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Estimation of monthly surface air temperatures from MODIS LST time series data: application to the deserts in the Sultanate of Oman

Mohamed E. Hereher

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Abstract Air temperature records in remote deserts and inaccessible mountainous regions rely upon data acquired from the nearest meteorological stations, which could be at tens of kilometers apart. The present study provides a reliable approach to extract air temperatures for any distant region using thermal data of satellite images. The study postulates that if there is a strong correlation between land surface temperatures (LST) from satellite images and air temperature records from ground meteorological stations, hence, air temperatures (day/night) could be directly extrapolated from regression equations with high confidence results. Data utilized in this study were obtained from 12 meteorological stations settled and distributed upon different physiographic units of Oman. Satellite images were acquired from the Moderate Resolution Imaging Spectroradiometer (MODIS) LST product. Regression analysis of max and min air temperatures from weather stations was conducted versus day and night LST from MODIS Aqua LST (MYD11A2) images. Results showed that the regression coefficients for the selected locations are strong for the night/min ($R^2 = 0.81$–0.94) and day/max ($R^2 = 0.72$–0.92) correlations of the 12 stations. The root mean square errors (RMSE) of the statistical models are 0.97 and 1.98 for the night and day temperatures, respectively. Moreover, the association between each pair of the data is significant at the 99% level ($p < 0.01$). As MODIS data cover large geographic extents, it was possible to produce national diurnal and annual air temperature maps of accurate records with considering the variation of the physiographic setting.

Keywords Oman · Air temperatures · MODIS · LST

Introduction

Ground meteorological stations usually occur in specific areas, such as airports, harbors, research stations, urban areas, and monitoring centers. They seldom occur in desert regions, particularly in mountainous ranges, sand dunes, and islands. However, in some cases, data provided by these ground meteorological stations are used to produce national maps of climatic parameters based on interpolation approaches from a number of weather stations that do not consider altitudinal or geographical positions, which could yield some discrepancies in their spatial and temporal representations (Marquínez et al. 2003). In addition, data acquired from ground weather stations in urban areas are influenced by the urban heat island effect (Li et al. 2004; Futcher et al. 2013) and air pollution (Mayer 1999; Aw and Kleeman 2003). Moreover, it is important to have timely based accurate air temperatures data for urban planning in regions experiencing accelerated urban growth in a world of a changing climate (Bechtel et al. 2017). The problem could be even worse in developing countries, where weather stations are limited at the national scale.

M. E. Hereher
Geography Department, College of Arts and Social Sciences, Sultan Qaboos University, Muscat, Oman

M. E. Hereher (✉)
Department of Environmental Sciences, Faculty of Science, Damietta University, New Damietta, Egypt
e-mail: mhereher@gmail.com

In addition, most of these stations occur along the coasts, where the maritime influence is significant, or within inhabited regions in deserts, where local topographic conditions differ from ambient surroundings (Hereher 2010).

Meteorological observations in the Sultanate of Oman started very early in 1900 by the private agencies and in 1975 Oman joined the World Meteorological Organization. A royal decree was issued in 1982 to establish the Directorate General of Meteorology. Currently, there are about 32 weather stations covering all the regions of the country and are connected to the head office at the Muscat International Airport and providing monthly and annually weather forecast reports. Climate research in Oman mostly focus on modeling of climate change and predicting of some climatic parameters, such as precipitation and wind potential for energy production (Al Hatmi et al. 2014; Charabi et al. 2016). For producing national maps of climatic parameters, previous studies performed interpolation techniques to extract and fill the records of these parameters between the locations of weather stations in the country (Charabi and Al-Hatrushi 2010; Al-Hatrushi 2012). This study is the first to utilize remotely sensed data in order to extract maximum and minimum daily temperatures. Therefore, the objectives are to assess the suitability of time series satellite images to produce national maps of air temperatures (day/night) and to analyze the spatial variations of air temperatures with regard to the physiography of the country. Implications of this study involve detection of higher solar insolation spots that could be qualified for renewable solar energy production and planning for new urban communities in desert regions.

The study area

The Sultanate of Oman was selected to implement the current study because of the large diversity in the physiography and the availability of the climatic data and satellite images. The country occurs at the southeast corner of the Arabian Peninsula, where the Tropic of Cancer passes at a few kilometers south of the capital city of Muscat. The landscape of Oman includes sandy deserts, mountains, plateaus, valleys, forests, and agricultural and urban areas (Fig. 1). The country is also varied in topography, with high mountains such as the Al-Hajar Mountain in the north and plains such as the Al-Batinah along the Sea of Oman. The Green Mountain in Al-Hajar series is the highest peak in Oman with a height of more than 3 km above the sea level. The Sultanate of Oman is estimated at 310,000 km^2 and its coastline overlooks more than 3000 km on three water bodies—the Arabian Sea, the Sea of Oman, and the Arabian Gulf. Geologically, dark ophiolite rocks are found in the northern part of the Sultanate, limestone rocks are heavily dispersed in Al-Hajar Mountains, whereas calcareous sand dunes occupy the dune field of ASharqiya along the eastern side of Oman. The climate of the country is generally hot and arid. Annual precipitation is generally below 100 mm for the majority of the country except the southern part at Dhofar, where monsoonal winds enforce summer precipitation with more than 250 mm during the months of June–Sept. Air temperatures vary considerably throughout the country due to the diverse topographic and maritime influences. In northern Oman, average temperatures range from 32 to 48 °C in summer and approach 50 °C in the interior regions. On the other hand, winter temperatures are generally mild and range between 15 and 23 °C. Highland temperatures in the north or in the south of the country are generally moderate all the year round (Kwarteng et al. 2009).

Materials and methods

Air temperatures data

Air temperature data were acquired from 12 weather stations distributed throughout the country (Fig. 1). Although most of these stations face the Sea of Oman and the Arabian Sea, some occur in the interior part of the country either at elevated lands, such as Ibra, or deep in the desert, such as Haima. Weather records from six stations cover the period (1/1/2000 to 31/12/2014). The remaining stations cover shorter periods (Table 1). Although temperature data were available after 2014, they were eliminated as some records were missing. In an Excel spreadsheet, all the records for January of all years were aggregated for the max and min observations. In a same manner, all the records for February of all years were averaged and so forth until December. Therefore, a max and a min value were assessed for each averaged month for each meteorological station.

Land surface temperature data

Extraction of air temperatures using remote sensing is an ongoing research pursuit. Air temperature measurements

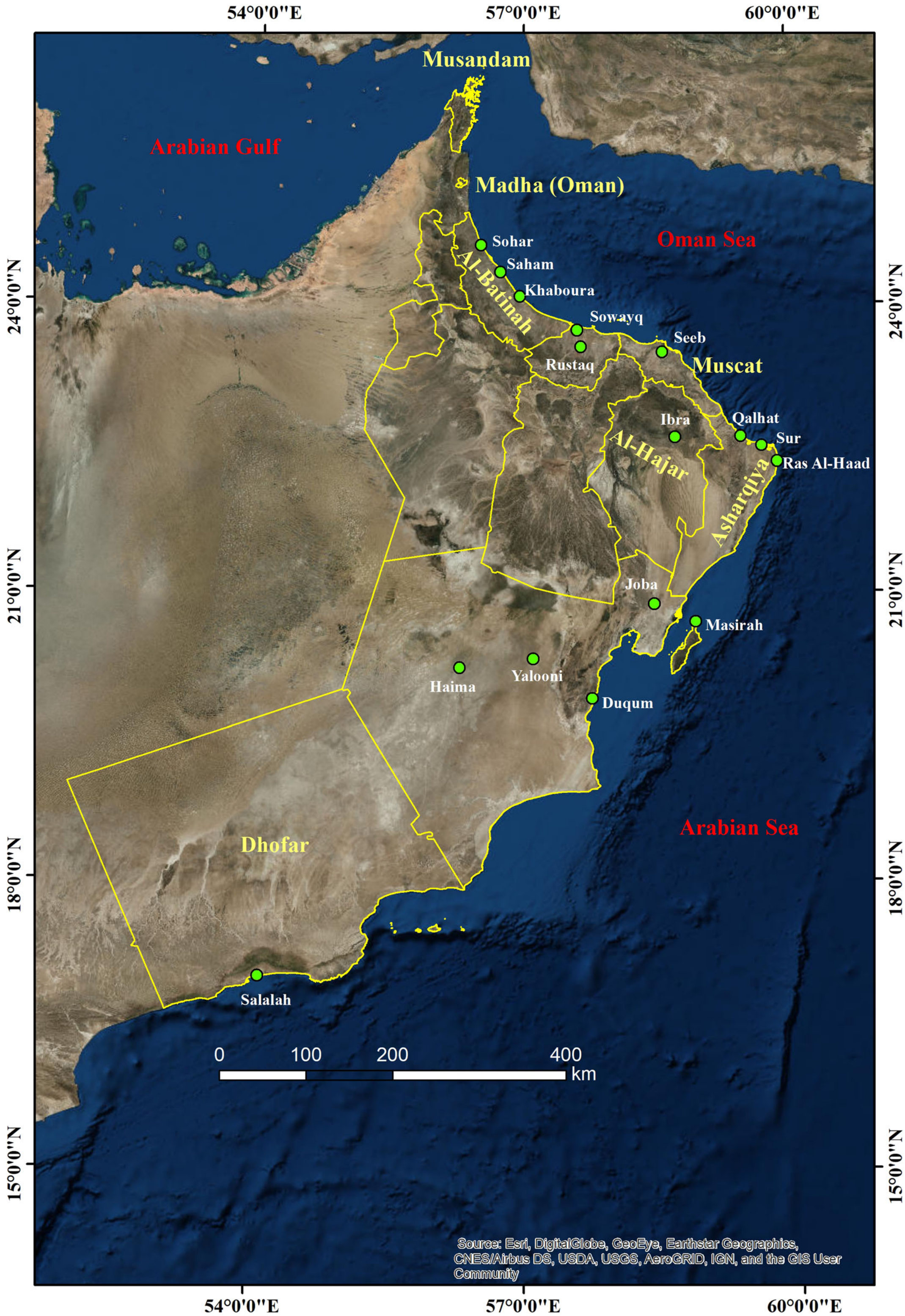

Fig. 1 A map of the Sultanate of Oman showing the locations of some ground weather stations. The source is ESRI DigitalGlobe, GeoEye Erthstar Geographics, CNES, Airbus DS, USDA, USGS, AeroGRD, JGN, and the GIS User community

Table 1 The period of air temperature data provided by the 12 weather stations

Station	Start date	End date
Sohar	1/1/2000	31/12/2014
Qalhat	1/1/2000	31/12/2014
Rustaq	1/1/2000	31/12/2014
Sur	1/1/2000	31/12/2014
Muscat	1/1/2000	31/12/2014
Ibra	1/1/2000	31/12/2014
Joba	15/7/2003	31/12/2014
Haima	5/10/2011	31/12/2014
Yaloni	16/5/2012	31/12/2014
Saham	24/11/2013	31/12/2014
Suwayq	24/4/2010	31/12/2014
Ras Al-Hadd	4/1/2005	31/12/2014

are extracted from LST data acquired by the thermal infrared bands in satellite images. LST is a symptomatic variable of the net surface energy balance influenced by many factors (Hereher 2017): topography, surface albedo, cloud cover, vegetation, and urban activities. Most of LST data were acquired from the MODIS satellite (Flores and Lillo 2010; Vancutsem et al. 2010; Benali et al. 2012; Zhu et al. 2013; Yoo et al. 2018). This satellite has a high temporal resolution that allows for day/night recording of earth's land surface temperatures. Although the MODIS sensor aboard two different satellites: Terra and Aqua, images from Aqua satellite are mostly preferred to extract maximum and minimum daily temperatures because the satellite acquires its images at 1:30 PM and 1:30 AM at the local time, whereas the Terra satellite does the job 3 h earlier (Justice et al. 2002). Hence, MODIS Aqua data are used to extract max and min air temperatures (Wenbin et al. 2013). MODIS is a sun-synchronous satellite orbiting the earth in a near-polar orbiting track. MODIS Terra was launched in 1999 in a descending node, whereas the MODIS Aqua was launched in 2002 in an ascending node. Both satellites provide their data in 36 spectral bands with LST data that correspond to the brightness temperature of the bands 31 (10.78–11.28 μm) and 32 (11.77–12.27 μm) (Wan and Dozier 1996) using the generalized split-window algorithm (Snyder et al. 1998). LST images are available at 1-km spatial resolutions either as daily or 8-day composite.

Since air surface temperature data were represented by the max and min monthly average, it was important to select the satellite that provides synchronized data to this range. Therefore, it was important to get the data from the MODIS Aqua satellite, because the sensor is the most suitable to provide data of max and min air temperatures (Noi et al. 2016; Zhang et al. 2018) as the sensor acquires the images at 1:30 PM and 1:30 AM every day. The data were downloaded from the Land Processed Distributed Active Archive Center of the United States Geological Survey web portal (https://lpdaac.usgs.gov/). These data were obtained from the MYD11A2-LST product, which provides 8-day composite records at 1-km spatial resolution and provides a day LST and a night LST layers. As the satellite was launched in 2002, it was better to download all the data starting from January 2003 onward until December 2014. For each month, four images were acquired at 8-day composite totaling 46 images per year and 552 images for the entire study period. Each image includes a daytime LST and nighttime LST layer covering a swath area of 1200 × 1200 km in a sinusoidal projection provided in GeoTIFF format. The pixel value represents the brightness temperature of the thermal band in Kelvin degrees. The entire country of Oman is covered by two adjacent tiles from MODIS satellite (H23V06 and H23V07). All images were converted to degree Celsius and the images for each month were stacked together. The total 552 images were stacked together to form one file for each tile. The two tiles include 1104 images for the study period. The daytime and nighttime LST layers were extracted for each 8-day composite using ERDAS Imagine Software.

Research hypothesis

Land surface temperatures or skin temperatures measured by thermal infrared remote sensing is a clear sky measurement of the internal heat flux at the earth's surface (Prihodko and Goward 1997). The surface air temperatures, on the other hand, depend on the heat flux loss to the atmosphere (Benali et al. 2012). Hence, the surface air temperatures directly correspond to the LST. However, some factors, such as vegetation cover, could impact the latent heat energy fluxes. Hence, in desert regions, such as Oman, where the vegetation cover is generally low, it is possible to extract air surface temperatures for distant regions if its LST value is known. Linear relationship between the two parameters (air temperatures and LST) could be used to extract air surface temperatures. Since the region is almost sunny all the year round, variations of air temperatures mostly depend upon elevation and regional setting.

Regression analysis and statistical significance

As each pixel in the MODIS image covers 1 km × 1 km, the location of each meteorological station was delineated in the MODIS data and the mean monthly LST value (day/night) of that pixel was plotted against the mean monthly air temperatures (max and min) of that weather station. This approach was adopted to all the 12 stations. The linear regression relationship was then estimated and the correlation coefficient was determined between the mean LST (day value) in the satellite image for each month with the maximum temperatures for that month from each weather station data. In a same manner, the correlation between the mean LST (night value) from the satellite data and the min air temperatures from the weather stations was determined. This technique (linear regression) was successfully applied to extract air temperatures from LST (Vogt et al. 1997; Wenbin et al. 2013; Chen et al. 2016). In order to determine the accuracy and significance of the regression correlation, the RMSE using the residual values was determined to measure the deviation of the error data from each value. Moreover, the statistical significance test of the correlation between max air temperatures/daytime satellite data and min air temperatures/nighttime satellite data was determined using *t* test procedures in SPSS software. The regression model for extracting the max and min air temperatures was determined by applying the correlation between all records from the 12 stations versus the LST data for day and night readings.

Vegetation cover and topography data

The topography of Oman was extracted from the Shuttle Radar Topography Mission (SRTM) digital elevation models (DEM) at 90-m spatial resolution. The data were acquired from the Consortium of Spatial Information (http://srtm.csi.cgiar.org/). DEM data were mosaicked and classified in ArcMap Software to show the spatial distribution of highlands and plains of Oman. Vegetation of Oman was extracted by applying the normalized difference vegetation index (NDVI) using MODIS Vegetation Index Product (MOD13Q1) at 250-m spatial resolution, as:

(Tucker 1979)

$$\mathrm{NDVI} = (\mathrm{NIR{-}RED})/(\mathrm{NIR} + \mathrm{RED})$$

Where NIR is the near-infrared band and the RED is red band in MODIS image. The values of NDVI range from − 1 to + 1, where the range between 0.2 and 0.9 is mostly common in continuous vegetation cover (Bustos and Meza 2015). Two tiles of MODIS (H23V06 and H23V07) acquired in January 2018 were mosaicked together and classified in ArcMap Software to show the NDVI values of the entire country. Finally, NDVI values > 0.2 were coded as a proxy to vegetation.

Results and discussions

The regression relationship between the air temperature data obtained from the 12 weather stations and the LST data obtained from the MODIS images reveals high correlations (Fig. 2). The regression coefficients (R^2) for the day/max relationships range from 0.72 to 0.92 and from 0.81 to 0.94 for the night/min relationship. For the day/max relationship, maximum coefficient value is recorded for Sohar station and the minimum is for Ras Al-Hadd region. On the other hand, for the night/min relationship, maximum coefficient value is recorded for Ibra region and the minimum value is for Saham region. It is noted that the night/min relationship is slightly greater than the day/max relationship. The regression equations to extract the day and night temperatures from satellite images for the monthly air surface temperatures are (Fig. 3):

$$Y = 0.8193\,X + 8.508\ (\mathrm{day}) \quad (1)$$

$$Y = 0.7962\,X{-}11.758\ (\mathrm{night}) \quad (2)$$

The values of Y are the calculated day and time temperatures, and the values of X refer to the observed max and min air temperatures from the weather stations, respectively. The statistical model RMSE is estimated at 1.98 and 0.97 for the day and night temperatures, respectively. Statistical analysis also showed that the correlation between day/max and night/min are significant at 0.99 level ($p < 0.01$). This means that the resulted correlations have high statistical confidence; hence, they could be used to extract unknown min and max air temperatures by substituting the values of the night and day LST of any region, respectively. Accordingly, these equations were used to produce monthly max and min air temperature maps of Oman (Figs. 4 and 5) as well as the annual and diurnal spatial variations over the country (Fig. 6). Yang et al. (2017) observed that the linear relationship between the MODIS LST and surface air temperatures could

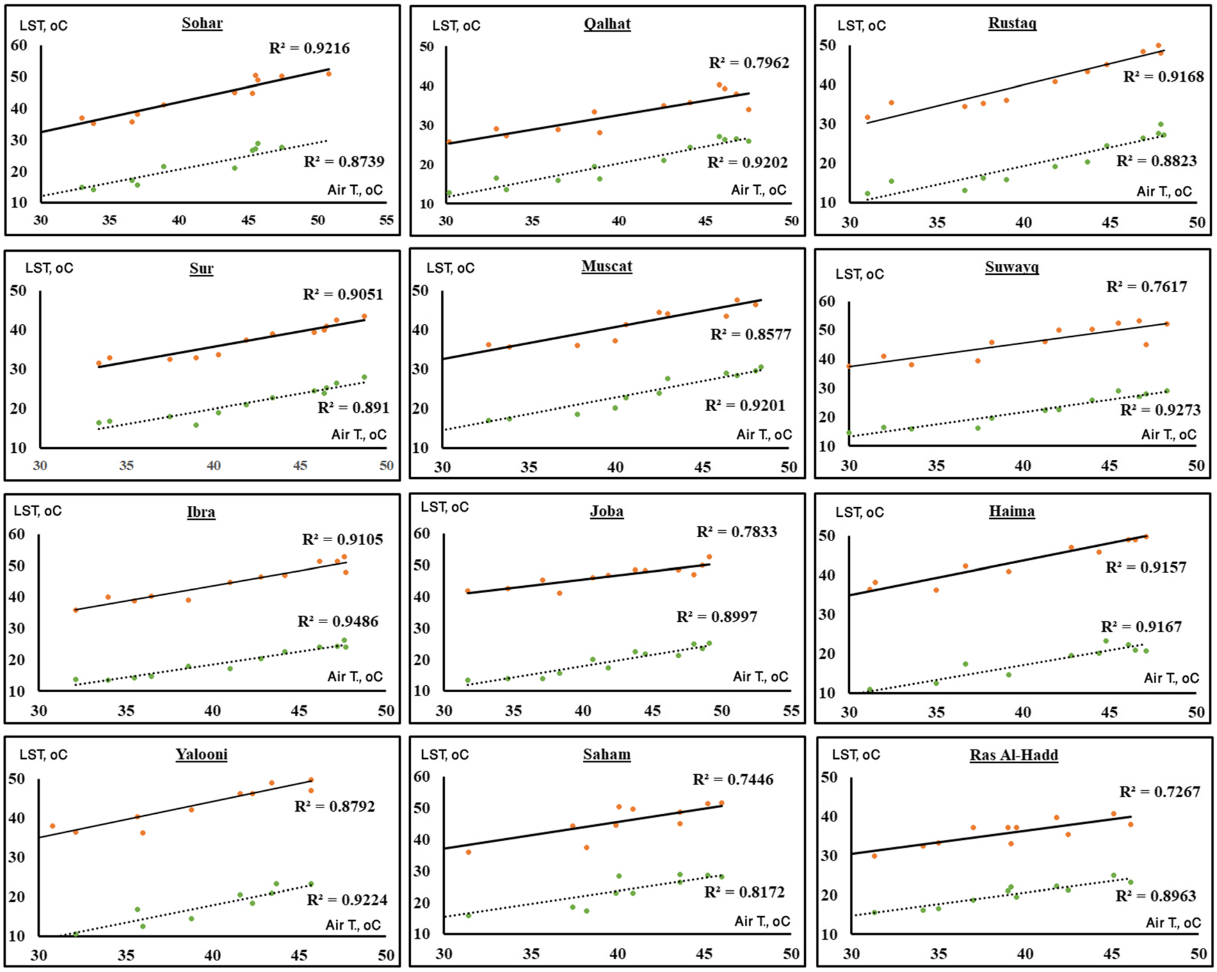

Fig. 2 Regression correlations between LST (day/night) and air temperatures (max/min) of the individual 12 weather stations. Note the high value of the regression coefficients (R^2) for all relationships

produce confident results for the min, max, and average air temperatures in Northeast China.

It is observed that LST for the day is greater than the max air temperatures and the LST for the night is less

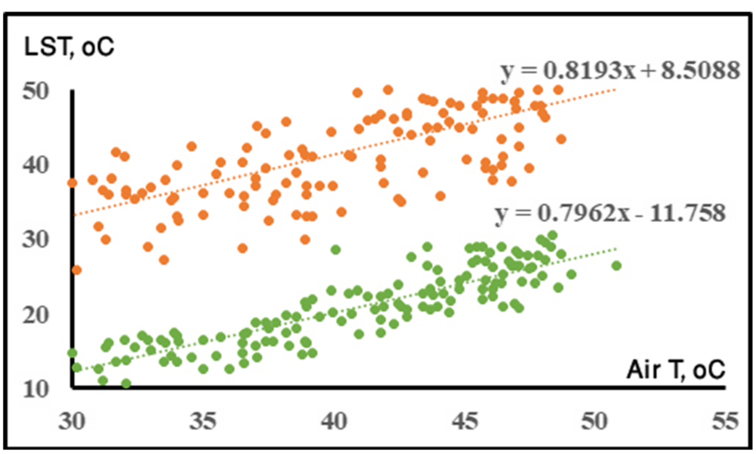

Fig. 3 Regression correlation of the all records for the 12 weather stations versus the MODIS LST data. The regression equations (Eq. 1 and Eq. 2) were estimated from this relationship to calculate the monthly day/night air temperatures of the study area

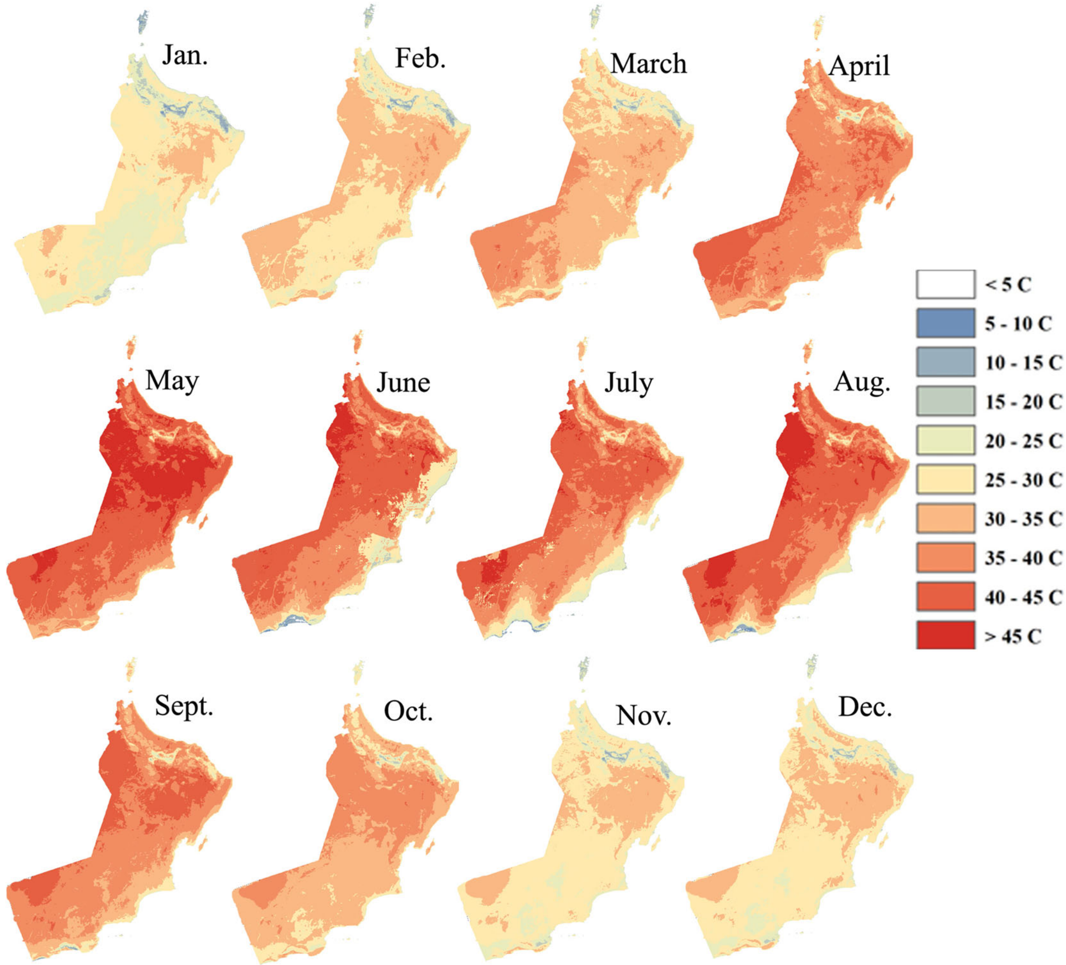

Fig. 4 The mean monthly day temperatures of Oman as extracted from MODIS LST day data based on the regression Eq. (1); $Y = 0.8193 X + 8.508$

than the min air temperatures. This difference could be attributed to the physics of radiation during the diurnal cycle. During daytime, the majority of energy at the earth's surface is attributed to emitted thermal radiations of the solar insolation; therefore, the LST gets higher energy, whereas during nighttime as solar radiation is absent, no emitted radiation from the sun occurs and the LST is low (Vancutsem et al. 2010). Benali et al. (2012) observed comparable results when they utilized MODIS LST data to extract min, max, and mean air temperatures in Portugal. In the study area, maximum air temperatures (day and night) occur during May and August, while minimum air temperatures occur between December and February.

The confidence of regional mapping of air temperatures over Oman using remote sensing depends on the ability to highlight the spatial variations due to the impact of topography, continentality, land cover, and marine influences. Results showed that these variations are better distinguished in MODIS images than from interpolation techniques of ground weather stations as performed in previous studies (e.g., Al-Hatrushi 2012). Topographic effects upon day and night temperatures are quite noticeable along Al-Hajar Mountain in the north and Dhofar highlands in the south. During the hot months of summer, there is at least 10 °C difference between the Green Mountain (~ 3000 m) in Al-Hajar series and the surrounding terrains (Figs. 6 and 7) due to the lapse rate difference (6 °C/1000 m, Bailey 1996). As the height difference between Dhofar mountains and Al-Hajar mountains is significant, the difference in temperature is just 5 °C. It is observed that inner and

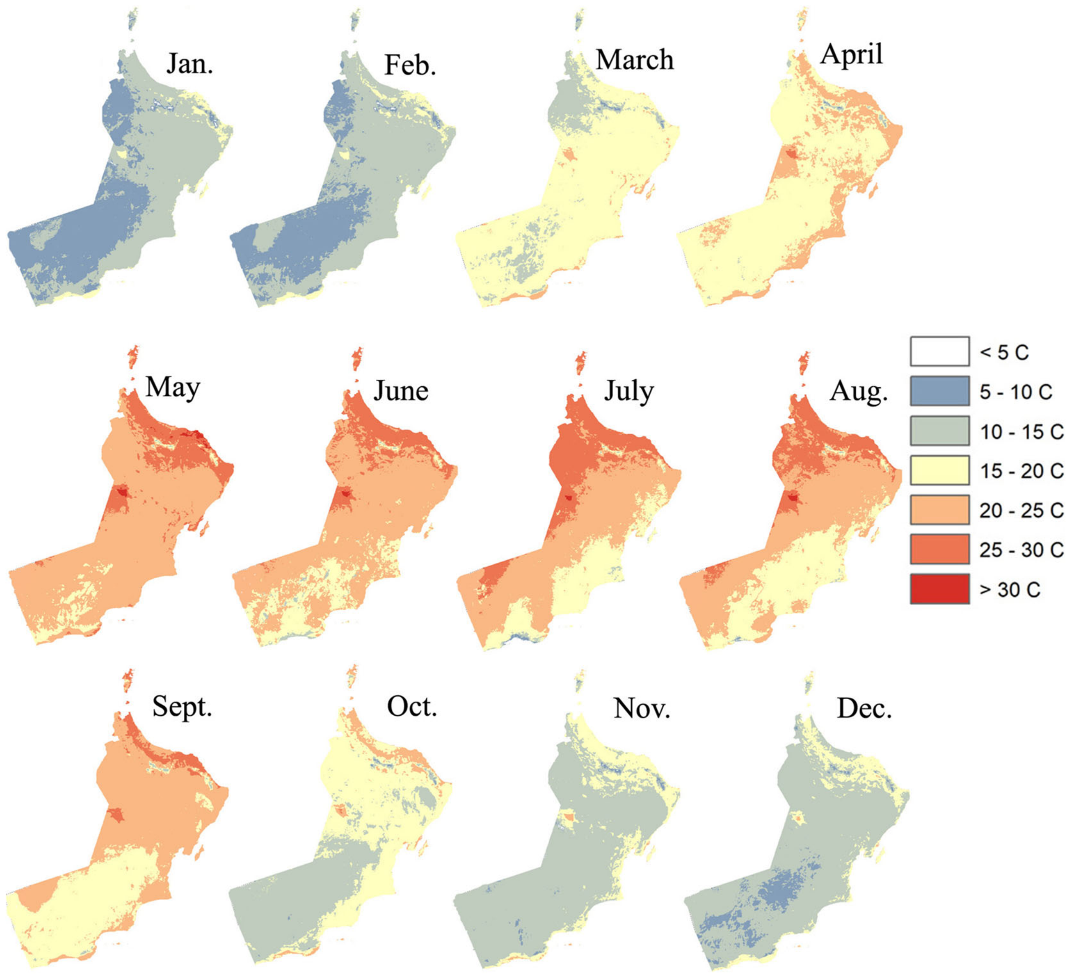

Fig. 5 The mean monthly night temperatures of Oman as extracted from MODIS LST night data based on the regression Eq. (2); $Y = 0.7962\ X - 11.758$

continental deserts in the country have the maximum day temperatures but the coolest during winter. Forested land cover in Salalah has a high NDVI value (Fig. 7) and it is obvious that this region has a lower LST than the surrounding terrains. It also has different temperature regimes in Oman, where there is a significant cooling in day and night temperatures during summer season (June–August). This is attributed to the marine influence at this region, where the summer monsoonal winds predominate during June–August period. During this time, the southwestern rainy winds blow from the Arabian Sea, which make the temperatures cooler for inland regions. Moreover, the forested land cover in Salalah occurs at an elevated terrain (Fig. 7). Hence, the impact of vegetation/topography upon LST is quite observed. This relationship is reported in the mountainous terrains of NV, USA (Mutiibwa et al. 2015). The impact of vegetation upon monthly air temperatures is quite clear in Fig. 4 where during monsoonal rainstorms, the forests of Dhofar turn to green and the temperatures significantly fall under the impact of the SW winds. In dry seasons, the temperature of the region is relatively high.

The implications of getting confident day/night air temperature results of vast inaccessible deserts help not only to obtain annual variability maps but they will provide diurnal spatial variations that could be important for urban planners, environmental managers, and agriculture development. As water resources are scant and climate is arid, the locations for new urban communities or agricultural projects in the vast desert of the country require careful selection. High temperatures are usually associated with high evaporation rates (Monteith 1981); hence, the interior deserts of Oman are not suitable for agriculture

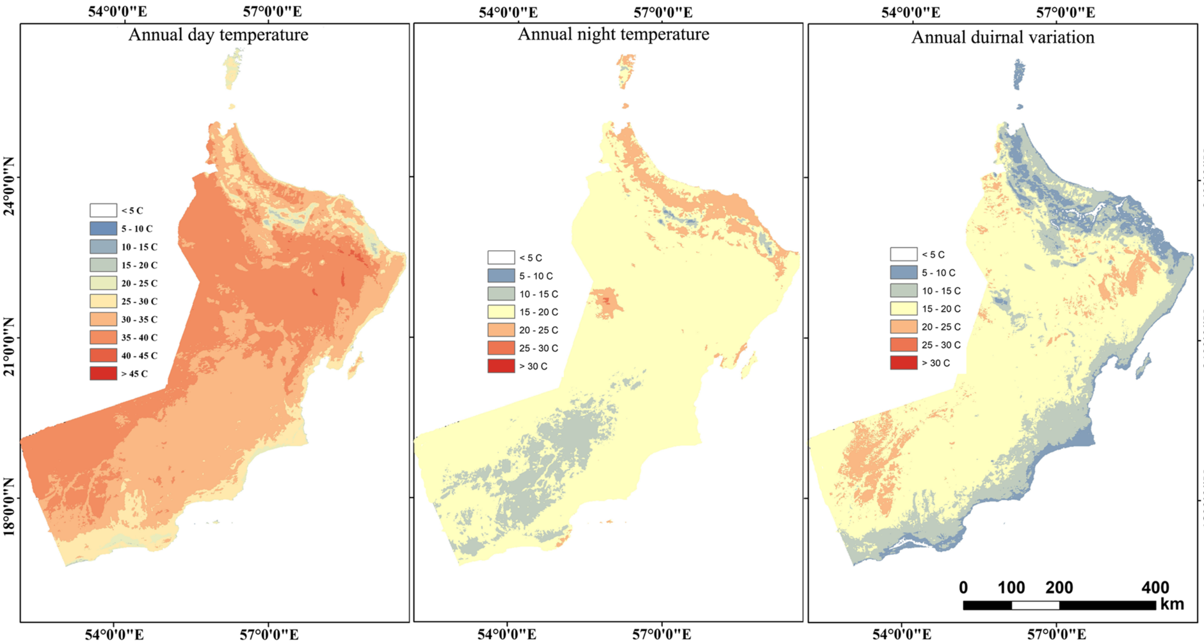

Fig. 6 The annual day and night as well as the diurnal variation temperatures of Oman

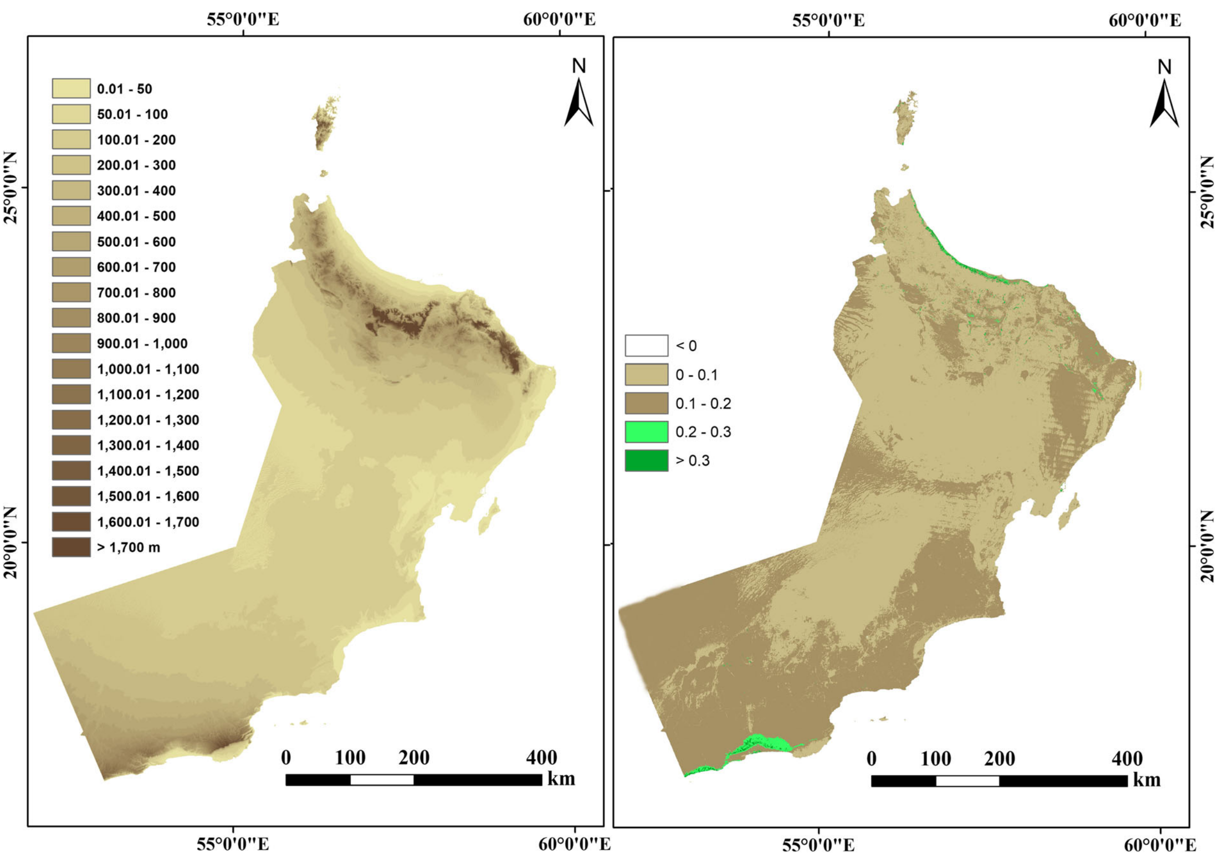

Fig. 7 A digital elevation model of Oman (left) showing the variations of topography of the country. Note the highlands of the Green Mountain north of Oman. The right map shows the NDVI map of Oman with high values coded in green color. Note the forested landscape at Salalah in the south with high NDVI value as a proxy to green vegetation

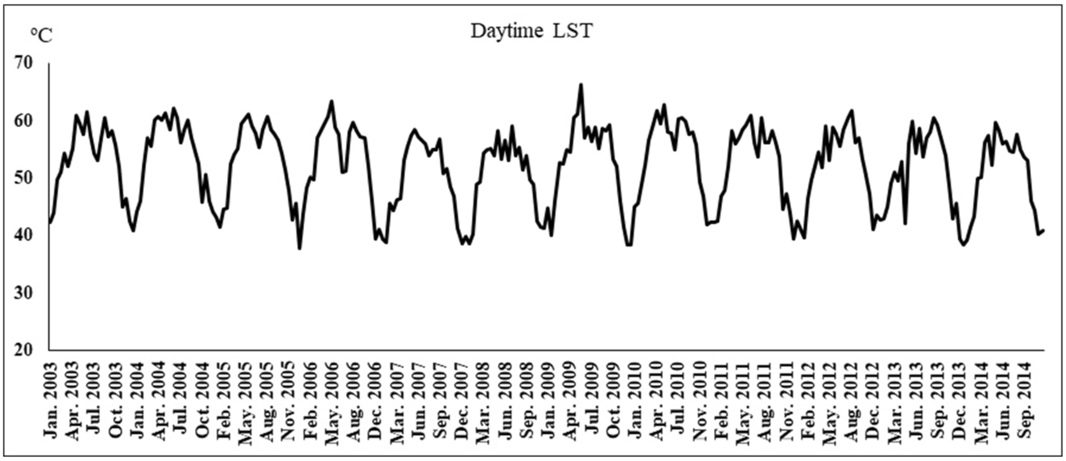

Fig. 8 A time series LST trend at ASharqiya sand dunes showing the high potential of the region for solar energy production

development. However, the coastal regions are most suitable. Al-Batinah plain along the Sea of Oman is, therefore, the major cultivated region in Oman due to the suitability of climate and the availability of water. It is crucial also to consider the diurnal variation of air temperatures when planning for new communities. The coastal region of Oman, where the diurnal variations are small (10–15 °C), could favor most of new urban projects, whereas the diurnal variations in the inner sandy regions, such as ASharqiya dunes, are large (20–25 °C). In terms of highlighting the candidate locations for electric production from solar energy, time series LST data are the most appropriate to delineate regions of high LST values as a proxy to solar insolation. The hottest region of Oman was observed in ASharqiya dune field, where the time series daytime LST trend between 2003 and 2014 (Fig. 8) indicates a mean LST value of 52.2 °C with a minimum value of 37.78 °C (January 2006) and a maximum value of 66.22 °C (May 2009). The high LST value accompanied by the sunny skies all the year round qualifies these regions as potential locations for solar energy production. Planners should consider these locations for future developments to minimize the dependence upon fossil fuels for energy production.

Conclusions

Due to the poor distribution of weather stations, particularly in inaccessible regions, it is possible to rely on satellite data to acquire sustainable supply of day and night air temperature records for any region because of a strong correlation between satellite data and observations from weather stations. Each pixel in the satellite data works as an independent weather station; hence, all the physiographic conditions are responsible for the actual temperature value rather than routinely interpolation techniques. Errors and limitations of using satellite data could be significant in regions with frequent cloud cover, which is not the case in the Arabian Peninsula, where the majority of the year is sunny. As the LST determines the strength of the solar insolation at any given point, LST data could be used to determine not only the air temperatures, but also the candidate locations for electrical production from solar energy. In Oman, there are many regions that could be suitable for solar energy production, particularly in ASharqiya dune field.

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