperature on air and soil temperatures. With an increase of incoming energy in the daytime of the warm season and its accumulation on the land surface, LST demonstrates significant increase relative to T-air. LST is 15 to 20°C higher than T-air with maximum values in warm season. During the cold season, the difference between them is decreased up to 5°C and the MODIS LST generally shows values higher than T-air. Similar results were approved in arid and semiarid regions in the north of Tibetan plateau (Zhu et al., 2019). Concerning Iran natural features with sparse vegetation cover and arid to semiarid climate in most areas, it can be concluded that the T-air is significantly underestimated relative to radiant temperature on the land surface.

Delay in transferring heat to deep layers and distributing surface heat energy to a larger volume of soil, control variations in correlation between LST and T-soil of various depths. In deeper layers of the soil, the scatter plot shows more dispersion. The comparison of daily long-term mean LST and MSM temperatures demonstrate linear correlation for T-air and Tsoil05, while for deeper soil layers, these correlation reshape to fusiform that represents the difference between surface and deeper soil temperatures in warm and cold periods of the year. The pattern of the scatter plot for LST and deeper soil layers at freezing temperatures is distinct from non-freezing temperatures and show that the interactions between surface and subsurface temperatures have been reduced by freezing of the land surface.

T-air and T-soil05 showed the highest coefficient of determination for LST, which is uniform in all stations observed; it showed that LST was highly correlated with MSM temperatures particularly for T-air and T-soil05 in different regions of Iran. Therefore, we can employ MODIS LST as a much higher resolution dataset in temperature studies as well as in deserts and at high altitudes where MSM is unavailable or sporadic in Iran. Lower correlation of LST with MSM temperatures in southern islands and shoreline may be due to the atmospheric moisture that can affect the quality of MODIS LST data (Wan, 1999). Soil temperature is decreased during the freezing process. This is attributed to the release of the latent heat resulting from freezing of water content of the soil. During the warming and melting, the latent heat is consumed to melt the ice. Latent heat consumption and release in upper soil layer result in more temperature stabilization in soil depth and reduce thermal conductivity between the surface and depth.

References

Aires, F., Prigent, C., & Rossow, W.B. (2004). Temporal interpolation of global surface skin temperature diurnal cycle over land under clear and cloudy conditions. *J. Geophys. Res*, 109, 1-18, DOI: 10.1029/2003JD003527.

Alfieri, S.M., Lorenzi, F.D., & Meneti, M. (2013). Mapping air temperature using time series analysis of LST: the SINTESI approach. *Nonlinear Process Geophys*, 20, 513–527, DOI: 10.5194/npg-20-513.

Benali, A., Carvalho, A.C., Nunes, J.P., Carvalhais, N., & Santos, A. (2012). Estimating air surface temperature in Portugal using MODIS LST data. *Remote Sens. Environ*, 124, 108–121, DOI: 10.1016/j.rse.2012.04.024.

Bhattacharya, B.K., Dadhwal, V.K., & Sorokovikov, V.A. (2005). Land surface temperature retrieval and its validation using NOAA AVHRR thermal data. *J. Indian Soc. Remote*, 33, 321-338.

Barbosa, S., & Scotto, M.G. (2022). Extreme heat events in the Iberia Peninsula from extreme value mixture modeling of ERA5-Land air temperature. *Weather and Climate Extremes*, 36, 1-11.

Chudinova, S.M., Frauenfeld, O.W., Barry, R.G., & Zhang, T. (2006). Relationship between air and soil temperature trends and periodicities in the permafrost regions of Russia. *J. Geophys. Res.*, 111, 1-15, DOI: 10.1029/2005JF000342.

Coll, C., Wan, Z., & Galve, J.M. (2009). Temperature-based and radiance-based validations of the V5 MODIS land surface temperature product. *J. Geophys. Res.*, 114, 1-15, DOI: 10.1029/2009JD012038.

Colombi, A., Michele, C.D., Pepe, M., & Rampini, A. (2007). Estimation of daily mean air temperature from MODIS LST in Alpine areas. *EARSeLe Proceedings*, 6(1), 38-46.

Diaz, R.C. (2013). Evaluation of MODIS Land products for air temperature estimations in Colombia. *Agron. Colomb*, 31(2), 223-233.

Duan, S.B., Li, Z.L., Tanga, B.H., Wu, H., & Tang, R. (2014). Generation of a time-consistent land surface temperature product from MODIS data. *Remote Sens. Enviro.*, 140, 339–349, DOI: http://dx.doi.org/10.1016/j.rse.2013.09.003.

Faysash, D., Eric, A., & Smith, A. (1999). Simultaneous Land Surface Temperature–Emissivity Retrieval in the Infrared Split Window. *J. Atmos. Oceanic Technol.*, 16, 1674-1689.

Galve, J.M., Coll, C., Caselles, E.V., Niclos, R., Sanchez, J.M., & Mira, M. (2007). Simulation and validation of land surface temperature algorithms for MODIS and AATSR data, Tethys, 4, 27–32, DOI: 10.3369/tethys.2007.4.04.

Ignatov, A., & Gutman, G., 1998, Diurnal cycles of land surface temperatures. *Adv. Space Res.*, 22(5), 641-644.

Jiménez, C., Prigent, C., Catherinot, J., Rossow, W., Liang, P., & Moncet, J.L. (2012). A comparison of ISCCP land surface temperature with other satellite and in situ observations. *J. Geophys. Res.*, 117, 1-8, DOI: 10.1029/2011JD017058.

Jin, M., & Dickinson, R.E. (1999). Interpolation of surface radiative temperature measured from polar orbiting satellites to a diurnal cycle 1. Without clouds. *J. Geophys. Res.*, 104, 2105-2116.

Kloog I., Nordio, F., Lepeule, J., Padoan, A., Lee, M., Auffrayg, A., & Schwartzb, J. (2017). Modelling spatio-temporally resolved air temperature across the complex geo-climate area of France using satellite-derived land surface temperature data. *Int. J. Climatol.*, 37, 296–304. DOI: 10.1002/joc.4705.

Lei, Z., Yaoming, M.A., Zhongbo, S.U., & Salama, M.S. (2010). Estimation of Land Surface Temperature over the Tibetan Plateau Using AVHRR and MODIS Data. *Adv. Atmos. Sci.*, 27(5), 1110–1118, DOI: 10.1007/s00376-009-9133-0.

Lipton, A.E. (1992). Effect of slope and aspect variations on satellite surface temperature retrievals and mesoscale analysis in mountainous terrain. *J. Appl. Meteorol.*, 31(3), 255-264.

Liu, Y., Ortega-Farías, S., Tian, F., Wang, S., & Li, S. (2021). Estimation of Surface and Near-Surface Air Temperatures in Arid Northwest China Using Landsat Satellite Images. *Front. Environ. Sci.*, 9, 1-17.

Mackiewicz, M.C. (2012). A new approach to quantifying soil temperature responses to changing air temperature and snow cover. *Polar Sci.*, 6, 226-236, DOI: http://dx.doi.org/10.1016/j.polar.2012.06.003.

Mendelson, R., Kurukulasuriya, P., Basist, A., Kogan, F., & Williams, C. (2007). Climate analysis with satellite versus weather station data. *Clim. Change*, 81, 71–83, DOI: 10.1007/s10584-006-9139-x.

Mostovoy, G.V., Roger, L.K., Reddy, K.R.V., Kakani, G., & Filippova, M.G. (2006). Statistical estimation of daily maximum and minimum air temperatures from MODIS LST data over the state of Mississippi. *GIsci Remote Sens.*, 43, 78-110, DOI: http://dx.doi.org/10.2747/1548-1603.43.1.78.

Nascimento, A., Galvani, E., Gobo, J., & Wollmann, C. (2022). Comparison between Air Temperature and Land Surface Temperature for the City of São Paulo. *Brazil*, *Atmosphere*, 13, 1-21.

Peng, X., Wu, W., Zheng, Y., Sun, J., Hu, T., & Wang, P. (2020). Correlation analysis of land surface temperature and topographic elements in Hangzhou, China. *Sci. Rep.*, 10, 1-16.

Quan, J., Chen, Y., Zhan, W., Wang, J., Voogt, J., & Li, J. (2014). A hybrid method combining neighborhood information from satellite data with modeled diurnal temperature cycles over consecutive days. *Remote Sens. Environ.*, 155, 257–274, DOI: http://dx.doi.org/10.1016/j.rse.2014.08.034.

Smerdon, J.E., Pollack, H.N., Cermak, V., Enz, J.W., & Kresl, M. (2006). Daily, Seasonal, and annual relationships between air and subsurface temperatures. *J. Geophys. Res.*, 111, 1-12, DOI: 10.1029/2004JD005578.

Snyder, W.C., Wan, Z., Zhang, Y., & Feng, Y.Z. (1997). Requirements for satellite land surface temperature validation using a Silt Playa. *Remote Sens. Environ.*, 6(2), 279–289.

Wan, Z. (1999). MODIS Land-Surface Temperature Algorithm Theoretical Basis Document (LST ATBD), University of California, Santa Barbara.

Wan, Z., & Li, Z.L. (2008). Radiance-based validation of the V5 MODIS land-surface temperature product. *Int. J. Remote Sens*, 29(17), 5373–5395, DOI: http://dx.doi.org/10.1080/01431160802036565.

Wan, Z., Zhang, Y., Zhang, Q., & Li, Z.L. (2002). Validation of the land-surface temperature products retrieved from Terra Moderate Resolution Imaging Spectroradiometer data. *Remote Sens. Environ.*, 83, 163–180.

Wan, Z. (2007). Collection-5 MODIS land surface temperature products users' guide. *ICESS, University of California, Santa Barbara.*

Wang, K., Wan, Z., Wang, P., Sparrow, M., Liu, J., Zhou, X., & Haginoya, S. (2005). Estimation of surface long wave radiation and broadband emissivity using Moderate Resolution Imaging Spectroradiometer (MODIS) land surface temperature/emissivity products. *J. Geophys. Res.*, 110, 1-13, DOI: 10.1029/2004JD005566.

Xu, Y., Shen, Y., & Wu, Z. (2013). Spatial and temporal variations of land surface temperature over the Tibetan plateau based on harmonic analysis. *Mt. Res. Dev.*, 33(1), 85–94, DOI: http://dx.doi.org/10.1659/MRD-JOURNAL-D-12-00090.1.

Yang, C., Yan, F., & Zhang, S. (2020). Comparison of land surface and air temperatures for quantifying summer and winter urban heat island in a snow climate city. *J. Environ. Manage.*, 265, 1-14.

Yu, Y., Duan, S.B., Li, Z.L., Chang, S., Xing, Z., Leng, P., & Gao, M. (2021). Interannual Spatiotemporal Variations of Land Surface Temperature in China From 2003 to 2018. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.*, 14, 1783-1795. doi: 10.1109/JSTARS.2020.3048823

Zeng, L., Brian, D.W., Tadesse, T., Shan, J., Hayes, M.J., Li, D., & Xiang, D. (2015). Estimation of daily air temperature based on MODIS land surface temperature products over the Corn Belt in the US. *Remote Sens*, 7, 951-970, DOI: 10.3390/rs70100951.

Zhan, M., Xia, L., Zhan, L., & Wang, Y. (2019). Recognition of Changes in Air and Soil Temperatures at a Station Typical of China's Subtropical Monsoon Region (1961–2018). *Adv. Meteorol*, 2019, 1-10.

Zhu, X., Zhang, Q., Xu, C.Y., Sun, P., & Hu, P. (2019). Reconstruction of high spatial resolution surface air temperature data across China: A new geo-intelligent multisource data-based machine learning technique. *Science of the Total Environment*, 665, 300-313.