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Majumdar, T. J.,[1] Mitra, D. S.,[2] and Nasipuri, P.[3]
[1]Earth Sciences and Hydrology Division, Marine and Earth Sciences Group, Remote Sensing Applications Area, Space Applications Centre (ISRO), Ahmedabad - 380 015, India, E-mail: tjmajumdar@rediffmail.com
[2]Remote Sensing and Geomatics Division, K. D. Malaviya Institute of Petroleum Exploration (O.N.G.C.) Dehradun - 248 195, India, E -mail: dsmitra@gmail.com
[3]Institutt for Geologi, Universiteteti Tromsø, Dramsveien 201, 9037 Tromsø, Norway
E-mail: nasipuri.pritam@gmail.com

Abstract
Surface temperature estimation has been attempted with ASTER (Advanced Spaceborne Thermal Emission and Reflectance radiometer) nighttime data over a part of the Cambay basin, India using TES (Temperature and Emissivity Separation) algorithm. Validation studies performed using IMD (India Meteorological Department) Bulletin data conform to the TES modeled results over Ahmedabad. A marked temperature gradient is observed from west to east in the study area. Superimposition of the thermal anomaly patterns over the oil-fields shows "low-temperature" anomaly, which might have occurred due to the formation of oil-water immiscible layer acting as a thermal barrier. Sharp changes are occurring near the oil fields in Ahmedabad and its surrounding regions e.g. Bakrol, Ahmedabad, Nawagaam etc. though the local land use and land cover at places might have masked the surface temperature caused by subsurface heat flow. Signature studies using high resolution nighttime thermal IR data over the oil fields in the Cambay basin are unique in nature.

1. Introduction

An infrared remote sensing imagery records the surface radiance emitted from the earth. If instrument calibration, atmospheric and topographic corrections are made, the resulting product represents the surface temperature (Sabins, 1987). Land surface temperatures are useful in global-change and heat-balance studies and also for estimation of radiation budgets. Emissivity is strongly indicative (diagnostic) of composition, especially for the silicate minerals that make up much of the land surface. Surface emissivity is thus important for studies of soil development and erosion and for estimation of changes in sparse vegetative cover where the substrate may be visible. Due to the absence of direct solar insolation, nighttime surface emissivity and temperature data will be controlled by other heat fluxes including the subsurface heat flow and would be found more useful for signature studies over the oil fields. The commonly used techniques are "Channel 6 Emittance Model", "Thermal Residual Log" and "Alpha residuals" (Hook, 1992). Another method called "Spectral Ratio Method" was developed by Watson (1992), whereas Gillespie (1986) has opined for "Decorrelation Stretch Image".

Surface temperature (T) is independent of wavelength and can be recovered from even a single band of remotely sensed radiance data, only when the surface emissivity (ε) and the atmospheric condition are properly known. However, thermal radiances vary with both surface temperature (T) and emissivity (ε), which, therefore, must be recovered from measurements. Except for water, vegetation and snow or ice, the problem gets complicated over land due to the following reasons: (i) land surface temperature is generally not homogeneous within a pixel, as is the case in the ocean (ii) the difference between the land surface temperature and the air surface temperature near the surface is large for land surface, and (iii) land surface emissivity may be quite different from unity and is spectrally variable (Becker, 1987, Salisbury and D'Aria, 1992, Becker and Li, 1995 and Majumdar and Mohanty, 1998). The inversion for temperature and emissivity is, therefore, under-determined as there is always at least one more unknown than the number of measurements. Extraction of temperature and emissivity information requires additional information, which has to be determined independently. We have used TES algorithm (Gillespie et al., 1999) where the additional data has been generated from the regression analysis of minimum emissivity to spectral contrast of laboratory spectra. The present paper summarizes the method and initial results of the experimental studies carried in parts of the Cambay basin using ASTER high resolution nighttime thermal IR data.

2. Objectives

The objectives of this study were:

i) Estimation of surface temperature with nighttime ASTER thermal IR data using TES (Temperature and Emissivity Separation) algorithm, and

ii) To study high resolution satellite thermal infrared data e.g. ASTER for detection of thermal anomalies and oil field signatures over known producing fields in the Cambay basin, Gujarat, India.

3. Data Source and the Area of Study

The ASTER is a high spectral/spatial resolution multispectral imager on the first platform on NASA's Earth Observation System. The ASTER instrument was built by the Japanese Government based on the scientific requirements of the ASTER Science Team. The technological specification of ASTER is given in Table 1 (Kahle et al., 1991 and Yamaguchi et al., 1991).

Table 1: Different bands of ASTER and their specifications

VNIR (15 m)	WAVE LENGTH (μm)
Band 1	0.52 - 0.60
Band 2	0.63 - 0.69
Band 3N	0.78 - 0.86
Band 3B	0.78 - 0.86
SWIR (30 m)	
Band 4	1.600 - 1.700
Band 5	2.145 - 2.185
Band 6	2.185 - 2.225
Band 7	2.235 - 2.285
Band 8	2.295 - 2.365
Band 9	2.360 - 2.430
TIR (90 m)	
Band 10	8.125 - 8.475
Band 11	8.475 - 8.825
Band 12	8.925 - 9.275
Band 13	10.25 - 10.95
Band 14	10.95 - 11.65

The ASTER sensor on TERRA platform has collected five channels of TIR data over a part of the Cambay basin (Scene center: Latitude: 22.88^{0}N, Longitude: 72.54^{0}E) on 18/05/2003 at 17h 23m 12s Universal Time (2300 hrs. IST – Indian Standard Time approx.). Environmental conditions were normal, with summer time high temperature, and cloud-free sky over the test area during the ASTER pass. Other data used in this study are *in-situ* meteorological data from IMD Bulletin and MODIS derived surface temperatures. A part of the Cambay basin, Gujarat, India has been selected for the study with intensive test site over Ahmedabad (Figure 1). Besides being geothermally active it contains several oilfields. The Cambay basin, bounded by latitudes 22° and 25° N and longitudes 71° 30' and 73° 30' E, is a marginal aulacogen basin situated in the western part of India. Geological and tectonic maps of the Cambay basin are shown in Figure 2a and b respectively. This is a proven petroliferous basin covering an area of about 53,500 sq. km. More than 90 oil & gas fields have been discovered, of which two fields, Ankleshwar and Gandhar, are of giant size. Over 5 km. thick Tertiary sediment (clay stone, sandy siltstone and shale) is present. The total prognosticated hydrocarbon resources are of the order of 2050 MMt (Metric Million tons) and established in-place reserves are of the order of 1188 MMt. Structural, tilted fault closure and strati-structural playas in tertiary sediments are the main exploration targets.

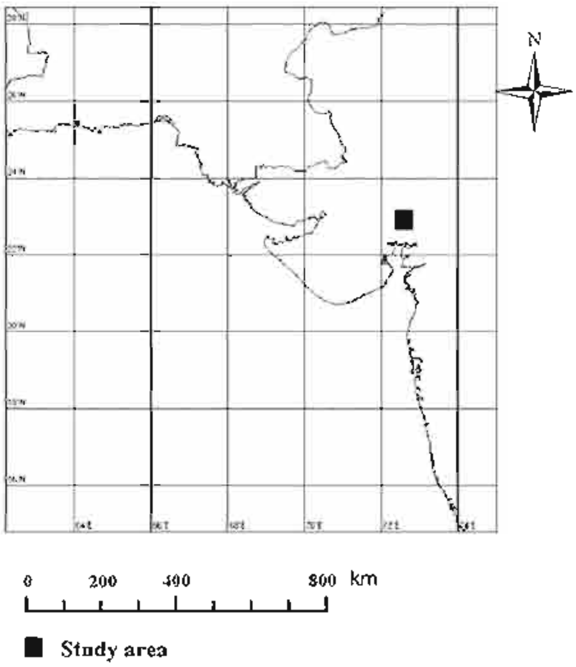

Figure 1: Location of the study area in Gujarat, India

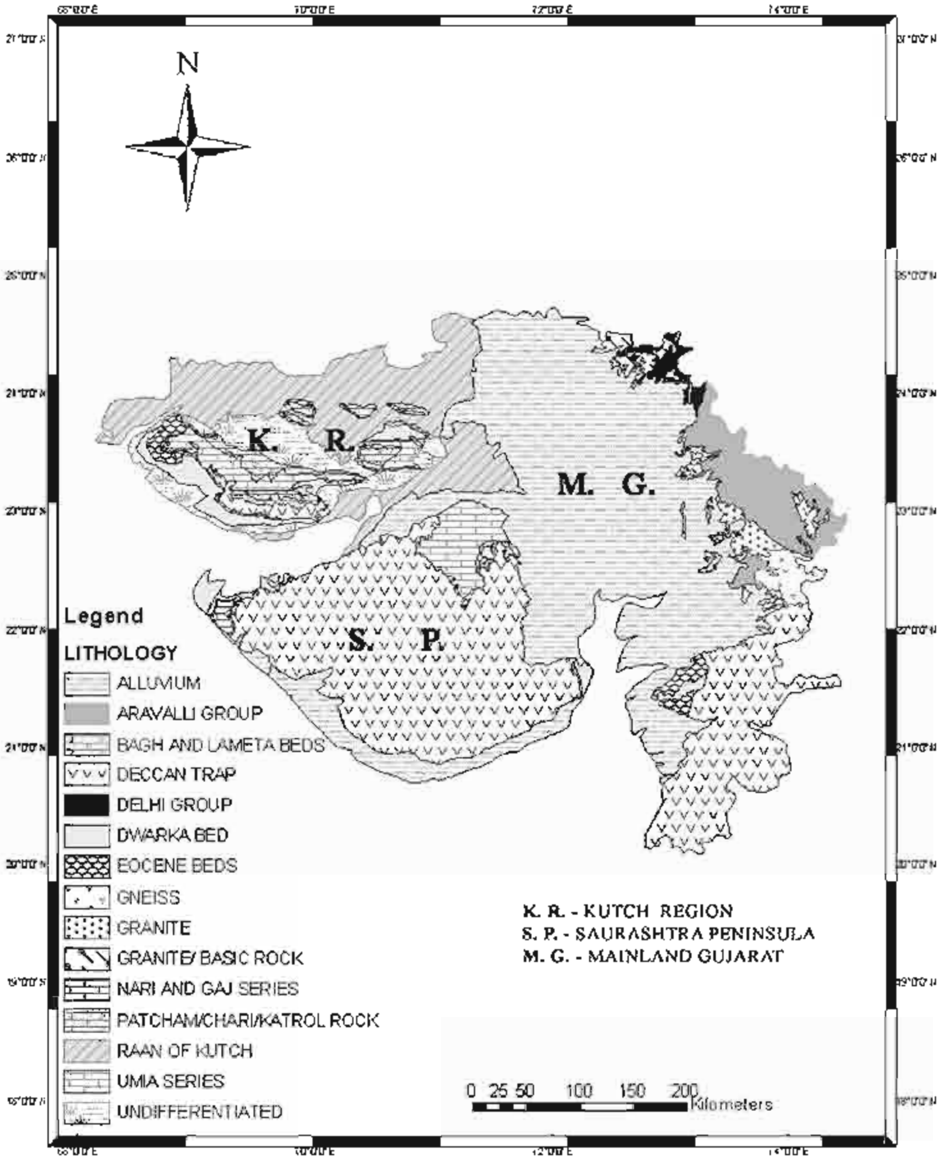

Figure 2a: Geological map of the Cambay basin, Gujarat, India

4. Geology of the Cambay Basin

The major geological events in Gujarat are confined to Mesozoic and Cenozoic Eras (Merh and Chamyal, 1997). The geological evolution of Gujarat was initiated in the Triassic with the breakup of Gondwanaland and the Cambay basin developed sequentially from north to south during India's northward drifting. Development of three major rift basins in the western margin, namely Kutch, Cambay and Narmada, seems to be related to the evolution of the western margin of India in three stages; namely, a) Separation of Africa from India in early Jurassic, b) Separation of Madagascar from India caused by Marion hotspot during middle Cretaceous, and c) Breakup of the Seychelles from India caused by the Reunion hotspot during late Cretaceous, which gave rise to the Deccan Trap basalts. The deepest part of the basin is recorded between the Narmada and Mahisagar rivers, where more than 5,000 meter of sediments has been deposited. Initially it is believed that the basin is divided into two parts by an east-west trending fault along Narmada River. However recent data indicate that except this fault, there are other faults in that basin which has divided the basin into various blocks (Figures 2a and b). Figure 2c shows the DEM generated over Gujarat using SRTM (Shuttle Radar Topography Mission) data. A strong positive topographical trend is clearly seen from west to east.

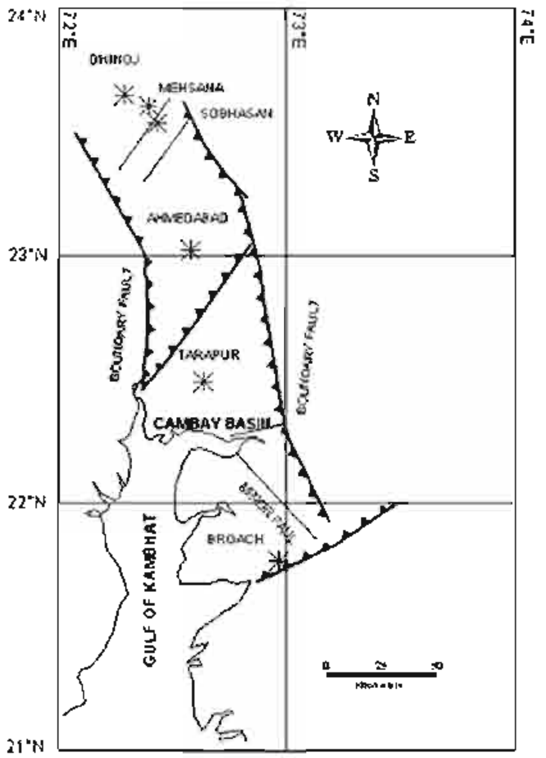

Figure 2b: Tectonic set up of the Cambay basin, Gujarat, India

5. Processing of Data and Data Flow in TES Algorithm

For atmospheric correction due to water vapor, best way is to estimate the atmospheric temperature profiles, water profiles, atmospheric pressure, trace gases and aerosols, and use MODTRAN software to estimate atmospheric transmissivity and path radiance. In this case, we have used a standard tropical atmosphere and did the atmospheric corrections using MODTRAN. Also, Level 2B04 products (Emissivity) were noisy, as suggested by ASTER ARO Office, Japan. Temperature/emissivity separation (TES) algorithm is difficult because there are five measurements but six unknowns. TES algorithm for multispectral remote sensing, especially for ASTER, has been discussed in details by Gillespie et al., (1998). It is a combination of three established algorithms; first it estimates the normalized emissivity and then calculates emissivity band ratios and using an empirical relationship, emissivity spectrum is recovered. Moreover, TES algorithm uses an iterative approach to remove reflected sky irradiance. However, the main sources of uncertainty in the output temperature and emissivity images are the empirical relationship between emissivity values and spectral contrast, compensation for reflected sky irradiance, and ASTER's precision, calibration, and atmospheric correction (Thome, 1998 and Palluconi, 1999).

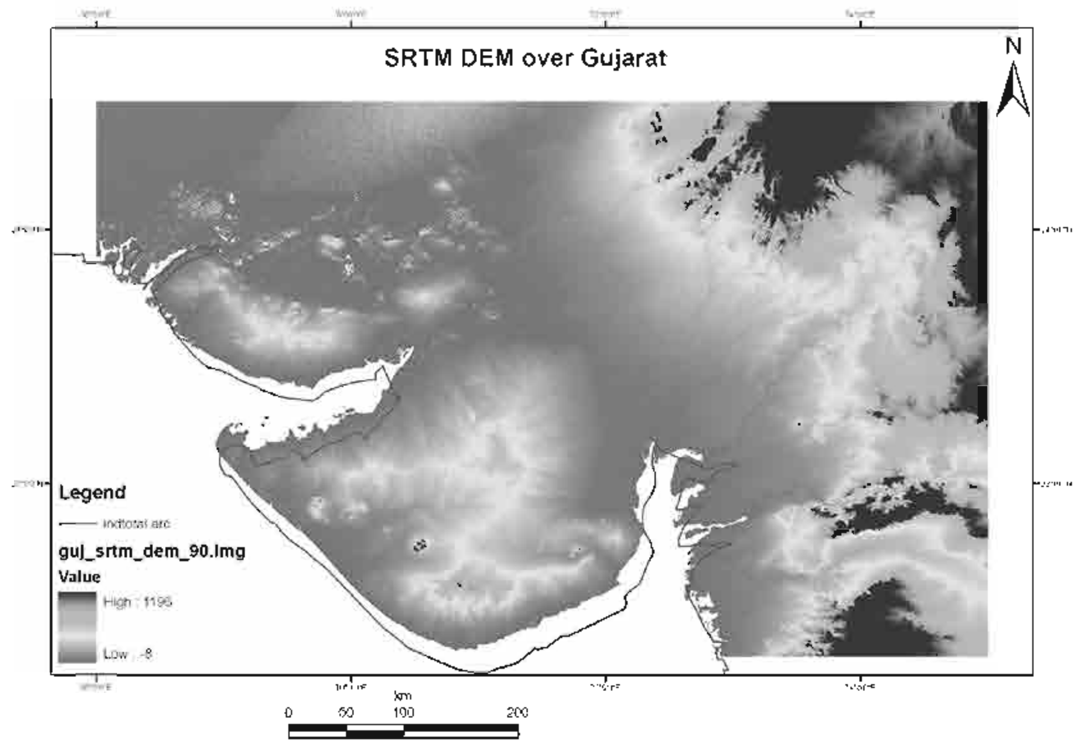

Figure 2c: SRTM DEM as generated over Gujarat

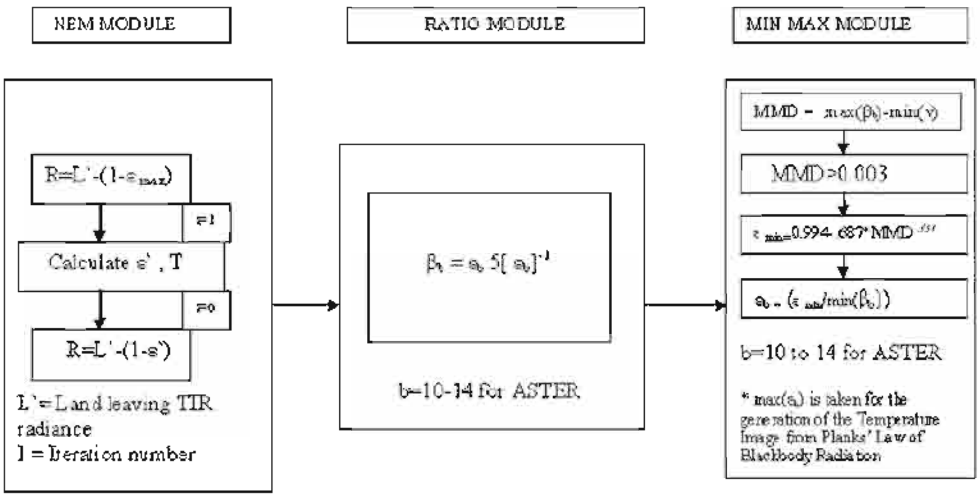

Figure 3a: Data flow in the TES algorithm (after Gillespie et al., 1998)

Figure 3b: Emissivity image generated using TES algorithm over a part of the Cambay basin (Ahmedabad region) using Min-Max Module

The data flow in TES algorithm is shown in Figure 3a. Initially we have assumed an emissivity of 0.99. After performing all the three modules we have generated the surface temperature images over the study areas (Ahmedabad and Mehsana). The emissivity image generated using min-max module and ERDAS IMAGINE over a part of the Cambay basin (Ahmedabad region) is shown in Figure 3b (emissivity variation between 0.85 to 0.96).

6. Interpretation of Temperature and Emissivity Images

The study areas are entirely parts of a pericratonic rift basin filled with alluviums by the Sabarmati river and vegetation cover, apart from settlement, cultivated and barren land. The nighttime surface temperature image over Ahmedabad and its surroundings is shown in Figure 4. The range of variation of surface temperature as observed from ASTER nighttime thermal IR data is between 300 to 307 K (Figure 4). A detailed validation study was attempted with the observation of IMD (India Meteorological Department) during 18 and 20 May, 2003 (Weather Bulletin, 2003). The minimum temperature recorded at Ahmedabad varies between 27-28 °C which conforms well to our ASTER data surface temperature estimation using TES Algorithm. Also, two important points to be kept in mind: firstly, the minimum temperature in a diurnal cycle occurs near 0400 hrs. IST (Indian Standard Time) whereas the ASTER pass is around 2300 hrs IST; secondly, what IMD (India Meteorological Department) observes is the ambient air temperature near surface whereas ASTER thermal IR sensor directly measures the skin temperature on the surface and at times there is a difference of around ± 2-4 °C during these observations in the night. Environmental conditions were just normal during the ASTER pass with cloud-free sky over Gujarat. The maximum temperature (in the night) is recorded in Ahmedabad city (Human settlements) ranging from 305 to 307.6 K. and the water bearing bodies shows variable temperatures ranging from 303 to 305.35 K. The temperatures from different locations that can be identified in the image are shown in Table 2. Figure 3b shows the emissivity image generated over Ahmedabad region using TES algorithm with variation from 0.85 to 0.96. Wide variation of emissivities has been reported for different features in the night. Typical urban area shows emissivity around 0.891, water body around 0.879, forest region 0.901, metal road around 0.895. The natural body with high emissivity will be warmer in night.

The clear water body emits thermal energy during night, hence should be warmer than its surroundings. In contrast to that, the Sabarmati River shows variable temperature along its course, in general cooler than its surroundings (Figure 4). The other water bodies, e.g. Lake Kankaria and Lake Chandola are also showing lower temperature than the surroundings (Figure 4). Emissivity measured at wavelength 8-12 µm is 0.972 for water; 0.993 for water with thin film of petroleum; 0.909 for silica/sandstone; 0.914 for sand, quartz and 0.815 for granite (Source: Sabins, 1987). The value of emissivity of 0.879 as obtained here may be due to water body along with silica/sandstone in the riverbed or lake playa. These indicate a full/partial dried-up river/lake bed, which is a very common phenomena during summer particularly when bedrock or substrate is exposed.

7. Discussion

- According to the second law of thermodynamics, heat flows from within the earth to its surface. Hydrocarbon–rich reservoirs form relatively efficient, though imperfect, thermal barriers, resulting in a dynamic equilibrium condition of negative temperature anomalies above and positive temperature anomalies below hydrocarbon reservoirs. Hence, one can expect hydrocarbon deposits to be accompanied by overlying temperature anomalies. Many authors have advocated that the temperature method can help locate oil and gas deposits and have demonstrated that there occurs a positive temperature anomaly below a pay zone and an equal and opposite direction (negative) anomaly above the hydrocarbon deposit in a known producing field (Majumdar et al., 1983, Fons, 1999, Hook et al., 1999 and Gorney et al., 2003). However, different rock types with different porosities and water contents (thus different thermal inertias) are also important factors for the existing temperature patterns in this area.

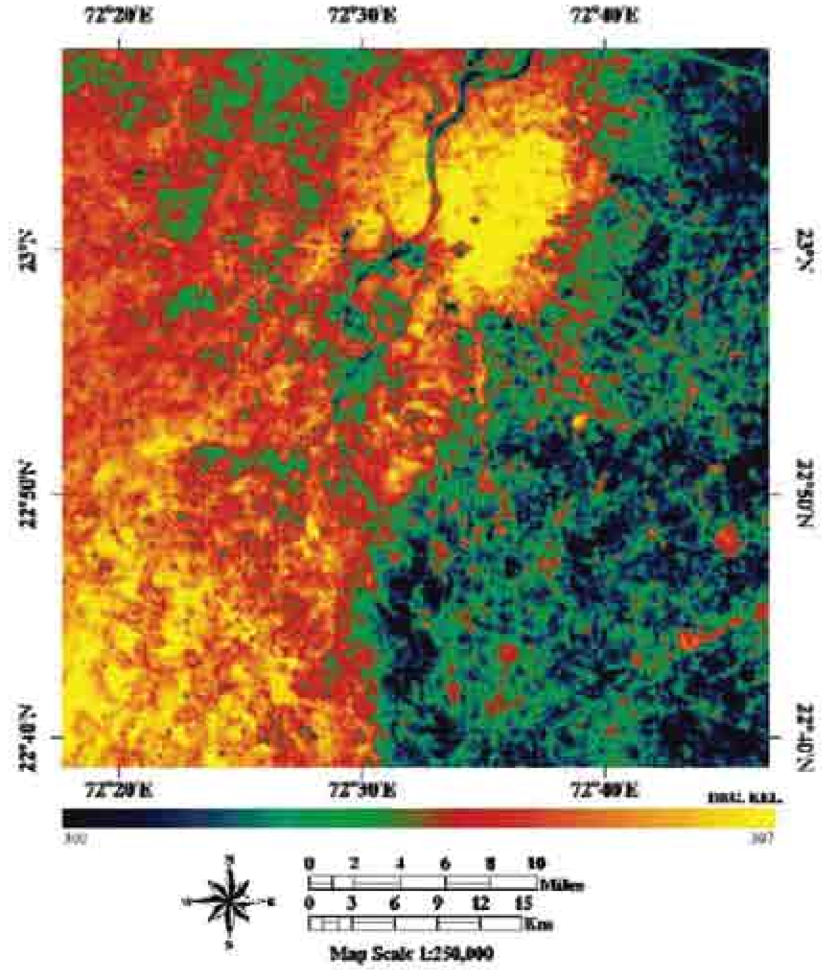

Figure 4: Surface temperature image as generated using TES algorithm over a part of the Cambay basin (Ahmedabad region)

Table 2: Nighttime temperatures at selected locations

Location	ASTER Temperature Image
Sabarmati River	Variable, ranging from 303.5 to 305.7 K
Lake Kankaria	303-305.35 K
Ahmedabad City	305-307.6 K
Metal Road	Variable, ranging from 304.8-306 K
Open Mixed Jungle	305.37 –306 K

Table 3: Variation of temperatures in selected oil fields

Oil Field Near (Refer Fig. 5)	Temperature (K)		
	Maximum (surrounding area)	Minimum (over the oil field)	Difference
BAKROL	305.4	302	3.4
AHMEDABAD	306.5	303.54	3.04
NANDEJ	305.43	303.13	2.30
WASANA	305.1	303	2.1
NAWAGAAM	305.6	302.2	3.4

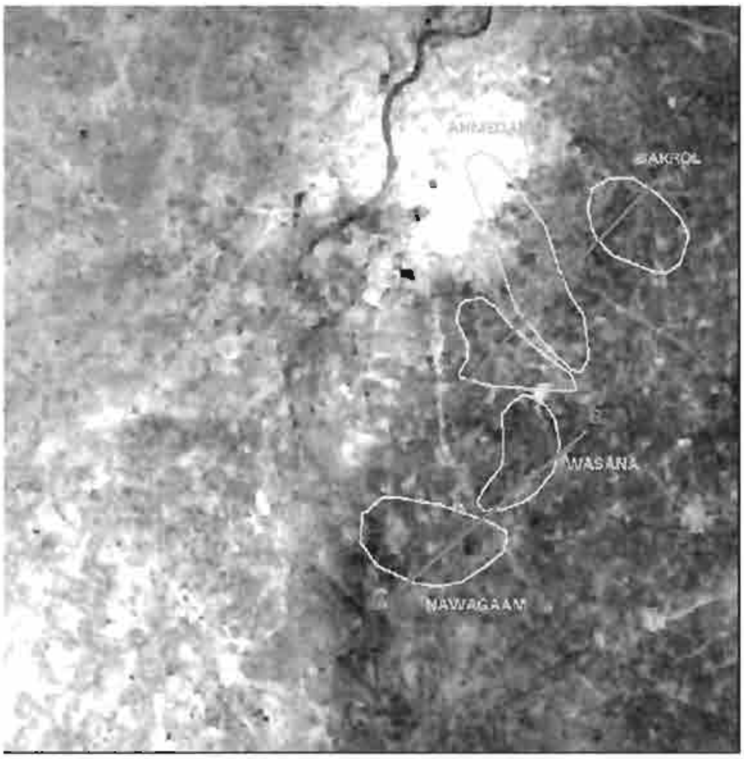

Figure 5: Location of selected oilfields and the profile lines over Ahmedabad region

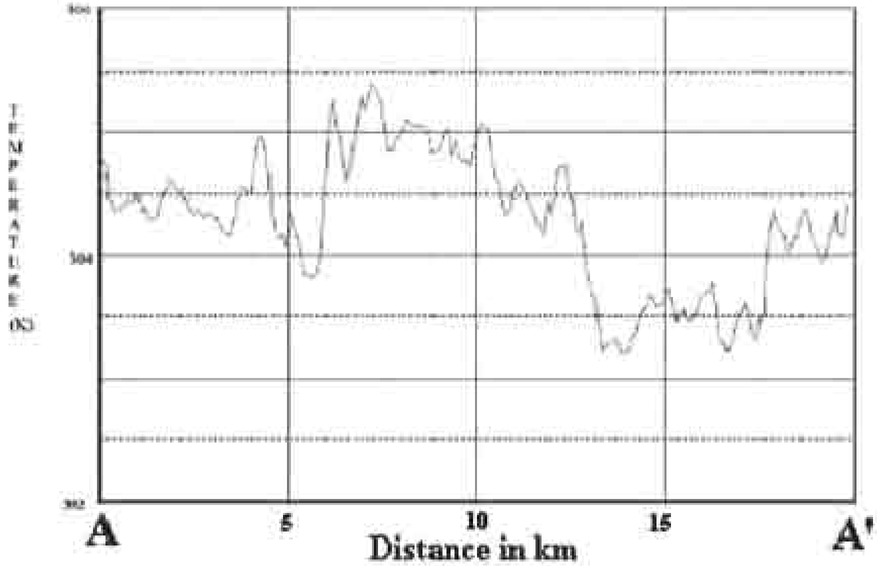

Figure 6 a: Variation of temperature along profile AA'

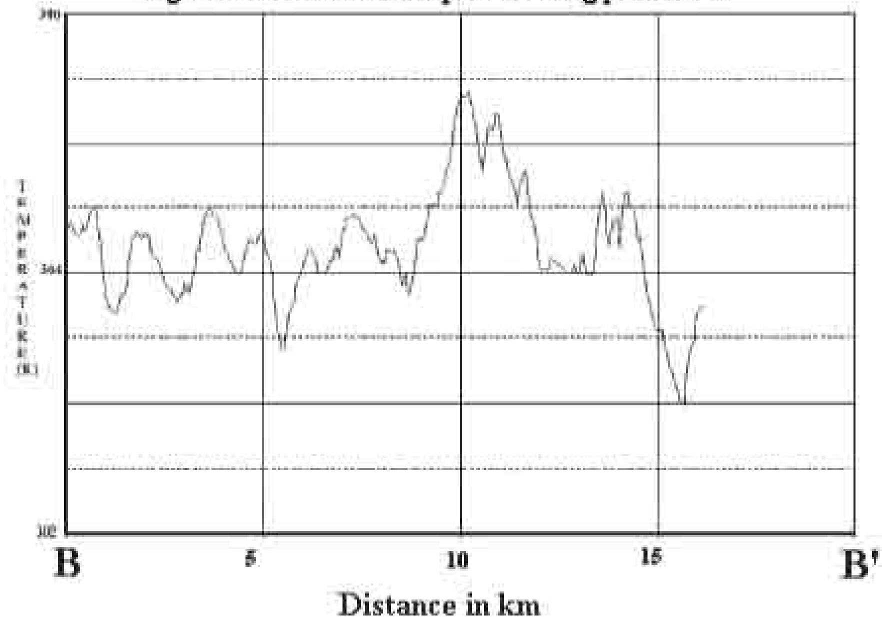

Figure 6 b: Variation of temperature along profile BB'

- The proven oilfields have been plotted over the ASTER image along with two profiles AA' and BB' (Figure 5). The temperature variation recorded in Ahmedabad areas over the proven oilfields are shown in Table 3 and in Figure 5 and Figure 6a-b. The temperature patterns over the two oilfields show sharp negative anomaly. The positive anomaly associated with the Ahmedabad oilfield is due to the urban settlement, which partially masks the surface temperature anomaly due to subsurface heat flow.
- Validation studies with *in-situ* IMD data over Ahmedabad (Weather Bulletin, 2003) conform to the observation from ASTER-derived surface temperatures using TES Algorithm.
- In the surface temperature image of Ahmedabad (Figure 4), the eastern part (covering the eastern margin of the Cambay basin) shows low temperature and the western part exhibit higher temperatures - a strong negative thermal gradient from west to east throughout the image. A strong positive topographical trend is observed from west to east in the SRTM generated DEM over Gujarat

(Figure 2c). However, it is difficult to correlate both the surface temperature and topographical trends.

- Superimposition of oil field maps in Ahmedabad regions (Figure 4 and Figure 5) reveals that, the temperature over the oilfields is less than the mean temperature of the adjacent area. This high temperature is due to the urban settlement and other land cover features, which partially masks the actual temperature.

8. Conclusions

- TES algorithm could be successfully applied on multispectral ASTER nighttime TIR data to generate the emissivity and surface temperature images and to study the temperature anomalies over the existing oilfields.
- In general, the surface temperature patterns over the proven oilfields show "low surface temperature" anomaly, which might have occurred due to the formation of oil-water immiscible layer acting as a thermal barrier for the heat flow from within the earth to the surface. However, different rock types with various thermal inertia patterns may also play a significant role to generate the existing surface temperature patterns.
- The local land use and land cover at places might have masked the surface temperature caused by subsurface heat flow.
- Signature studies using high resolution nighttime thermal IR data over the oil fields in the Cambay basin are unique in nature.

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