Satellite-Based Analysis of Extreme Land Surface Temperatures and Diurnal Variability Across the Hottest Place on Earth

Marzi Azarderakhsh, Satya Prakash, Yunxia Zhao, and Amir AghaKouchak

***Abstract*— Understanding land–atmosphere interactions in extremely hot environment offers insights on how such interactions will change in a warmer world. For this reason, scientists from a wide range of fields, including hydrology, meteorology, ecology and geology, have been interested in identifying the hottest places on Earth. A study back in 2006 based on the moderate resolution imaging spectroradiometer (MODIS) land surface temperature (LST) data identified the Lut Desert in Iran as the "thermal pole of the Earth." Since then, Lut Desert has been regarded as the hottest place on Earth with the record temperature of 70.7 °C observed in 2005. Using the latest MODIS-derived LST collection 6 which offers an improved LST estimates with a high spatial resolution (1 km), we investigate the hottest temperatures, as well as its diurnal variability in Lut Desert. The results show that Lut Desert is much hotter than previously thought with a record LST of 80.83 °C in 2018 (approximately 10 °C higher than previously reported LST) mainly due to improvements in the new LST estimations from space, and use of higher spatial resolution of the data. Further, our results show that Lut Desert has an incredible diurnal variability range, up to around 71 °C depending on the season.**

***Index Terms*— Extreme temperature, land surface temperature (LST), Lut Desert, moderate resolution imaging spectroradiometer (MODIS), remote sensing.**

I. Introduction

IDENTIFYING the hottest place on Earth has always been of interest to a broad range of scientists including meteorologists, geologists, and ecologist [1], [2]. However, the hottest places are often in remote desert environments with limited ground-based observations or even accessibility [3]. A 2006 study based on land surface temperature (LST) data from the moderate resolution imaging spectroradiometer (MODIS) sensor identified the Lut Desert (also known as Dasht-e Lut) in Iran as the "thermal pole of the Earth" [1]. Since then, Lut Desert has been regarded as the hottest place on Earth with the record temperature of 70.7 °C observed in 2005 [1], [4].

LST is a key variable for understanding land–atmosphere interactions, climatic changes, and also ecosystem variability and change [5]–[7]. LST is also an important variable for estimating the upwelling longwave radiation, and sensible and latent heat fluxes. Generally, LST or land skin temperature can be measured using *in situ* devices, and satellite-based or aircraft-/drone-mounted radiation thermometers [8]–[10]. The satellite-based LST can be estimated globally using MODIS after removing the effects of atmospheric attenuation on space-based radiances [10]–[14].

Several studies have investigated LST across different spatial scales using earlier versions (e.g., collection 5 or earlier) of MODIS-derived LST products [2], [3], [15]. In this letter, we investigate LST in the hottest place on Earth using the latest version of MODIS-derived LST (collection 6) at a much finer spatial resolution (1 km) compared to previous studies (see Section III). Overall, in recent years, the quality of LST observations have improved significantly, typically ranging within 0.5 °C–1 °C for clear sky conditions [7], [14]. Recent evaluation studies indicate that with respect to biases and errors, the MODIS-derived collection 6 LST product exhibits substantial improvement relative to the previous versions, primarily due to improvements in the split-window retrieval algorithm, and the adjustment in the emissivity difference for bare soil (e.g., [16]). The overarching goal of this letter is to shed light on LST extremes and their diurnal variability in Lut Desert, known as the hottest place on Earth, based on satellite observations.

II. Study Area; Lut Desert

The Lut Desert, widely referred to as Dasht-e Lut, is a large salt desert located in the provinces of Kerman and Sistan, and Baluchestan, Iran. Eastern part of Lut Desert consists of a vast stretch of sand dunes, whereas the western part is characterized by Kaluts (also known as Yardangs) [17]–[19]. Kaluts are formations created by wind abrasion and deflation [4], [17]. In fact, strong winds are common in extremely hot environments where diurnal temperature difference is very high [3], [20]. This approximately 51 800 km^2 desert environment includes a wide range of land surface conditions from yellowish-red Pleistocene clay to black sand deposits, and dark volcanic materials. It displays significant variability in surface reflectance across space.

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Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

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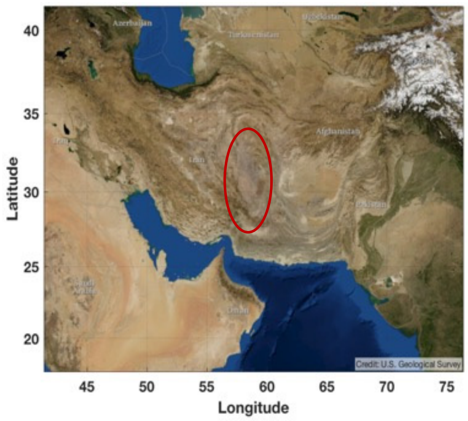

Fig. 1. Location of Lut Desert (shown by oval shape) and its surrounding regions based on USGS topographic imagery.

The study area extends from 45°E to 75°E longitude and 20°N to 40°N latitude including Lut Desert, Zagros and Alborz mountains, parts of Caspian Sea, Persian Gulf, and its neighboring countries with mainly desert and semiarid environment, Afghanistan, and parts of Tajikistan that overall forms an area with very diverse land-cover types, and climate regimes (Fig. 1). For investigating LST observations in Lut Desert, a desert mask was applied to exclude areas outside the boundaries of Lut Desert.

With an estimated annual precipitation of less than 30 mm/year (based on neighboring stations), Lut Desert is well known for not only its incredibly high temperatures, but also prolonged dry conditions [21]. The desert regions of Iran have more than 30% of virga precipitation occurrence that contributes to false precipitation in satellite-based precipitation estimates [22]. Despite its harsh climate, Lut Desert sustains an incredible biodiversity including desert fox, different types of lizards, spiders, insects, and more [4]. This rich ecosystem in an ecosystem prone to extreme environmental conditions has led a wide range of research questions about adaptability of biodiversity in harsh climates. However, there is no permanent data collection station, and hence, the weather and climate of the region has been largely unexplored.

III. Data and Methods

LST observations from the MODIS instrument onboard the Aqua satellite from July 4th 2002 to October 30th 2019 has been used in this research [23]. The local equatorial crossing times of this satellite are about 1:30 P.M. for the ascending orbits, and about 1:30 A.M. for the descending orbits. We selected observations from the Aqua satellite because its overpass time is closer to the maximum diurnal temperature [24]. The MODIS MYD11A1 collection 6 data provides daily LST data in a 1200 km × 1200 km grid for both day and night times with a spatial resolution of 1 km. Only clear-sky conditions have been considered for the development of this product. LST products from the MODIS are often influenced by clouds and other atmospheric disturbances, which result in remarkable data loss. The MODIS-derived LST collection 6 product showed higher LST estimates than collection 5 product, primarily over the arid regions [25]. The bias and errors in the MODIS-derived collection 6 product showed

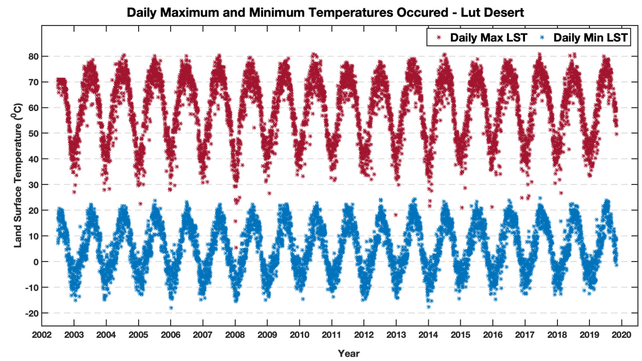

Fig. 2. Time series of daily maximum (daytime; red dots) and minimum (nighttime; blue dots) satellite-based LSTs from MODIS in the Lut Desert from July 2002 to October 2019.

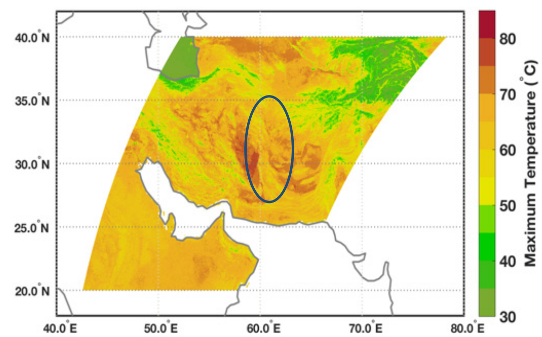

Fig. 3. Map of maximum daily LST in the region from July 2002 to October 2019 using MODIS. The oval shape highlights the desert region where maximum temperatures are often observed.

substantial improvement in LST over collection 5 product due to refinements in the split-window retrieval algorithm, and the adjustment in the emissivity difference for bare soil [16]. In another studies, Duan *et al.* [26], [27] confirmed that arid regions with bare soil land-cover are the only areas that exhibit significant difference between collection 5 and 6 LST estimates. Therefore, substantial differences are expected in reporting record temperature occurrences in Lut Desert.

In order to cover the study area for Lut Desert and its surrounding region, four tiles are required to be mosaicked together making an area of 2400 km × 2400 km. The highest (daytime) and lowest (nighttime) observed LST data in the region at each pixel were utilized to study the temperature records for the Lut Desert. Daily maximum and minimum LST occurrences in the whole region were extracted to evaluate the trend in their changes over almost 18 years. The difference between day and night measurements when both observations were available, computed as a proxy of diurnal amplitude of LST in the Lut Desert. We considered clear-sky pixels but removed low-quality flagged pixels in this study. Moreover, MODIS MYD14A1 Aqua Thermal Anomalies and Fire Daily 1 km Global V006 data product [28] was used to mask the LST pixels with fire. Here, we excluded all pixels that had any of “fire (low confidence),” “fire (nominal confidence),” and “fire (high confidence)” flags. Our evaluations of the data reveal that up to 50% of the data were generally missing during the wintertime, however, only 10% of the data were missing or removed because of fire or cloud during summertime when maximum temperatures occur in the Lut region.

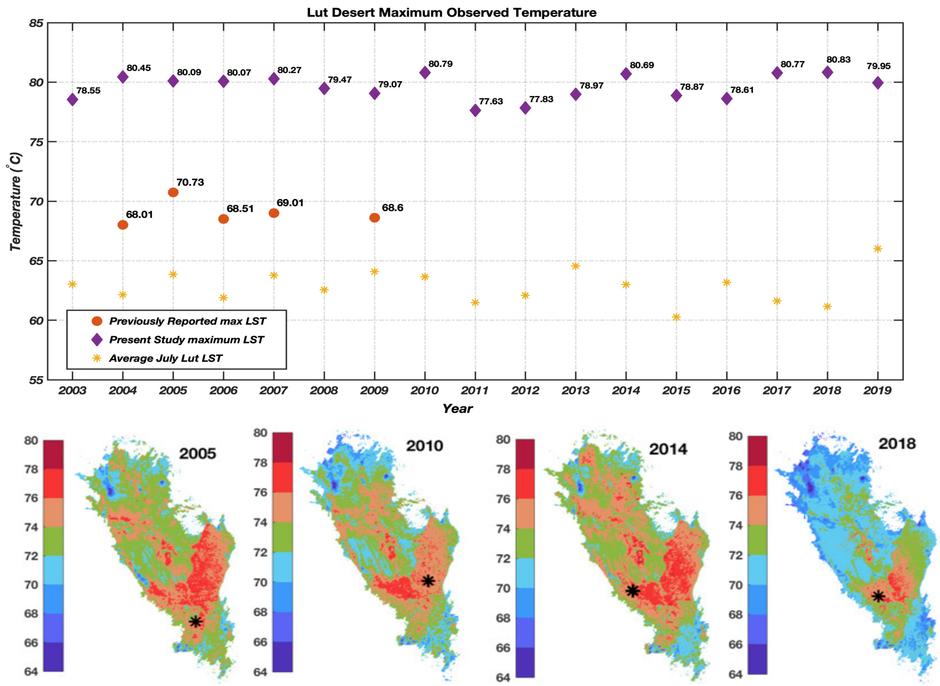

Fig. 4. (Top) Observed LST annual maxima in Lut Desert from 2003 to 2019 based on this letter (diamonds), previously reported [2] LST temperature maxima (circles), and the average July LST values. (Bottom panel) Spatial map of LST maxima over Lut Desert for years 2005, 2010, 2014, and 2018 when the highest records have been observed. The "∗" symbol indicates locations where the maximum temperatures were observed.

A linear regression model was applied to describe the trends, and the patterns of changes in maximum LST (LST_{max}), minimum LST (LST_{min}), and diurnal amplitude time series of the LST over Lut Desert after removal of annual cycles. The maximum and minimum occurred temperatures based on daily maximum and minimum data are extracted for each year. Finally, a maximum temperature record map in the desert is generated for the entire record (e.g., 2002–2019) at every 1 km^2. It should be noted that a comprehensive and reliable trend analysis requires longer observations. However, this particular observation is only available for the past two decades.

IV. Results and Discussion

Fig. 2 shows the daily maximum and minimum LSTs for the Lut Desert since July 2002 until October 2019. It is noted that LST_{max} values for the region oscillate mostly between 30 °C and as high as 80 °C. For LST_{min} values, the range for changes is between almost−15 °C and 23 °C. Over the time of study (2002–2019), a positive trend is observed in both daily LST_{max} and LST_{min} values. We calculated the rate of temperature change over the entire record after removing the seasonal cycles from the data. The rate of change in daytime temperature anomalies is about +0.4 °C per decade for LST_{max} which translates to +0.73 °C warming over the entire record. The rate of change in nighttime minimum temperature (LST_{min}) anomalies is even higher than daytime values with the rate of +0.62 °C per decade or +1.12 °C over the entire record.

We also performed a spatial variation of temperature analysis within the Lut Desert based on the standard deviation (SD) of LST in the region. We found that daytime temperature tends to have a higher spatial variation with SD of about 3 °C–4.5 °C than nighttime temperatures with SD of 2.5 °C–3.5 °C which is consistent with the significant heterogeneity of the surface reflectance property of Lut Desert. In addition, there seems to be some rather low maximum temperature observations in Fig. 2 which could be due to winds, and other day to day weather variability in the region.

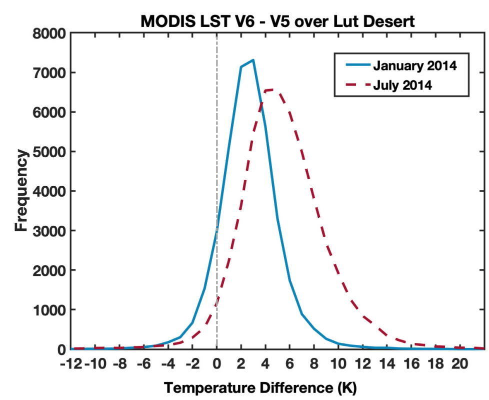

Fig. 5. Histograms of differences between collection 5 and collection 6 MODIS at 1:30 P.M.

The highest LST occurrences at each pixel from July 2002 to October 2019 were extracted using daytime observations to define record high temperatures of the region. Fig. 3 depicts the temperature record of LST_{max} in the 2400 km × 2400 km region which includes the Lut Desert in the middle marked by an oval (Fig. 3). In the heart of the desert the maximum temperature is often at least 76 °C (higher than the previously published record high temperature of the region). The southern part of the desert, near where the so-called "Hidden Sea" [4] is located shows maximum temperature mostly around and above 80 °C. Although the Arabian Peninsula has similar dry bare soil land cover type with more sun exposure, it shows lower temperature records

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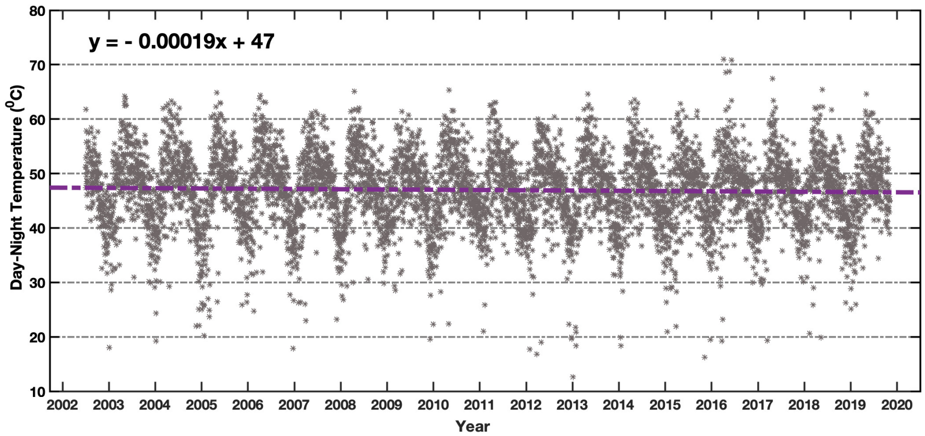

Fig. 6. Time series of daily maximum observed diurnal temperature ranges from MODIS in Lut Desert from July 2002 to October 2019. The diurnal ranges were determined by computing the temperature differences of MODIS day (1:30 P.M.) and night (1:30 A.M.) observations.

of around 65 °C. This is possibly because the Lut region is primarily a desert depression. Additionally, the generated image clearly reflects the land features in the surrounding region such as northeastern Afghanistan, Alborz and Zagross mountainous regions with lower LST_{max} record ranging from 30 °C to 55 °C.

The yearly record maximum temperature was also found by analyzing the maximum temperatures occurred at any point within the Lut Desert each year. Fig. 4 (top panel) shows the time-series of LST annual maxima (LST_{max}) in Lut Desert from 2002 to 2019. Previously reported temperature records of the region by Mildrexler *et al.* [2] are also shown in this figure. The maximum temperatures are shown to range between 77 °C and 80 °C. The maximum temperature occurred in the entire period was 80.83 °C (177.5 °F) on July 16th, 2018–a record temperature far higher than what was previously known as the global record high temperature of 70.7 °C in Lut Desert in 2005 [2], [4]. This sets a new temperature record based on the revised collection 6 MODIS LST product by NASA [23] that improved the temperature retrieval algorithm over arid regions. Previously reported temperature records of the Lut Desert as the hottest place on Earth are about 10 °C lower than the results presented here. Overall, there are three main reasons for such high differences; 1) emissivity corrections and updates for regions with bare soil land-cover [16]; 2) split-window retrieval algorithm uncertainties and improvements in the new product [16]; and 3) the higher spatial resolution of our study (1 km) versus the previous studies (5.6 km). In order to quantify the contribution of these factors on the observed differences between our analysis and that of Mildrexler *et al.* [2], we compared the temperature records of both MODIS LST versions (collection 5 and collection 6) at the same spatial resolution (5.6 km as in [2]). Fig. 5 shows the differences between the MODIS LST collection 6 versus collection 5 for July and January 2014. As shown, the differences between the two versions are on average around 3 K during the wintertime, and 5 K in the summer. This difference could be attributed to changes in emissivity, and retrieval algorithm improvements. The remaining difference can be attributed to the differences in spatial resolution of the two data sets. When observations are aggregated to a coarser spatial resolution, the corresponding values tend to be smoother because of the averaging effects across space [29]. New studies all tend to confirm that the quality of collection 6 MODIS LST product is much more improved compared to collection 5 when evaluated against real ground-based measurements and model outputs with less than 2.0 K bias [25]–[27]. In the past 18 years, the maximum observed temperature in Lut Desert surpassed 80 °C in eight years (2004, 2005, 2006, 2007, 2010, 2014, 2017, and 2018) based on the new LST data. Selected maps of yearly LST_{max} of Lut Desert are shown at Fig. 4 (bottom panel) for 2005, 2010, 2014, and 2018. In all maps, the southern part has clearly higher temperatures than most of the remaining regions in and around Lut Desert with maximum observed temperatures of 74 °C–78 °C.

The whole region of Lut Desert showed a higher temperature in year 2014. Although the maximum recorded temperature happened in 2018, the majority of the region seems to have lower LST_{max} in that year. The average July observations for the entire desert region is also depicted in Fig. 4 (top panel) that shows the whole desert has an average temperature between 60 °C and 66 °C with milder regions in north, and warmer places in the south.

The differences between day and night observations (at 1:30 A.M./P.M.) were also derived at each pixel as a proxy for diurnal amplitude of temperatures in Lut Desert. The actual time of daily minimum/maximum temperature may occur sometime after/before 1:30 A.M./P.M. as described by Sharifnezhadazizi *et al.* [30]; however, the difference between the two can be a good proxy for the overall diurnal variability. The maximum daily differences in Lut Desert are plotted in Fig. 6 for the entire record.

Overall, Fig. 6 demonstrates that Lut Desert not only has high LST, but also incredibly high diurnal amplitude of 47 °C on average with SD of 6.3 °C. The amplitude values are fluctuating between 12 °C and 71 °C depending on the season. The figure shows that differences between day and night in May and June can reach up to 71 °C. A trend regression analysis (LST diurnal change in 18 years) reveals that these differences are decreasing at the rate of −0.7 °C per decade or about −1.18 °C for the entire record. This is in line with what we found in Fig. 2 indicating that both daytime and nighttime temperatures are increasing, but the desert is warming up at higher rate at nighttime.

V. Conclusion

This letter analyzed the record LSTs and diurnal variability across the Lut Desert, known as the hottest place on Earth using MODIS LST collection 6 product (2002–2019). The results showed that this desert had experienced maximum LST record of 80.83 °C in 2018 that is much higher than the previously reported world record (70.7 °C) from the same region. The observed ∼10 °C difference is mainly due to improvement in LST retrieval algorithms and applied emissivity values, and use of higher spatial resolution of the LST collection 6. The results indicate that the land surface can get much hotter than what was previously thought based on remote-sensing observations.

Our results show that not only Lut Desert experiences the highest maximum temperatures, it also undergoes an extreme diurnal temperature variability of up to 71 °C in late spring that makes the ecology of the region unique. The trend analyses reveal that both maximum and minimum temperatures are increasing in the region at the rates of 0.4 °C/decade and 0.62 °C/decade, respectively. The southern part of Lut Desert consistently shows higher LST values. This letter was the first step toward understanding the environment of one of the most remote and unexplored places on our planet. Efforts are underway to explore other climatic and ecological aspects of this environment using remotely sensed products.

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