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Surface Temperature Estimation Using Special Sensor Microwave/Imager (SSM/I) Data over Saudi Arabia

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ABSTRACT. This study is concerned with the application of passive microwaves to land surface temperatures in an arid region. Simple and multiple linear regressions were used to test the statistical validity of the correlation coefficients between the Special Sensor Microwave/Imager (SSM/I) brightness temperatures and land surface temperature over Saudi Arabia. Two samples were performed to investigate the response of SSM/I brightness temperatures to land surface temperatures. The first sample is at satellite ascending overpass time (about 6:00a.m. local solar time), and the second sample is at satellite descending overpass time (about 6:00p.m. local solar time). It was found that poor correlation coefficients occurred between the SSM/I brightness temperatures and land surface temperatures at satellite ascending overpass time. However, good correlation coefficient occurred between the SSM/I brightness temperatures and land surface temperatures at satellite descending overpass time. It was shown to be able to estimate the averaged land temperature at about 6:00p.m. local solar time using SSM/I brightness temperatures (V22, V37, H37, V85, H85) for areas of 1° latitude × 1° longitude grid.

Introduction

The land surface plays an important role in terms of feedback to the atmosphere. Land surface temperature information over large areas is an important physical variable for many applications such as meteorological, hydrological and agricultural applications. In meteorology, land surface temperature is needed for providing boundary condition variable for dynamic atmospheric models. Also, it is needed as an input in numerical weather prediction models. In hydrology and agriculture, surface temperature is needed as input in flood forecasting, growth and crop yield models, crop stress detection, and soil moisture models. Improved land surface temperature estimation could improve the accuracy of these models.

Accurate estimations of surface temperature for large areas are helpful when obtained within short periods. However, direct measurements of surface temperature over large areas are difficult because of the cost of installation and operation of instruments. On the other hand, remote sensing from earth satellites gives a possible way for determination of the spatial distribution of surface temperature over large areas within a short time.

The goal of this research is to use the observed microwave brightness temperatures from the SSM/I to obtain estimates of land surface temperature over Saudi Arabia.

Background

A primary advantage of using microwave sensors, as opposed to infrared techniques, is the ability of the microwave radiation to penetrate cloud cover, thus giving them an all-weather capability for the retrieval of surface parameters. Since 1969, several microwave radiometers on satellites have been flown aboard polar-orbiting to measure the radiation emitted by the earth surface at selected frequencies between 3.5 and 200GHz. Several researches have been completed to apply remote sensing of passive microwave to detect surface parameters, such as sea ice, soil moisture, snow cover, sea surface temperature, and sea surface wind. However, until 1987, no research has been done on the relationship of passive microwave brightness temperatures to land surface temperatures (Lambert, 1987) due to many types of surfaces and the variation of the physical characteristics within each surface type. First research, correlating passive microwave brightness temperatures to land surface temperatures, was accomplished by Lambert (1987), and Lambert and McFarland (1987). They found that there are correlations between the passive microwave brightness temperatures from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) in the 18 and 37GHz vertical and horizontal channels, and air temperature for dry range and prairie areas in the northern Great Plains. The vertically polarized brightness temperature gave slightly better correlations with land surface temperature than did the horizontally polarized brightness temperature. Furthermore, McFarland *et al.* (1990) determined surface temperature over land areas in the Central Plains of the United States (32 to 50º latitude, and 95 to 105º longitude) using passive microwave brightness temperatures from the DMSP Special Sensor Microwave/Imager. They found that a regression analysis between all of the SMM/I channels and minimum screen air temperatures (representing the surface temperature) showed good correlations, with root mean-square roots of 2-3ºC.

Data Collection and Preparation

Land Surface Temperature Data

Unfortunately hourly land surface temperature at 0cm over Saudi Arabia could not be obtained either from Meteorology and Environmental Protection Administration (MEPA), Ministry of Defense and Aviation, Kingdom of Saudi Arabia or from the Hydrological Division, Ministry of Agriculture and Water, Kingdom of Saudi Arabia. According to Glossary of Meteorology the surface temperature is defined as “the temperature of the air near the surface of the earth, almost invariably determined by a thermometer in an instrument shelter” (Huschke, 1986). Several investigators such as Price, 1983, Lambert and McFarland, 1987, and McFarland *et al.,* 1990 used air temperature above the ground 1-2 meters to represent land surface temperature. Therefore, the data used for this comparative study for testing the validation of the satellite data "the objective of this study", is the hourly surface air temperature which was obtained from MEPA in the form of routine meteorological observations. This surface air temperature is the temperature of free air at height between 1.25-2.00 meters above the ground which is standard of the World Meteorological Organization (WMO) level of the screen that shelters the thermometers. This data comprises of twenty-nine stations (Table 1), distributed throughout the Kingdom of Saudi Arabia. Data of two stations, Hafr Al-Batin and Wadi Dawasir, were not available during the time of the study. A real time data acquisition is made from the twenty-seven stations including all the meteorological parameters. From these data, temperature is taken and tabulated. Each of the given twenty-seven stations gives 24-hour routine meteorological observation, with the exception of two stations Al-Jouf and Sulayel. Both reported 15 hour-a-day which exclude the 0300Z data one of the desired data for the comparative study.

TABLE 1. Surface meteorological stations in Saudi Arabia.

Station name	Station indicator	Latitude			Longitude			Elevation
		Deg.	Min.	Sec.	Deg.	Min.	Sec.	Meter
Abha	41112	18	13	59	42	39	39	2093.35
Al-Ahsa	40420	25	17	53	49	29	11	178.17
Al-Baha	41055	20	17	41	41	38	35	1651.88
Al-Jouf	40361	29	47	19	40	05	55	668.74
Arar	40357	30	54	08	41	08	26	548.88
Bisha	41084	19	59	28	42	37	09	1161.97
Dhahran	40416	26	15	34	50	09	39	16.77
Gassim	40405	26	18	28	43	46	03	646.71
Gizan	41140	16	53	49	42	35	05	7.24
Gurait	40360	31	24	27	37	16	56	503.90
Hafr-Al-Batin	40377	27	54	–	45	32	–	413.00
Hail	40394	27	26	04	41	41	28	1001.52
Jeddah	41024	21	40	42	39	08	54	3.58
K. Mushait	41114	18	17	58	42	48	23	2055.93
Madinah	40430	24	32	53	39	41	55	635.6
Makkah	41030	21	26	16	39	46	08	240.35
Najran	41128	17	36	41	44	24	49	1212.33
Qaisumah	40373	28	19	08	46	07	49	357.6
Rafha	40362	29	37	17	43	29	49	444.1
Riyadh Old	40438	24	42	40	46	44	18	619.63
Riyadh New	40437	24	55	31	46	43	19	613.55
Sharurah	41136	17	28	04	47	06	29	724.65
Sulayel	41062	20	27	45	45	36	55	614.39
Tabouk	40375	28	22	35	36	36	25	768.11
Al-Taif	41036	21	28	44	40	32	56	1452.75
Wadi Dawasir	41061	20	26	30	44	40	49	701.02
Turaif	40356	31	41	16	38	44	22	852.44
Wejh	40400	26	12	19	36	28	37	23.73
Yenbo	40439	24	08	24	38	0	50	10.40

Satellite Data

The data used in this investigation contained passive microwave data from the Special Sensor Microwave/Imager (SSM/I). The SSM/I is a passive multichannel microwave radiometer deployed on the Defense Meteorological Satellite Program (DMSP) Block 5D-2 F8 satellite, which was launched into a near-polar orbit in June 1987. The satellite is at an altitude of about 833km with an orbit period of 102min. The orbit produces 14 revolutions a day.

The SSM/I scans the Earth in a conical pattern with a swath width of 1400km and an earth-incidence angle of 53.1°. It measures upwelling atmospheric, ocean and terrain microwave brightness temperatures at four frequencies (19.35, 22.235, 37.0 and 85.5GHz) for both vertical and horizontal polarization, except for 22.235GHz, which has only vertical polarization. The spatial resolutions of the samples depend upon the frequency and are given in Table 2. The SSM/I covers the globe twice a day, so it is possible to get two passes over Saudi Arabia per day at about 6a.m. (Node A) and 6.pm. local solar time (Node D). Further details of the SSM/I are given in the *Special Sensor Microwave/Imager User Guide* (Hollinger *et al.,* 1987).

TABLE 2. Temporal and spatial resolution of SSM/I channels.

Frequency (GHz)	Polarization	Integration period (ms)	3 dB Footprint size (km)	
			Along-track	Cross-track
19.350	vertical	7.95	69	43
19.350	horizontal	7.95	69	43
22.235	vertical	7.95	50	40
37.00	vertical	7.95	37	28
37.000	horizontal	7.95	37	29
85.500	vertical	3.89	15	13
85.500	horizontal	3.89	15	13

Supplementary Data

The daily precipitation amounts were obtained for all SSM/I overpass times to infer land surface moisture. The data were extracted from the records of the Meteorology and Environmental Protection Administration (MEPA), Ministry of Defense and Aviation, Kingdom of Saudi Arabia, and the Hydrological Division, Ministry of Agriculture and Water, Kingdom of Saudi Arabia.

Data Analysis Methods

The study area, Saudi Arabia, was divided into small grid cells, 1° latitude × 1° longitude. Grid cells that are at least 0.25° from the Red Sea and the Arabian Gulf, and have at least two SSM/I data were chosen for this study. Some of the available overpass SSM/I brightness temperatures over Saudi Arabia were used for analysis and others were used to test the results. These SSM/I data was selected (Table 3) because they cover most of Saudi Arabia after five dry days on most of the study area.

Table 3. The overpass SSM/I data over Saudi Arabia used for this study.

Revolution number	Date	Time (Local Solar Time) – 03 GMT	Cover area of Saudi Arabia	Reported rainfall over the region on the last five days
1088	September 05, 87	06:00	Except east region of Saudi Arabia	3mm over Khamis Mushait on Sep.2
1010	August 30, 87	18:00	Except northwest region of Saudi Arabia	5.5mm and 16.2mm over Abha on Aug. 28 and 29 respectively
1102	September 06, 87	06:00	Except southeast region of Saudi Arabia	3mm over Khamis Mushait on Sep. 2
1137	September 08, 87	18:00	Except northwest region of Saudi Arabia	No rainfall

The presence of precipitating clouds will influence the brightness temperatures. Therefore, data with precipitating clouds should be excluded from the analysis. The existence of precipitating clouds will be examined only by using SSM/I brightness temperatures Mashat's method (Mashat, 1995) such that when H19-V85 > 0, then the data will be excluded from the analysis. For Node A, it is found that all the data had H19-V85 < 0, so all the data will be used in the analysis; however, for Node D several data points had H19-V85 > 0. This agrees with the synoptic situation over southwest Saudi Arabia at this time of year, namely, that clouds form and rainfall occurs in the afternoon over the region.

The "ground truth" land surface temperature for the selected days were estimated for each grid cell using the measured temperatures at the meteorological stations. For each selected days, the measured temperatures were plotted on Kingdom maps, and isotherm lines were drawn for each 1ºC. The isotherm lines were drawn by hand and by using Surfer software. They gave similar results. From this analysis, the average area of land surface temperature for each grid cell will be estimated and used as "ground truth" temperature.

The average brightness temperature at each SSM/I frequency for each cell was defined as the arithmetic mean of the brightness temperatures available in each grid cell. A new data for each revolution was created containing grid cell number, the seven channels of the SSM/I brightness temperatures, and the consistent "ground truth" land surface temperature. The data sets were analyzed using software called SPSS, which is statistical software.

Results and Discussion

Results of the Analysis

A simple linear regression method was used to determine the degree of correlation of land surface temperature and the seven channels of SAM/I brightness temperatures. The initial analysis consisted of two data sets of the study area. The first data set is for the satellite ascending overpass time (node A) at about 6:00a.m. local solar time for revolution number 1088 (September 05, 1987), and the second data set is for the satellite descending overpass time (node D) at about 6:00p.m. local solar time for revolution number 1010 (August 30, 1987). The data used in this investigation contained the means of brightness temperatures at each SSM/I frequency were calculated for each grid cell consistent with "ground truth" land surface temperature in the form of a $1^o \times 1^o$ cell. The grid cells close to the sea or covered by precipitating clouds, which were determined through an examination of the V85 and H19, were excluded from the analysis. It was found that one hundred thirty four grid cells for revolution number 1088 and one hundred thirty five grid cells for revolution number 1010 met the above conditions.

Statistical correlation analyses for both data sets were performed. A simple linear regression was used to determine the degree of correlation between the SSM/I brightness temperatures and land surface temperature over Saudi Arabia. The results of the analyses are summarized in Table 4. Low correlation coefficients occur between the SSM/I brightness temperatures in each channel and land surface temperature. This is a result of differences in emissivity of the land among the grid cells.

Table 4. Correlation coefficients (R) of SSM/I brightness temperatures and land surface temperature for revolution number 1088 and revolution number 1010 over Saudi Arabia.

SSM/I brightness temperatures	Correlation coefficients for revolution number 1088 (06:00 local solar time)	Correlation coefficients for revolution number 1010 (18:00 local solar time)
V19	0.1146	0.4222
H19	– 0.3492	– 0.3974
V22	0.1501	0.4694
H37	0.1166	0.3496
V37	– 0.3433	– 0.3601
V85	0.2035	0.3243
H85	– 0.0721	– 0.0990

Multiple linear regression (stepwise method) of SSM/I brightness temperatures and land surface temperature over the study area was used to test the statistical validity of the correlation coefficients. The variable of the SSM/I brightness temperatures, the correlation coefficients for the multiple linear regressions, and the equations for revolution number 1088 and revolution number 1010 are listed in Tables 5 and 6 respectively. It was found that the degree of correlations between land surface temperature and the SSM/I channels improved when more than one variable of the SSM/I brightness temperatures were used.

Low correlation coefficients ($R \leq 0.5108$) occur between the SSM/I brightness temperatures or combination of the SSM/I brightness temperatures and the land surface temperature for revolution number 1088 (Table 5). The low correlations occurring at the morning overpass could be due to the differences in "ground truth" land surface temperature at 3:00GMT between east region where the land get warming (sun rise at 2:20GMT) and west region where the land get cooling (sun rise at 3:10GMT) of Saudi Arabia.

TABLE 5. Correlation coefficients (R) between the land surface temperatures and SSM/I brightness temperatures for revolution number 1088 over Saudi Arabia.

Variables used	Multiple R	Equation
H19	0.3492	– 0.230094 × H19 + 357. 57
H19, V85	0.4888	– 0.3111308 × H19 + 0.295546 × V85 + 295.88
H19, H37, V85	0.5128	0.135380 × H19 – 0.517435 × H37 + 0.349596 × V85 + 298.96
H37, V85	0.5108	– 0.369368 × H37 + 0.337290 × V85 + 299.14

TABLE 6. Correlation coefficients (R) between the land surface temperatures and SSM/I brightness temperatures for revolution number 1010 over Saudi Arabia.

Variables used	Multiple R	Equation
V22	0.4694	0.350246 × V22 + 207.65
V22, H37	0.6668	0.428938 × V22 – 0.344996 × H37 + 275.75
V22, V37, H37	0.7375	1.265406 × V22 – 0.696442 × V37 – 0.312918 × H37 + 223.38
V22, V37, H37, H85	0.8217	2.185302 × V22 – 1.668889 × V37 – 0.758480 × H37 + 0.91774 × H85 + 101.74
V22, V37, H37, V85, H85	0.8349	2.099059 × V22 – 1.261757 × V37 – 1.043283 × H37 – 0.630388 × V85 + 1.333800 × H85 + 151.95

The correlation coefficients for revolution number 1010 ranged from 0.47, when only V22 was used, to 0.83 when V22, V37, H37, V85, H85 were used (Table 6). From the regression analysis performed on the data for Saudi Arabia, it appears that all SSM/I channels, except channels 19GHz, are the best channels to retrieve the land surface temperature. The 19GHz channels were important only when surface moisture was present. The land surface temperature (*LST*) for areas of 1° lat × 1° long grid for revolution number 1010 can be estimated using the following formula:

$$LST = 2.099059 \times V22 - 1.261757 \times V37 - 1.043283 \times H37 - 0.630388 \times V85 + 1.333800 \times H85 + 151.95 \quad \text{(eq. 1)}$$

Test the Results

It is useful to examine the results obtained above. Two data sets were used to test the results (see Table 3). The first data set is for the satellite ascending overpass time at about 6:00a.m. local solar time for revolution number 1102 (September 06, 1987), and the second data set is for the satellite descending overpass time at about 6:00p.m. local solar time for revolution number 1137 (September 08, 1987).

For morning satellite overpass (revolution number 1102), simple and multiple linear regressions were used to test the statistical validity, and determine the degree of correlation of land surface temperature and the seven channels of SSM/I brightness temperatures. The variable of the SSM/I brightness temperatures, and the correlation coefficients for the simple and the multiple linear regressions for revolution number 1102 are listed in Table 7. It was found that low correlation coefficients occur between the SSM/I brightness temperatures or combination of the SSM/I brightness temperatures and the land surface temperature for revolution number 1102. The rest results are similar to the analysis results that poor correlation coefficients occurred between the SSM/I brightness temperatures and land surface temperatures at morning overpass. This indicates that the SSM/I brightness temperatures cannot be used to estimate early morning land surface temperatures over Saudi Arabia without knowing the land emissivity.

TABLE 7. Correlation coefficients (R) between the land surface temperatures and SSM/I brightness temperatures for revolution number 1102 over Saudi Arabia.

Variables used	Correlation coefficients
V19	0.3620
H19	– 0.0180
V22	0.4051
H37	0.3579
V37	0.0091
V85	0.4308
H85	0.2562
H37, V85	0.4976

For afternoon satellite overpass, revolution number 1137 was used to test the results obtained in the analysis of revolution number 1088. The land surface temperatures were estimated using SSM/I brightness temperatures for revolution number 1137, and equation 1. The estimated land surface temperatures using SSM/I data were correlated to the measured land surface temperature. It was found that good correlation coefficient (R = 0.81, with standard error 2.4) occurs between the estimated and the measured land surface temperatures. Isothermal lines for measured land surface temperatures (Fig. 1) and isothermal lines for estimated land surface temperatures using SSM/I data (Fig. 2) were plotted on Saudi Arabia maps. Figures 1 and 2 show that the land surface temperatures obtained using ground observations have similar patterns to the land surface temperatures obtained using afternoon SSM/I data. It is suggested that the SSM/I brightness temperatures can be used to estimate afternoon land surface temperatures over Saudi Arabia.

Conclusions and Recommendations

Conclusions

The major findings from this research are as follows:

Land surface temperature cannot be estimated using single channel of SSM/I brightness temperatures.

Using several channels is much better than using single channel of SSM/I brightness temperatures to estimate land surface temperature.

SSM/I brightness temperatures cannot be used to estimate land surface temperature over Saudi Arabia at satellite ascending overpass time (about 6:00a.m. local solar time) without knowing the land emissivity.

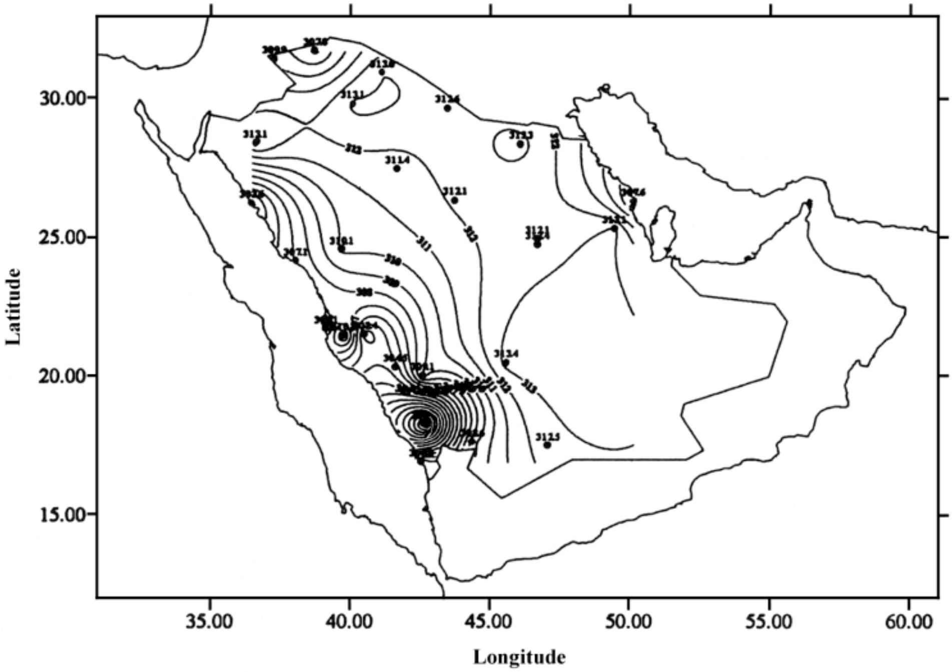

FIG. 1. Isothermal map (°K) of study area for September 08, 1987, at 15 GMT.

It appears that reasonable estimates of averaged land temperature over Saudi Arabia at satellite descending overpass time (about 6:00p.m. local solar time) are readily obtained for areas of 1° latitude × 1° longitude grid when V22, V37, H37, V85, H85 were used.

For future study, it is necessary to know the land surface type such as vegetation cover, soil type, soil moisture, surface temperature, and topographic characteristics to obtain the correlations between brightness temperatures and land surface temperatures.

Recommendations

Further testing of the use of the passive microwave brightness temperatures as a means of estimating land surface temperature is needed. The results of this study have indicated a number of additional studies that need to be conducted in order to better understand the effects of surface inhomogeneities within the study area. An effective program of using satellite data to retrieve the surface temperature over land should be initiated in Saudi Arabia. Coordination with King Abdulaziz City for Science & Technology, Saudi Center for Remote Sensing, and the Meteorology and Environmental Protection Administration (MEPA) in Jeddah and possibly other governmental agencies should be considered. The effective use of the refined research methodology will rely on correct data from various sources. Also, consideration should be given to collaborative studies various agencies and universities in Saudi Arabia.

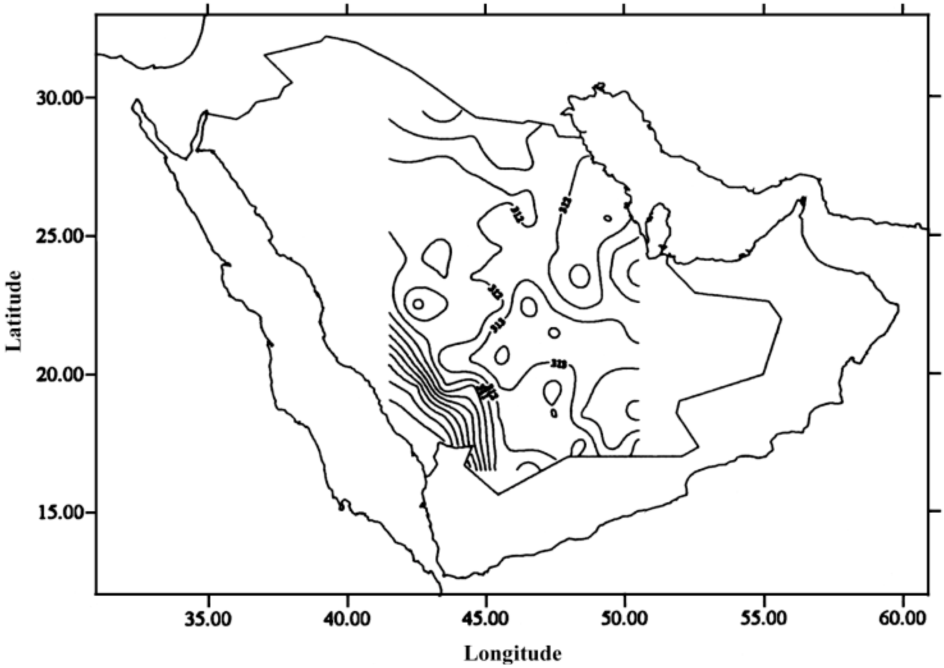

FIG. 2. Isothermal map (°K) of study area for September 08, 1987, at 15 GMT. The land surface temperatures were estimated using SSM/I data (revolution number 1137).

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تقـدير درجـة الحـرارة السطحيـة للمملـكة العربيـة السعوديـة باستخـدام عنصر حساس للموجات الدقيقـة

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المستخلص . يهتم هذا البحث بتطبيق الأمواج الدقيقة (الميكروويف) الهامدة على الحرارة السطحية للمناطق الجافة . لقد استخدم الانحدار الخطي البسيط والمركب لاختبار العلاقة الإحصائية لمعامل الارتباط مابين درجات الحرارة السطحية وحرارات السطوع المقاسة بواسطة المجس SSM/I فوق المملكة العربية السعودية . فقد تم أخذ عينتين لإجراء تجربتين ، الأولى عند صعود التابع (حوالي الساعة السادسة صباحًا) ، والثانية عند انحدار التابع (حوالي الساعة السادسة مساءً) .

من خلال التجربتين وجُد أن العلاقة ما بين درجات الحرارة السطحية وحرارات السطوع ضعيفة عند مرور التابع صباحًا ، في حين أن العلاقة قوية عند مرور التابع مساءً فوق منطقة الدراسة . وقد أمكن تقدير درجات الحرارة السطحية لمربع أبعاده درجة واحدة خط عرض وخط طول عند حوالي الساعة السادسة مساءً باستخدام حرارات السطوع للمجس SSM/I .