Temporal monitoring of coal fires in Jharia Coalfield, India

Article *in* Environmental Earth Sciences · June 2016

DOI: 10.1007/s12665-016-5799-7

Anjali Singh
Mohan Lal Sukhadia University

Sudhir Kumar
National Institute of Hydrology

Pitambar Pati
Indian Institute of Technology Roorkee

Environ Earth Sci (2016)75:989
DOI 10.1007/s12665-016-5799-7

ORIGINAL ARTICLE

Temporal monitoring of coal fires in Jharia Coalfield, India

Ashwani Raju[1] · Anjali Singh[2] · Sudhir Kumar[3] · Pitambar Pati[4]

Received: 28 June 2015 / Accepted: 30 May 2016

Abstract Jharia Coalfield (JCF) in India has one of the densest congregations of surface–subsurface coal fires in the world. Evaluation of spatial dynamics and trend of coal fires propagation through ASTER thermal data has indicated that the magnitude of coal fires in JCF has been fluctuated with time from 2000 to 2009. The area located around western, eastern and southeastern parts of the JCF covering Shatabdi opencast, Barora; Sijua opencast; Godhar colliery, Kusunda; Bokapahari; Kujama; and Lodna is under intense coal fire. From 2000 to 2004, spatial extent of coal fire has shown a minor decrease of 6.74 % and then shows a substantial increase of 11.93 % between 2004 and 2009. Systematic analysis of the results has revealed that the movement of coal fire in JCF is structurally controlled. Propagation of the coal fires has been observed in Kustor, Bastacolla and Lodna collieries, and fire appears to be spreading along the strike of coal seams toward Jharia Township.

Keywords ASTER · Time series · Coal fires · Temporal monitoring · Mapping · Dynamics

✉ Ashwani Raju
ashwani.geo@gmail.com

Anjali Singh
anjalisingh.iitr@gmail.com

Sudhir Kumar
sudhir.nih@gmail.com

Pitambar Pati
impitambarpati@gmail.com

1 Geological Survey of India, Jabalpur 482003, Madhya Pradesh, India

2 School for Environmental Science, Babasaheb Bhimrao Ambedkar University, Lucknow, Lucknow, Uttar Pradesh, India

3 National Institute of Hydrology, Roorkee, Roorkee 247667, Uttarakhand, India

4 Department of Earth Sciences, Indian Institute of Technology Roorkee, Roorkee 247667, Uttarakhand, India

Introduction

All known occurrences of high-rank coal around the world are invariably associated with the problem of 'coal fires,' particularly in China, USA, Australia, Indonesia and India (Cracknell and Mansor 1992; Mansor et al. 1994; van Genderen et al. 1996; Rosema et al. 1999; Stracher and Taylor 2004; Zhang et al. 2004; Whitehouse and Mulyana 2004; Gangopadhyay and Lahiri Dutt 2005; Kuenzer et al. 2007; Kolker et al. 2009; Prakash and Gens 2010). 'Coal fire' is a term used for the naturally occurring fire within in situ coal seam or in stored coal. Coal is chiefly composed of carbon and has inherent property to self-ignite and undergo spontaneous combustion (Feng et al. 1973). The self-ignition of coal originates at the interface of coal and atmosphere. It occurs when the heat evolved by coal oxidation exceeds the amount of heat dissipated by conduction, convection or self-radiation (Ackersberg 2003). Once a fire starts in a coal seam, it continues for a long time by spreading along the coal seam (Schmal 1987). Fire can be burning or smoldering in nature, located at the ground or beneath the ground. Underground coal fires result in the development of linear cracks, vents, fissures, etc. on the surface. Such features are sporadic in spatial extent and vary in dimension from few meters to tens of meters. Coal fire can cause severe environmental and economic problems (Stracher and Taylor 2004). It reduces valuable coal reserves and leads to the emission of gases that diffuse out

Published online: 08 June 2016

into the atmospheric. These gases are actively contributing to greenhouse effect in the atmosphere (van Dijk et al. 2011; Engle et al. 2011). The smoke and windblown ash can plague the areas and cause significant environmental changes around coal fire-affected areas. Spontaneous burning not only induces deleterious effect on the human health, but also poses serious threat to the local inhabitants (flora and fauna) living around the area. Thus, coal fires can be considered as a root of socialeconomic and environmental problems that has worldwide influence at both local and global level.

Indian coal mining has been one of the most disaster-prone industries which have witnessed numerous severe accidents leading to repeated loss of life and energy resources. Jharia Coalfield (JCF), particularly, is potentially advantageous to the India's coal production as this coal field is the only contributor of the coking coal. Depth-wise breakup of the total resource of coking coal in JCF indicates that about 75.1 % (4039.41 MT) of proved resource of coking coal exists up to a depth of 600 m below ground level (GSI 2004). Due to this reason, the JCF has been extensively explored and exploited since twentieth century (Chandra 1992). To meet the ever-increasing demand for energy for industrial growth, the haphazard coal mining activities are being intensely practised in JCF especially by opencasts operations. Opencast activities expose the burning coal seam to the atmosphere and hence accelerate the combustion of coal in uncontrolled manner. Uncontrolled coal fires are highly dynamic and can propagate by feeding on the coal seam. Fire in most cases also blocks the excavation of available coal resources and often makes the area unapproachable.

Coal fires have drawn the attention of researchers, managers, miners, local residents and news media alike since more than last two decades (Raju et al. 2012). Precise mitigation and reclamation measures to reduce the consequences of this geo-hazard essentially require temporal monitoring and mapping of coal fires. Inaccessibility of the areas under intense coal fire hampers the study of this phenomenon properly. Field surveys cannot be executed frequently and considered unfeasible from economic point of view. Satellite data-based analyses have potential advantage over traditional field survey methods. Remote sensing techniques as a tool have widely contributed to analyzing of such thermal phenomenon. It is cost effective, less time consuming, and temporal datasets are available for time series analysis. This may help to plan sustainable mining and environmental remediation on a long-term basis.

Previous studies of coal fires in JCF: a brief review

Mine fires in JCF have a long history (Sinha 1986). Coal fires in JCF have been well monitored from space using aerial scanner and satellite sensors since last two decades. In 1990s, airborne thermal images were first used to detect and monitor surface–subsurface coal mine fires in JCF (Bhattacharya et al. 1991; Mukherjee et al. 1991; Bhattacharya and Reddy 1994). However, after the launch of Landsat-4 with multispectral scanning system (MSS) and Thematic Mapper TM sensor, monitoring and mapping of coal fires have been widely extended to an advance level. With availability of repetitive satellite data, coal fires in JCF were temporally monitored. Cracknell and Mansor (1992) evaluated the utility of Landsat-5 Thematic Mapper TM thermal infrared (band 6) and short-wavelength infrared (bands 5 and 7) data for detecting and mapping of surface–subsurface coal fires at some selected sites of JCF. The results of the study showed a good correlation with ground measurements and suggested that Landsat TM has significantly enabled the detection, mapping and quantification of subsurface coal fires zones. Reddy et al. (1993) used the short-wave infrared region (SWIR) to detect the high-temperature surface fire and related geo-environmental features in JCF. Prakash (1996) exclusively carried out remote sensing–GIS-based studies of coalmine fires in JCF. The study broadly describes the various aspects and characteristics of coal fires using Landsat MSS and TM data. Landsat TM band 6 data were potentially used to detect the surface thermal anomaly associated with underground coal fires in JCF. The area affected by underground coal fires was precisely mapped by using the density slicing technique on DN values (Prakash et al. 1995). In JCF, surface fires are sporadic in nature and relatively small in spatial extent. TM-6 is useful for mapping subsurface fires, and TM-5 and TM-7 are useful for mapping surface fires (Prakash et al. 1997). Prakash and Gupta (1999) briefly reviewed the potential of short-wave infrared (SWIR) bands in estimating temperatures of high-temperature objects and computed sub-pixel area with corresponding sub-pixel temperature using dual-band approach (Landsat TM bands 5 and 7). Chatterjee 2006 used true spectral radiance from raw digital data using scene-specific calibration coefficients of the detectors and thermal emissivity of surface materials to obtain pixel-integrated kinetic temperature at each ground resolution cell of Landsat TM thermal IR data. The methods also involve field-based modeling to observe lateral propagation of coal fires in JCF.

Chatterjee et al. (2007) attempted to study the coal fire dynamics in Jharia during the 1990s from medium resolution satellite thermal IR data such as Landsat-5 TM and Landsat-7 ETM + data. The dynamics of coal fire was studied on the two aspects: (a) changes in the spatial extent of fire-affected areas and (b) propagation of coal fire during the 1990s. The results show a marked decrease in the spatial extent of fire-affected areas between 1992 and 2001. The propagation of coal fire was found to be more erratic than regular in nature and propagates mainly toward south from 1992 to 1996 and toward north till 2001. Further studies reveal that the area affected by coal fires has significantly increased by 0.51 km^2 from 2003 to 2006 (Martha et al. 2010). Mapping of coal fires suggests that the west-central and eastern part of the JCF is more affected by coal fires than the western part (Mishra et al. 2014).

In the present research, temporal monitoring and qualitative analysis of the coal fires in JCF have been accessed using three sets of ASTER data from 2000 to 2009, and temporal fluctuations in the spatial extent and dynamics of coal fires have been precisely measured with time.

Study area: Jharia coal field, India

Jharia Coalfield (JCF) is located in and around Dhanbad district, Jharkhand, with a spatial coverage of 450 km^2. The area falls between latitude between N 23°37′57.88″–N 23°49′55.47″ and longitude E 86°08′13.72″–E 86°28′42.50″ and has an elevation of 77 m above mean sea level (Fig. 1). Elevation contours reveal that the area is relatively flat with only minor topographic variation.

JCF is comprised of sedimentary litho-package belonging to Gondwana Supergroup of Permo-Carboniferous age. The package is composed of alternating sequence of sandstone and shale with interbedded coal seams of fluvial–lacustrine origin deposited within intra-cratonic Archean gneissic basement. The area has deformed considerably to form broad gentle syncline plunging toward west and exhibit regional E–W to NW–SE strike with shallow dip of about 3°–8° toward south. Coal seams in JCF are grouped into 18 major seams (I–XVIII) with individual thickness of 2.1–18 m (Paul and Chatterjee 2011). All coal seams are restricted to the Barakar Formation of Gondwana Supergroup. Jharia coal belongs to medium to high volatile subbituminous to bituminous range coal containing 0.13–2.81 % of moisture, 12.0–26.63 % of ash, 6.93–28.40 % of volatile matter and >60 % of fixed carbon (Karmakar et al. 2013). In JCF, fire is mainly confined to coal seams X and XIV–XVIII (Chandra 1992) and occurs up to maximum depth of 110–130 m. At present, nearly 67 active fire sites are reported from 23 large underground and nine large opencast mines in JCF (BCCL 2008).

Methodology overview and data analysis

The flowchart of the methodology followed in the present study is shown in Fig. 2. It involves acquisition, processing, analysis and interpretation of the satellite datasets for precise estimation of coal fire through time.

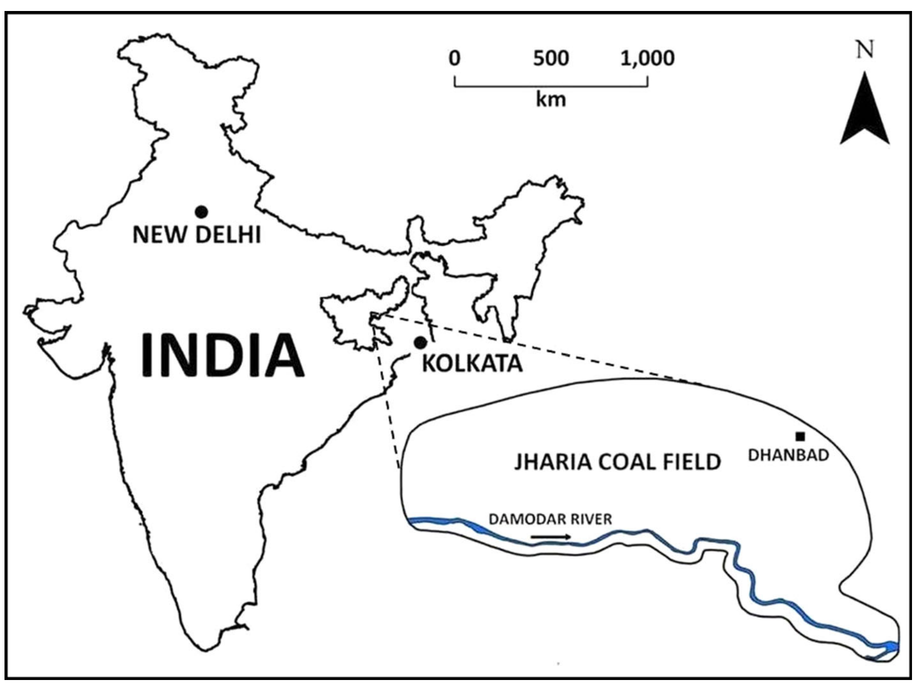

Fig. 1 Location map of the Jharia Coalfield, Dhanbad district, India

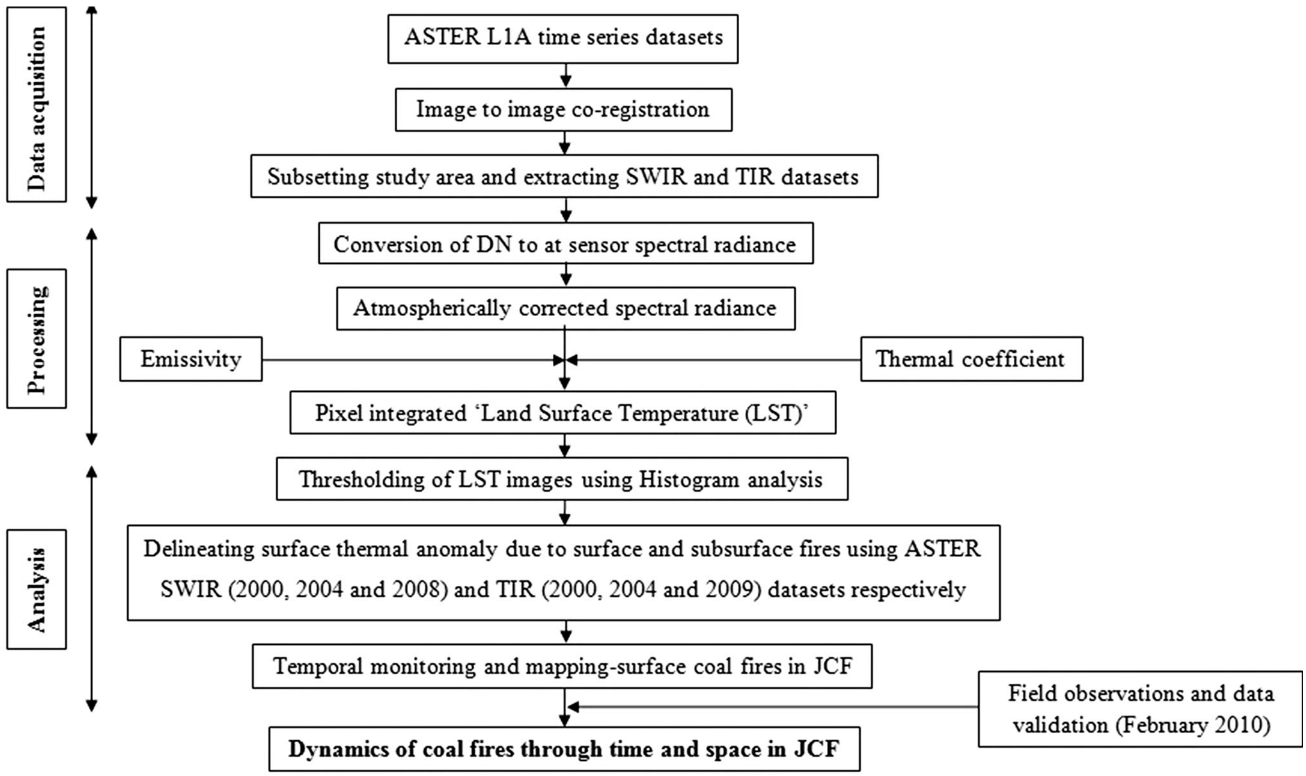

Fig. 2 Schematic diagram showing the data processing and methodology adopted for mapping and monitoring of coal fires in JCF

Table 1 Specifications of the remote sensing datasets used in the present study (Abrams et al. 1999)

Satellite/sensors	Spectral bands	Spectral interval (µm)	Central wavelength (µm)	Spatial resolution (m)	Radiometric resolution
TERRA/ASTER	Band 1	0.52–0.60	0.56	15	8 bit
	Band 2	0.63–0.69	0.66		
	Band 3	0.76–0.86	0.81		
	Band 4	1.60–1.70	1.65	30	
	Band 5	2.145–2.185	2.165		
	Band 6	2.185–2.225	2.205		
	Band 7	2.235–2.285	2.260		
	Band 8	2.295–2.365	2.330		
	Band 9	2.360–2.430	2.395		
	Band 10	8.125–8.475	8.291	90	12 bit
	Band 11	8.475–8.825	8.634		
	Band 12	8.925–9.275	9.075		
	Band 13	10.25–10.95	10.657		
	Band 14	10.95–11.65	11.318		

ASTER satellite registers the spectral response in six SWIR and five TIR channel functioning in 1.60–2.43 and 8.125–11.65 µm ranges of the electromagnetic spectrum, respectively (Table 1; Abrams et al. 1999). ASTER TIR channel acquired data in 12 bits high radiometric quantization level. It has high detectable temperature limit with an ability to measure the small difference in radiation emitted from low-temperature phenomenon like subsurface fire. Data from repetitive passes of ASTER (SWIR and TIR) spanning almost a decade have been used for the analysis (Table 2). In the present study, ASTER TIR datasets of 3 years 2000, 2004 and 2009 have been used for

Table 2 Details of the ASTER data used in the present study

Study area	ASTER scene ID	Time	Acquisition date
Jharia Coalfield, India	AST_L1A_00311242000050737_04062003143049	Day	November 24, 2000
	AST_L1A_00302052004045511_02162007095936	Day	February 05, 2004
	AST_L1A_00303192008045415_04172009132739	Day	March 19, 2008
	AST_L1A_0031182009163246_11250009543938	Day	November 18, 2009 (only VNIR and TIR datasets are available)

delineating coal fire. Since April 2008, ASTER SWIR data are not useable (USGS LP DAAC). Hence, for detecting high-intensity surface fire ASTER SWIR 2000, 2004 and 2008 data are used.

All sets of ASTER data have been first co-registered with reference to the geometrically corrected ASTER 2009 image (base image) using 37 well-distributed ground control points (GCPs) and second-degree polynomial transformation. The accuracy of the co-registration has been defined in terms of root mean square error (RMSE) of <0.13 of a pixel.

ASTER data used in the present study are L1A data that are processed using radiometric calibration coefficient to obtain scaled radiance. Calibrated radiance emitted from the 'hot ground features' in form of thermal anomalies has been effectively measured by the onboard satellite sensors. At-sensor spectral radiance for ASTER data can be obtained using following formula:

$$L_\lambda = (\mathrm{DN}_\lambda - 1) \times \mathrm{UCC}_\lambda \tag{1}$$

where DN is the digital number of a pixel and UCC is the unit conversion coefficient (W $\mathrm{m^{-2}\ sr^{-1}\ \mu m^{-1}}$).

Measured radiant energy release has been subsequently used to obtain per pixel radiant temperature of the area from the Planck's function (Gillespie et al. 1999).

$$B_\lambda = \frac{C_1/\pi\ \lambda^5}{e^{\left(\frac{C_2}{\lambda T_b} - 1\right)}} \tag{2}$$

where B = blackbody radiance (W $\mathrm{m^{-2}\ sr^{-1}\ \mu m^{-1}}$); λ = wavelength (μm); $C_1 = 2\pi hc^2$ (3.74×10^{-16} W $\mathrm{m^2}$; first radiation constant); T = temperature (K); $h = 6.63 \times 10^{-34}$ W $\mathrm{s^2}$ (Planck's constant); $c = 2.99 \times 10^8$ m $\mathrm{s^{-1}}$ (speed of light); C_2 = hc/k ($1.43876869 \times 10^{-2}$ m K; second radiation constant); $k = 1.38 \times 10^{-23}$ W s $\mathrm{K^{-1}}$ (Boltzmann's constant).

Spectral radiance received at the satellite sensor is commonly affected by atmospheric transmittance and upwelling radiance (atmospheric path radiance) due to atmospheric haze, aerosols, etc. (Gupta 2003). Atmospheric parameters have been derived for ASTER TIR bands from metadata file. It has been observed that the ASTER band 13 (10.25–10.95 μm) has maximum atmospheric transmittance and minimum upwelling radiance among rest of the ASTER TIR bands. Hence, ASTER TIR band 13 has been used for delineating subsurface thermal anomaly associated with underground coal seam fires. The atmospheric parameters have been corrected from the measured radiant intensity of the ASTER band 13 TIR band. Effective at-sensor spectral radiance of ASTER band 13 is then further applied to calculate pixel-wise temperature distributions of 'land surface temperature (LST)' using ASTER band 13 emissivity derived from temperature emissivity separation (TES) algorithm (Gillespie et al. 1999; Gangopadhyay et al. 2012) using Eq. (3)

$$T_\mathrm{k} = \frac{K_2}{\left\{\ln\left(\frac{K_1}{B_\lambda} + 1\right)\right\}\varepsilon^{1/4}} \tag{3}$$

where T_k = kinetic temperature or land surface temperature (K); K_1 = calibration constant 1 (W $\mathrm{m^{-2}\ sr^{-1}\ \mu m^{-1}}$); K_2 = calibration constant 2 (K); L_λ = spectral radiance at the sensor's aperture (W $\mathrm{m^{-2}\ sr^{-1}\ \mu m^{-1}}$); ln = natural logarithm; ε = ASTER TIR band 13 emissivity.

Precise threshold of the LST has been employed finally to delineate thermal anomaly and mapping of coal fires in JCF. In the present research, ASTER band 9 (SWIR) and band 13 (TIR) have been used for mapping of surface and subsurface coal fires in JCF, respectively.

Detecting thermal anomaly and temperature distribution due to coal fire

Thresholding of sensors response for delineating thermal anomalies due to fire is an important aspect of thermal remote sensing. Several methods have already been applied in recent past for thresholding of subtle surface thermal anomaly associated with underground coal seam fire using TIR data (Raju et al. 2012). In the present approach, the histogram showing temperature distribution of the pixel-integrated LST images has been carefully analyzed to set threshold for discriminating coal fire from non-fire area in JCF. The anomalous areas have been subsequently validated by field observations. Following this methodology, spatial distribution of surface–subsurface coal fire has been determined using both SWIR and TIR datasets. Finally, temperature distribution maps for 3 year (2000, 2004 and 2009) are produced and variation in spatial extent of the surface–subsurface coal fire has been detected at temporal interval in JCF.

Ground-based measurements

Ground truth information about the recent status of the coal fires in JCF has been obtained from the field observations using portable thermometer (Table 3). Surface signals are suppressed by the effect of solar heating. Due to this fact, field survey was carried out during the winter month of February 2010 to enhance the compatibility for validation of the results obtained from satellite data. To observe the coal seam fire in an exposed scenario, the field work was exclusively carried out in Sijua area of the JCF. An approximately 30-m-thick complete lithological section exposed in an opencast site near Sijua colliery, Tetulmari (N 23°48′21.1″/E 86°19′53.76″), was selected for thermal profile measurement. A schematic diagram and corresponding field photographs displaying the synoptic view of the Sijua opencast in an exposed scenario are shown in Fig. 3a.

Two interbedded coal seams (VI and VII from the surface) of approximately 2 m in thickness were identified at 9.98 and 30.52 m depth within sandstone striking N70°E–S70°W with 3°–5° very gentle dip toward SSE. Sandstone units overlying and underlying the coal seam VII were capped by approx. 2-m-thick pile of sandy soil at the top and were 6.98 and 18.54 m thick, respectively. Both coal seams VI and VII were observed to be under the intense and smoldering fire and showing temperature of more than >250 and >80 °C, respectively. Linear cracks, pits, vents and fracture system were intensely developed over the rock surface or terraces due to volume reduction in the underlying burning coal seam. Destruction due to underground

Table 3 Details of field observations carried out in Jharia Coalfield, India

S. no.	Site	Latitude (N)	Longitude (E)	Surface temperature range (°C)	Land cover type
1	Bokapahari	23°45′9.2″	86°25′4.2″	43.6–71.2	Area of intense shallow subsurface fire with sparse vegetation. Linear cracks have developed parallel to the strike of coal seams
					Destruction of nearby infrastructure
2	Baghadih	23°43′50.2″	86°24′52.8″	22.7–39.5	Subsidence area with sparse vegetation
3	Lodna	23°42′58.0″	86°25′17.5″	42.8–122.1	Overburden dump site. Anomalies are due to dump fire and subsurface fire with surface temperature ranges from 165.2 to 332.4 °C at some places
4	Sudamdih	23°40′1.5″	86°25′19.8″	32.2–42.2	Anomalies are due to subsurface fire. Open cracks and smoke emitting vents are well recognized around the area
5	Bhowrah	23°41′2.3″	86°23′29.9″	41.5–76.8	Overburden dump site. Anomalies are due to smoldering fire in dump
6	Tetulmari, Sijua	23°48′24.8″	86°19′57.8″	39.8–85.4	Opencast mine. Anomalies are due to high-intensity burning coal seam fire (217.0–254.5 °C) exposed due to intense mining activity. Linear cracks, vents and sinkhole are developed on the surface
7	Bansjora	23°47′41.8″	86°20′40.1″	24.3–26.4	Overburden dump site.
8	Kankani	23°46′42.2″	86°20′45.1″	32.5–101.3	Opencast mine. Minor thermal anomalies due deep subsurface fire.
9	Dhansar	23°46′29.8″	86°24′33.2″	27.4–30.9	Overburden dump site. Sparse vegetation
10	Kusunda	23°46′57.2″	86°23′36.7″	32.5–59.0	Overburden dump site. Minor anomalies due deep subsurface fire. Surface fire also observed in and around the area
11	Baseria	23°47′10.6″	86°22′30.2″	37.8–41.4	Overburden dump site.
12	Kenduadih	23°46′18.7″	86°22′27.3″	26.6–28.7	Underground mine. No subsurface fire
13	Alkusha, Kustore	23°45′40.6″	86°23′26.3″	34.3–38.8	Overburden dump site
14	Karkenda	23°46′12.1″	86°22′14.7″	32.3–33.1	Opencast and overburden dump site
15	Murlidih, Baghmara	23°43′52.2″	86°16′22.2″	27.3–33.0	Underground mine. Relatively dense vegetation at the surface
16	Phularitand	23°46′4.7″	86°13′53.7″	23.4–24.6	Opencast and overburden dump site
17	Sunardih	23°47′46.7″	86°15′45.6″	36.7–42.1	Abandoned mine
18	Barora	23°47′40.7″	86°14′46.7″	42.6–46.8	Opencast mine. Surface fire in in situ coal seam. Smoldering fire in dump

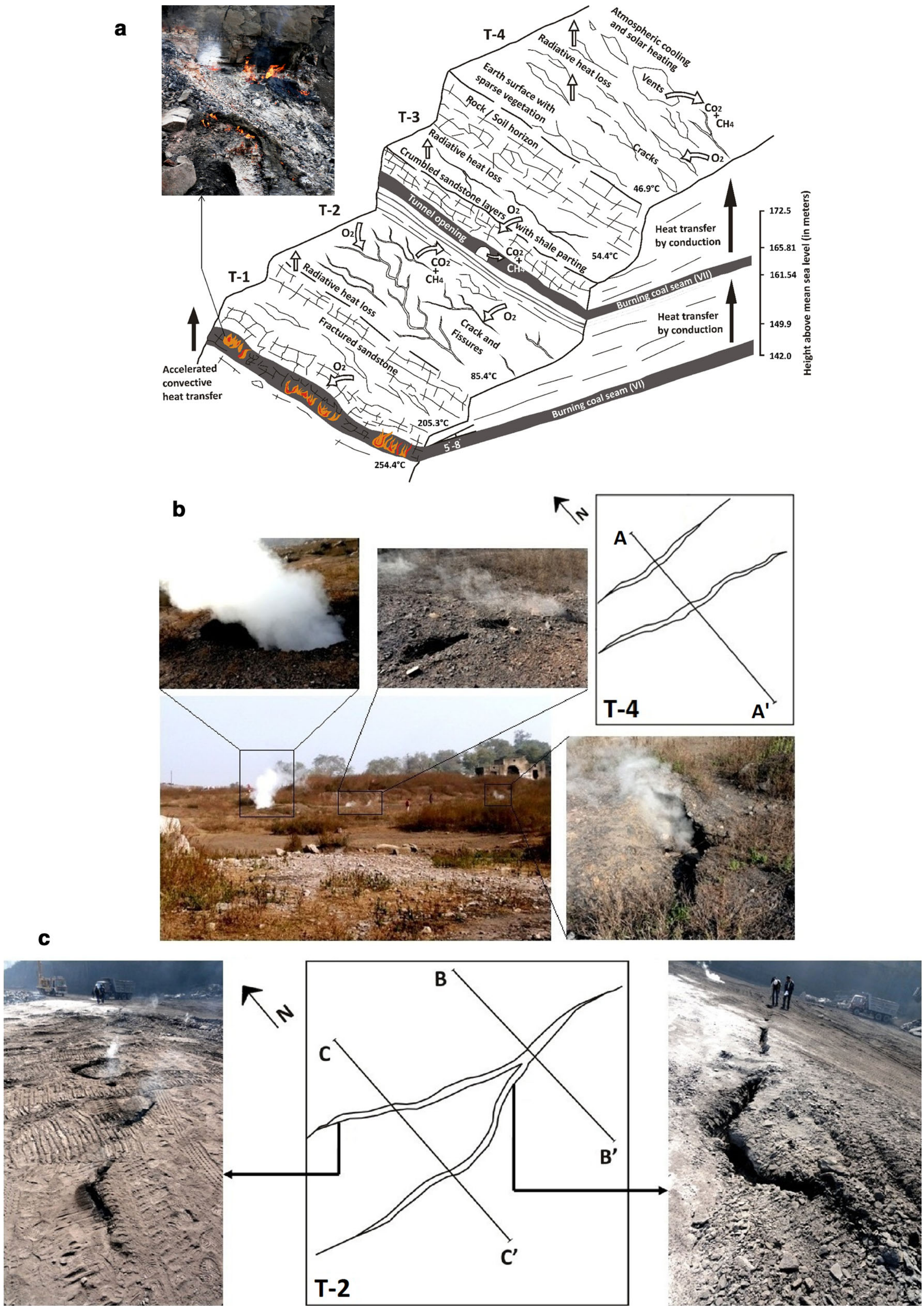

Fig. 3 **a**–**c** Schematic diagram showing synoptic view of the exposed underground coal seam fire and corresponding field photograph of burning coal seams in Sijua opencast, Tetulmari, JCF. Thermal profiles A–A′; B–B′ and C–C′ running across the gas emitting vents and pits developed along the strike of the coal seam at T-4 (terrace 4, ground surface) and T-2 (terrace 2), respectively

coal fire is very evident around the area (Fig. 3b, c). Temperature was measured at terraces T-4 (ground surface) and T-2 using portable field thermometer, and thermal profiles were drawn to analyze the depth function of the thermal anomaly (Fig. 3b, c).

It has been observed that the surface anomaly obtained is the function of depth. For a fire existing at 30 m depth, background temperature may lie in the range of 30–35 °C (Fig. 4a, profile A–A′). But for a very shallow subsurface fire, it may be 50–100 °C (Fig. 4b, c, profiles B–B′ and C–C′). This may be due to decrease in the intensity of heat dissipated from the burning coal seam.

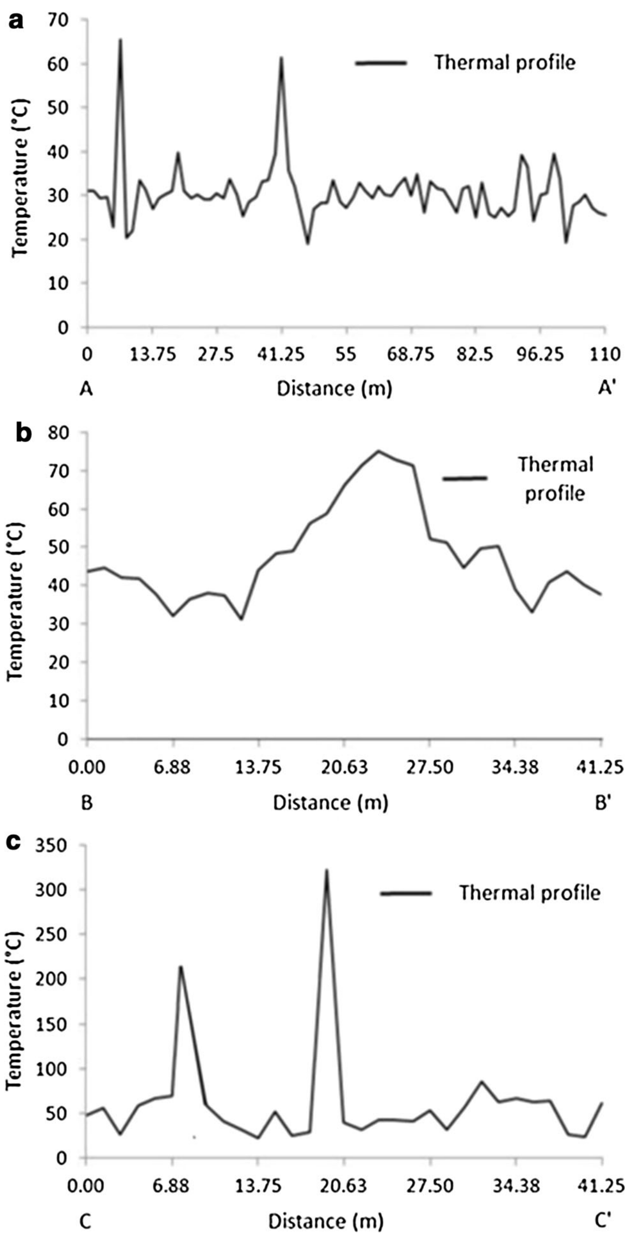

Fig. 4 a–c Temperature distribution along profiles A–A′, B–B′ and C–C′ showing relation between background temperature and thermal anomalies obtained at T-4 and T-2 (terrace 4 and 2)

Detection of coal fires in JCF through time

Coal fires can be easily recognized on the basis of their variable spectral and textural characteristics as observed on the ASTER CIR composites (Table 4). The present study has been carried out with an objective to evaluate the distribution of coal fire through time and space. For better observance at colliery level, whole JCF has been divided into three different blocks namely Blocks 1, 2 and 3 covering western, central and eastern part of the coalfield. Each block has been subsequently subdivided into different collieries (BCCL 2008; Fig. 5). Results obtained have been further analyzed, and spatial distribution of the surface–subsurface coal fire is assessed through 2000–2009 at colliery level.

Spatial and temporal distribution of surface coal fire

Surface fires are high-temperature phenomenon of relatively local extent (Prakash and Gupta 1999). Different bands have different temperature sensitivity. Temperature sensitivity increases with the decrease in wavelength. Very high thermal phenomenon can be detected with in bands of shorter wavelength region. ASTER SWIR band 9 operates in 2.36–2.43 μm range at normal gain setting and has the capability to detect pixel-integrated temperature ranges between 66 and 222 °C. In the present study, the pixels with highest radiance response have been carefully analyzed in SWIR band 9 and no saturated pixel (pixel with DN value of 255) was identified. Hence, ASTER SWIR band 9 has been preferably chosen to map coal mine surface fires for years 2000, 2004–2008.

It has been observed that high-intensity surface coal fires are the exposed shallow subsurface coal seam fire. In 2000, majority of the surface fire was located around WSW and SE of Baghmara, B-II Project colliery; east Barora colliery (Shatabdi opencast); Gondudih quarry near Sijua colliery; all along Alkusha–Kusunda–Kustor quarry located SE of Kenduadih and near Bhagatdih. Spatial extent of the fire in B-II Project colliery and east Barora collieries has increased from 2000 to 2004. In 2004, a new fire has been sighted near east of Godhar (Kusunda colliery) covering an area of 0.01 km^2. Two high-intensity zones of fire located near Bokapahari and NE of Lodna were noticed from 2000 to 2004 in Bastacolla colliery (Table 5).

In 2008, intense mining activities in Katras and Kusunda collieries exposed the very shallow subsurface fires. Fire in WSW of Baghmara had vanished and existed only in SE of Baghmara (B-II Project colliery) during 2008. In east

Table 4 Spectral and textural characteristics of coal fires as observed on ASTER CIR composites

Land use/land cover type	Coal fires					
	Dump fire			Coal seam fire		
	Overburden dump fire	Mined coal dump fire		In situ coal seam fire		Buried subsurface coal seam fire
Textural characteristics	No or small sporadic fire	Scattered and irregular in nature. Lies in close association with freshly exposed in situ coal seam		Linear/segregated fire		Clustered fire
	Appears as pale to bright yellow patches on 8–6–4 of ASTER color composite					
Detectable sensors response in different spectral channel	High visible reflectance and no or very low thermal emission	Low visible reflectance and low thermal emission		Very low visible reflectance and high thermal emission		High surface reflectance and moderate to high thermal emission
		No TIR + minor SWIR anomaly	Minor TIR anomaly	High SWIR anomaly	Saturation or high TIR anomaly	High TIR anomaly

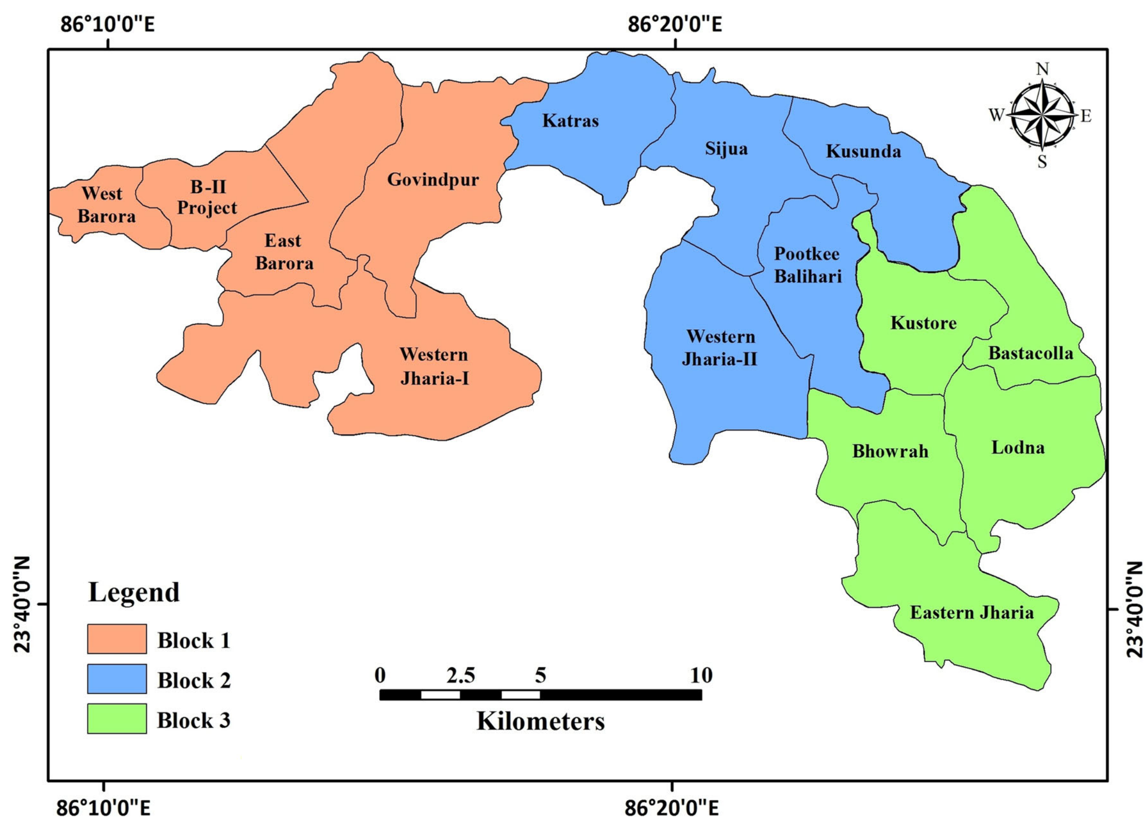

Fig. 5 Division of JCF into three different blocks (Blocks 1, 2 and 3) covering western, central and eastern part of the coalfield and their subsequent subdivision at colliery level

Barora colliery (Shatabdi opencast), surface fire had increased in spatial extent from 0.019 to 0.064 km^2 during 2000–2008 (Table 5). Two major fires were spotted near Kantapahari and north of Alkusha quarry in Katras colliery covering an area of 0.032 and 0.048 km^2, respectively. Surface fires have also been observed near Lodna–Tisra–Bhulanbarai area and NW of Bhowrah–Patherdih area in Lodna and eastern Jharia collieries, respectively. Spatial

Table 5 Spatial extent of surface coal fire in different blocks at colliery level in JCF from 2000 to 2008

Spatial extent of surface coal fire in different blocks at colliery level from 2000 to 2008							
Block name	Colliery name	Area of colliery (in km^2)	Surface fire area (in km^2)			Decrease/increase in the surface fire area from 2000 to 2004	Decrease/increase in the surface fire area from 2004 to 2008
			2000	2004	2008		
Block 1	West Barora	5.81	NF	NF	0.000	NF	NF
	B-II Project	9.36	0.055	0.013	0.000	−0.042	−0.013
	East Barora	20.05	0.019	0.077	0.064	0.058	−0.013
	Govindpur	21.79	NF	0.012	NF	0.012	NF
	Western Jharia-I	33.7	NF	NF	NF	NF	NF
Total area under surface fire in Block 1		90.72	0.074	0.090	0.064	0.016	−0.025
Block 2	Katras	14.41	NF	0.002	0.032	0.002	0.030
	Sijua	17.21	0.009	0.014	0.005	0.005	−0.009
	Western Jharia-II	21.57	NF	0.003	NF	0.003	NF
	Pootkee Balihari	16.19	0.003	0.006	0.002	0.004	−0.005
	Kusunda	14.31	0.016	0.010	0.048	−0.007	0.039
Total area under surface fire in Block 2		83.69	0.028	0.035	0.087	0.007	0.052
Block 3	Kustor	13.47	0.062	0.095	0.053	0.033	−0.042
	Bastacolla	13.45	0.096	0.068	0.025	−0.028	−0.043
	Lodna	18.62	0.038	0.039	0.052	0.001	0.013
	Eastern Jharia	19.29	0.016	0.014	0.009	−0.003	−0.005
Total area under surface fire in Block 3		64.84	0.212	0.216	0.140	0.004	−0.076
Total area under surface fire in JCF		239.25	0.314	0.341	0.291	0.027	−0.050

'NF' stands for 'no fire' in the colliery. Negative sign represents the decrease in surface fire area through time

extent of the surface fire area has been significantly increased in Kusunda colliery from 2000 to 2008.

Spatial and temporal distribution of subsurface coal fire

ASTER TIR data can detect the minor difference in spectral response and have been potentially used for temporal monitoring of coal fires in JCF. In the present study, coal fire maps for three subsequent years have been prepared and the status of subsurface coal fires has been analyzed through time and space. ASTER-derived coal fire map of the JCF during 2009 is shown in Fig. 6.

Coal fire in Block 1

In Block 1, coal fire has been mainly observed in B-II Project and east Barora collieries (Fig. 7). A significant decrease in spatial extent of coal fire from 1.355 to 0.362 km^2 has been observed in B-II Project colliery during 2000–2009, whereas the area affected by fire in east Barora has increased from 0.677 to 0.907 km^2 during 2000–2004 and then decreased to 0.727 km^2 in 2009 (Table 6).

Coal fire in Block 2

In Block 2, coal fires are mainly noticed in Katras, Sijua and Kusunda collieries (Fig. 7). In 2000, fire existed only in Sijua and Kusunda collieries covering an area of 0.492 and 0.244 km^2 which has been decreased to 0.129 and 0.049 km^2, respectively, in 2004 (Table 6). A significant increase in spatial extent of fire has been noticed in 2009 where fire covers an area of 0.689 and 1.171 km^2 located all around Alkusha–Kusunda–Kustor area near SE of Kenduadih in Sijua and near Bhagatdih in Kusunda collieries, respectively. Kusunda colliery is most affected by fire which has shown a significant increase from 0.496 to 1.171 km^2 through 2004–2009, respectively (Table 6).

Coal fire in Block 3

Block 3 is the most affected part of JCF. Intense mining activities and persistent fire have been observed all around the Kustor, Lodna and Bastacolla collieries. However, fluctuations in spatial extent of fires have been noticed through 2000–2009 (Fig. 7). In eastern Jharia colliery, spatial extent of fire has significantly decreased in west of Bhowrah from 0.341 to 0.090 during 2000–2009. Block 3

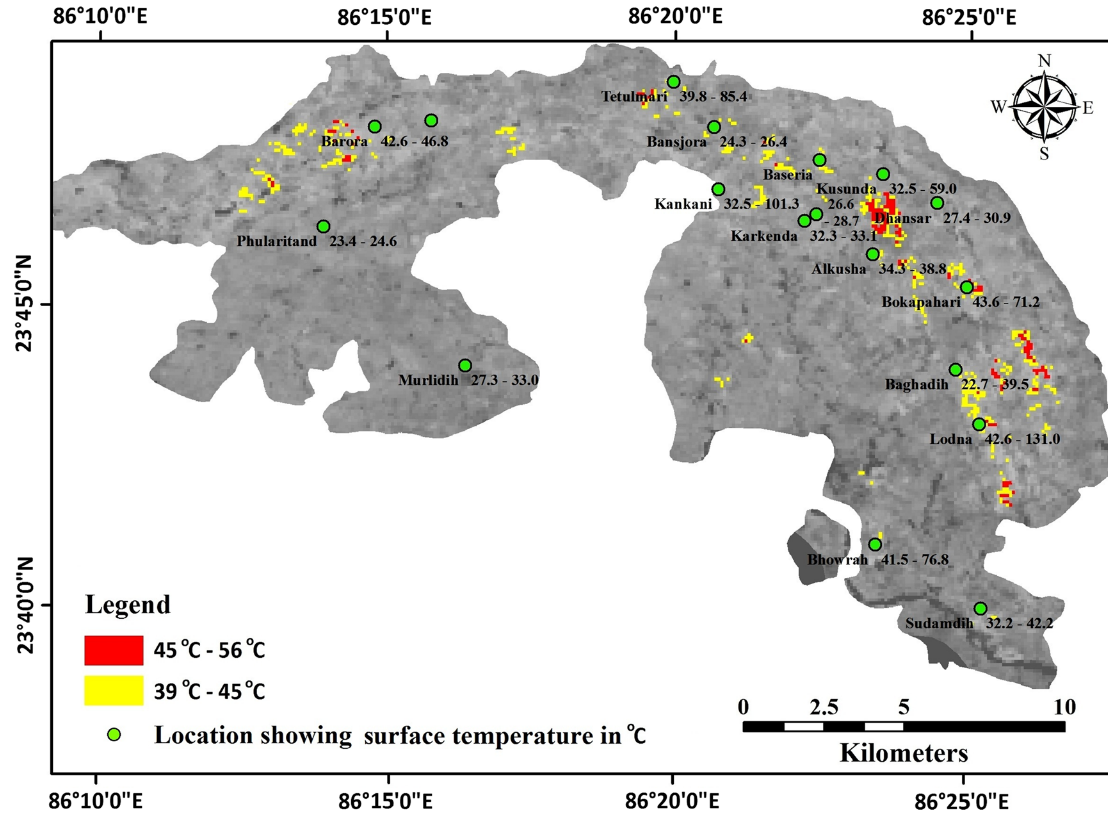

Fig. 6 ASTER derived coal fire map of JCF (2009). *Red* and *yellow* represent the pixel-integrated LST derived from ASTER 2009 band 13 data. Surface temperature obtained during field-based observations in February 2010 area is also shown

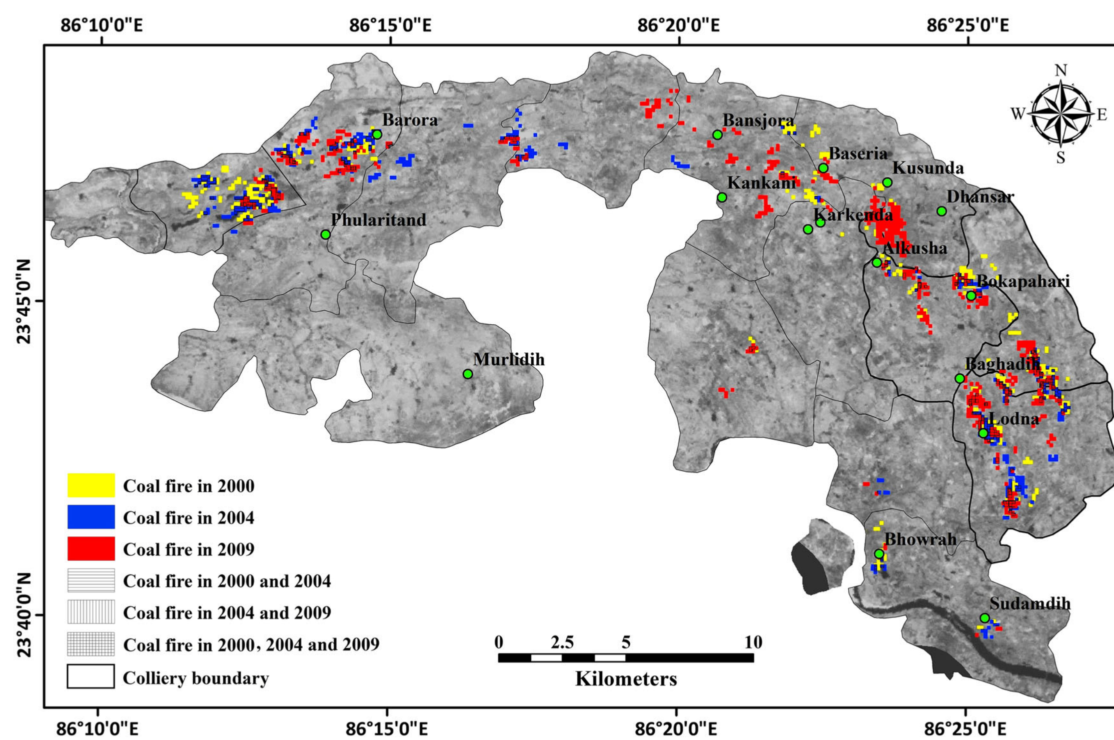

Fig. 7 Colliery-wise distribution of spatial extent of coal fires in JCF during 2000–2009

Table 6 Spatial extent of coal fire in different blocks at colliery level in JCF from 2000 to 2009

Spatial extent of coal fire estimated by ASTER TIR datasets in different blocks at colliery level from 2000 to 2009

Block name	Colliery name	Area of colliery (in km^2)	Coal fire area (in km^2)			Decrease/increase in the coal fire area from 2000 to 2004	Decrease/increase in the coal fire area from 2004 to 2009
			2000	2004	2009		
Block 1	West Barora	5.81	0.170	0.151	0.000	−0.019	−0.151
	B-II Project	9.36	1.355	0.992	0.362	−0.363	−0.630
	East Barora	20.05	0.677	0.907	0.727	0.230	−0.180
	Govindpur	21.79	0.266	0.474	0.294	0.208	−0.180
	Western Jharia-I	33.7	NF	0.016	NF	0.016	NF
Total area under coal fire in Block 1		90.72	2.468	2.540	1.383	0.072	−1.157
Block 2	Katras	14.41	0.162	0.274	0.345	0.113	0.071
	Sijua	17.21	0.492	0.129	0.689	−0.364	0.561
	Western Jharia-II	21.57	0.023	0.022	0.106	−0.001	0.084
	Pootkee Balihari	16.19	0.040	0.022	0.041	−0.018	0.019
	Kusunda	14.31	0.244	0.049	1.171	−0.195	1.122
Total area under coal fire in Block 2		83.69	0.961	0.496	2.352	−0.465	1.857
Block 3	Kustor	13.47	0.334	0.266	0.575	−0.068	0.310
	Bastacolla	13.45	0.907	0.517	0.744	−0.389	0.226
	Lodna	18.62	0.919	1.268	1.044	0.350	−0.224
	Eastern Jharia	19.29	0.341	0.445	0.090	0.104	−0.355
Total area under coal fire in Block 3		64.84	2.500	2.497	2.453	−0.003	−0.044
Total area under coal fire in JCF		239.25	5.93	5.53	6.19	−0.400	0.660

'NF' stands for 'no fire' in the colliery at respected year. Negative sign represents decrease in the coal fire area through time

has significantly affected by the coal fire through 2000–2009 with a persistent spatial extent of approximately 2.5 km^2 (Table 6).

Dynamics of coal fire through time and space

Results obtained from the coal fire mapping in JCF reveal that the surface fires are sporadic in nature and occur as discrete patches in majority of the places. Surface fires in JCF exhibit minor fluctuations in magnitude from 2000 to 2008 at colliery level (Table 5). In 2008, two new surface fires have been observed near Kantapahari, in Katras colliery and north of Alkusha quarry in Katras colliery. Fire in Gondudih quarry, near Sijua Bansjora in Sijua and Kusunda collieries has diminished after 2000. Spatial extent of the surface fire in JCF has increased by 8.6 % since 2000–2004 and then decreased by 14.66 % from 2004 to 2008, respectively.

Majority of the area falling under the territories of Shatabdi opencast, Barora (N 23°47′40.68″/E 86°14′46.68″), Sijua opencast (N 23°48′9.80″/E 86°19′28.05″), Godhar colliery, Kusunda (N 23°46′1.11″/E 86°23′53.83″), Bokapahari (N 23°45′10.25″/E 86°25′3.38″), Kujama (N 23°44′2.38″/E 86°26′8.20″) is continuously under intense fire with cumulative areal coverage of 5.93, 5.53 and 6.19 km^2 in 2000, 2004 and 2009, respectively (Fig. 7, Table 6). Since 2000–2004, a minor decrease (6.74 %) in coal fire has been observed. However, 2009 is apparently marked by a substantial increase in coal fire area by 11.93 %. In Block 1, fire area in all collieries has decreased by 45.55 % (1.157 km^2) from 2004 to 2009. A new fire site with a spatial extent of 1.171 km^2 has been noticed around Alkusha–Kusunda–Kustor area in Kusunda colliery. Katras, Sijua and Kusunda collieries of Block 2 are most affected and marked by a significant increase in fire area through 2004–2009. During the same period, an increase in fire area by 0.31 and 0.226 km^2 has also been noticed in Kustor and Bastacolla collieries of Block 3, respectively.

Structural control of the coal fire propagation

Jharia basin is structurally highly deformed. The area is marked by an intense system of faults and folded coal seams. Movement of the fire in the area has been found to be under structural control and has been well observed in the area around Kustor–Bastacolla–Lodna collieries. Coal fires are quite persistent in these three collieries. Temporal monitoring of coal fires shows that the fire is significantly spreading toward Jharia Township from all directions. Fire

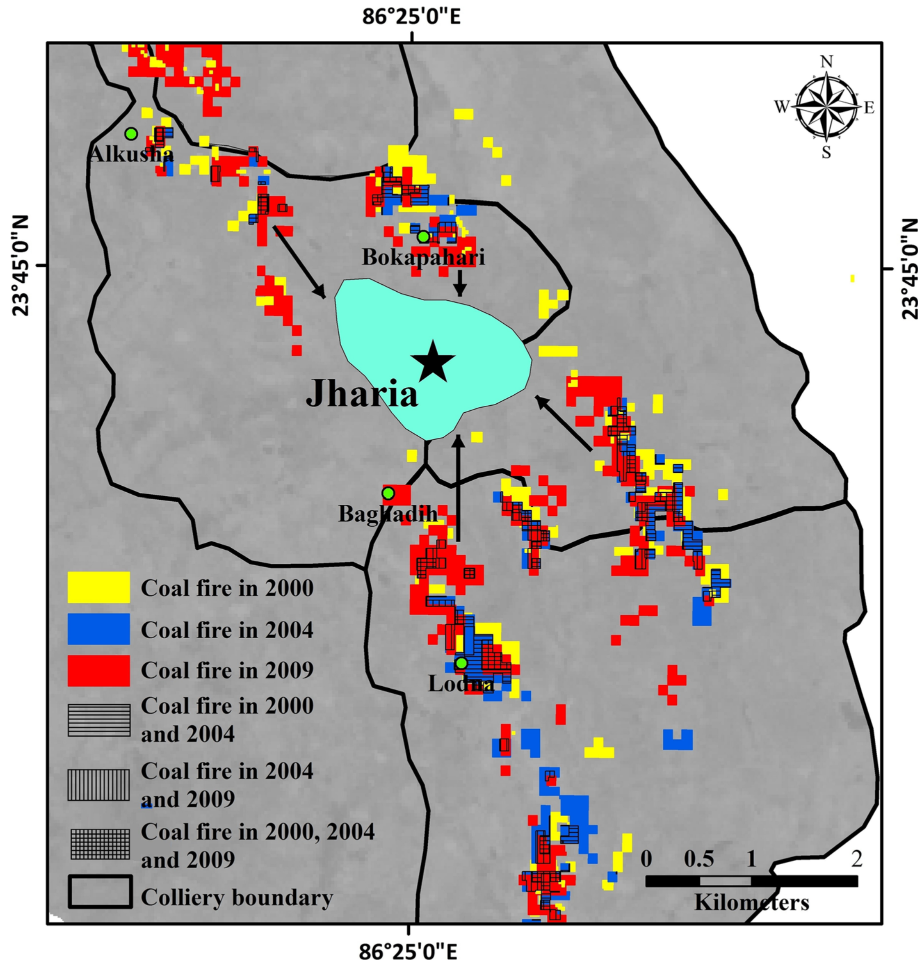

Fig. 8 Dynamics of coal fire in Kusunda–Kustor–Bastacolla–Lodna collieries in JCF. Map shows that the fires located near east of Jharia (in Bastacolla colliery) and Jiyalgarh, Lodna (in Lodna colliery) are propagating in NNW and north direction toward Jharia, respectively. Besides, fires located near Bokapahari and SE of Alkusha (in Kustor colliery) are propagating in south and SE direction heading toward Jharia

located east of Jharia (in Bastacolla colliery) and Jiyalgarh, Lodna (in Lodna colliery) is propagating into NNW and north direction toward Jharia, respectively, along the strike of the coal seam. Besides, fire located near Bokapahari and SE of Alkusha, near Bhagatdih (in Kustor colliery) is propagating in south and SE direction heading toward Jharia (Fig. 8).

Conclusion

Coal fire in Jharia Coalfield is highly dynamic in nature. The magnitude of fire in JCF has been fluctuating with cumulative areal coverage of 5.93, 5.53 and 6.19 km^2 from 2000, 2004–2009, respectively. Spatial extent of coal fires in JCF is quite persistent in Blocks 1 and 3 during 2000–2004. From 2004 to 2009, considerable decrease of 1.157 km^2 in the magnitude of fire has been noticed in the collieries (west and east Barora, B-II Project and Govindpur) located in the western most part (Block 1) of the JCF. It is observed that the west-central part (Block 2) of the JCF comprising Katras, Sijua, Western Jharia-II and Kusunda collieries is most affected and marked by a significant increase in fire area of 1.857 km^2 from 2004 to 2009. This significant increase in spatial extent of fire is due to the appearance of new fire site located south of Kusunda and north of Alkusha in 2009. Since 2004, spatial extent of the fire has increased by 1.122 km^2 exclusively in Kusunda colliery. Fire is quite persistent with minor increase in Kustor, Bastacolla and Lodna collieries located south and southeastern part (Block 3) of the JCF. Results indicate that urgent and serious efforts are required to control coal fire in JCF. Although, the methodology adopted in the present study is conservative and robust in nature, but it would provide precise evaluation and monitoring of coal fire to plan sustainable mining through time and space in JCF.

Acknowledgments A. R. is thankful to USGS Land Processes Distributed Active Archive Centre (USGS LP DAAC) for providing three sets of ASTER L1A data product through online https://lpdaac.usgs.gov/data_access. The authors thanked reviewers and the editor for their valuable comments and suggestions that helped immensely in improving the manuscript.

References

Abrams M, Hook S, Ramachandran B (1999) ASTER user handbook, version 2 Jet Propulsion Laboratory, Pasadena, CA and EROS Data Center, Sioux Falls, SD

Ackersberg R (2003) Understanding self-ignition of coal. Internal unpublished project report, German Montan Technology and Federal Institute for Materials Research and Testing, Germany

BCCL (2008) Master plan for dealing with fire, subsidence and rehabilitation in the leasehold of BCCL, March 2008, Bharat Coking Coal Limited

Bhattacharya A, Reddy CSS (1994) Underground and surface coal mine fire detection in India's Jharia coal field using airborne thermal infrared data. Asian-Pacific Remote Sens J 7(1):59–73

Bhattacharya A, Reddy CSS, Mukherjee TK (1991) Multi-tier remote sensing data analysis for coalfire mapping in Jharia Coalfield of Bihar, India. In Proceedings of the 12th Asian conference on remote sensing, 1991, Singapore (Singapore: National University of Singapore), pp 22-1–22-6

Chandra D (1992) Jharia coalfield. Geological Society of India, Bangalore

Chatterjee RS (2006) Coal fire mapping from satellite thermal IR data—a case example in Jharia Coalfield, Jharkhand, India. ISPRS J Photogramm Remote Sens 60(2006):113–128

Chatterjee RS, Wahiduzzaman M, Shah A, Raju EVR, Lakhera RC, Dadhwal VK (2007) Dynamics of coal fire in Jharia Coalfield, Jharkhand, India during the 1990s as observed from space. Curr Sci 92:61

Cracknell AP, Mansor SB (1992) Detection off subsurface coal fires using Landsat Thematic Mapper data. Int J Photogramm Remote Sens 29(b7):750–753

Engle MA, Radke LF, Heffer EL, O'Keefe JMK, Smeltzer CD, Hower JC, Hower JM, Prakash A, Kolker A, Eatwell RJ, Ter Schure A, Queen G, Aggen KL, Stracher GB, Henke KR, Olea RA, Román-Colón Y (2011) Quantifying greenhouse gas emissions from coal fires using airborne and ground-based methods. Int J Coal Geol 88(2011):147–151

Feng KK, Chakravorty RN, Cochrane TS (1973) Spontaneous combustion—a coal mining hazard. CIM Bull 66:75–84

Gangopadhyay PK, Lahiri Dutt K (2005) Detecting coal fires with remote sensing: a comparative study of selected countries, resource management in Asia-Pacific working paper no. 58. Resource management in Asia-Pacific program, Research School of Pacific and Asian Studies, The Australian National University, Canberra, ISSN-1444-187X

Gangopadhyay PK, Van der Meer Freek, Van Dijk P, Saha K (2012) Use of satellite-derived emissivity to detect coalfire-related surface temperature anomalies in Jharia Coalfield, India. Int J Remote Sens 33(21):6942–6955

Geological Survey of India (GSI) (2004) Coal resource scenario of India (as on 01 Jan 2004). http://www.gsi.gov.in/indiacol.pdf

Karmakar B, Ghosh, MT, Ojha K, Pathak AK, Devraju J (2013) Effects of chemical composition and petrography of coal for coalbed methane evaluation with special reference to in situ gas content. In: 10th Biennial international conference and exposition, Kochi 2013

Gillespie A, Rokugawa S, Hook SJ, Matsunaga T, Kahle AB (1999) Temperature/emissivity separation algorithm theoretical basis document, version 2.4, Jet Propulsion Laboratory, Pasadena, CA, Aug 16, 1996. http://asterweb.jpl.nasa.gov/asterhome/atbd/ATBD-AST-03.doc

Gupta RP (2003) Remote sensing geology, 2nd edn. Springer, Berlin. ISBN-13: 978-3540431855

Kolker A, Engle M, Stracher G, Hower J, Prakash A, Radke L, ter Schure A, Heffern E (2009) Emissions from coal fires and their impact on the environment: U.S. Geological Survey Fact Sheet, 2009–3084

Kuenzer C, Zhang J, Li J, Voigt S, Mehl H, Wagner W (2007) Detecting unknown coal fires: synergy of automated coal fire risk area delineation and improved thermal anomaly extraction. Int J Remote Sens 28(20):4561–4585

Mansor SB, Cracknell AP, Shilin BV, Gornyi VI (1994) Monitoring of underground coal fires using thermal infrared data. Int J Remote Sens 15(8):1675–1685

Martha TR, Guha A, Kumar KV, Kamaraju MVV, Raju EVR (2010) Recent coal-fire and land-use status of Jharia Coalfield, India from satellite data. Int J Remote Sens 31(12):3243–3262

Mishra RK, Roy PNS, Pandey J, Khalkho A, Singh VK (2014) Study of coal fire dynamics of Jharia coalfield using satellite data. Int J Geomatics Geosci 4(3). ISSN 0976-4380

Mukherjee TK, Bandopadhyay TK, Pande SK (1991) Detection and delineation of depth of subsurface coalmine fires based on an airborne multispectral scanner survey in a part of the Jharia Coalfield, India. Photogramm Eng Remote Sens 57:1203–1207

Paul S, Chatterjee R (2011) Mapping of cleats and fractures as an indicator of in situ stress orientation, Jharia Coalfield, India. Int J Coal Geol 88(2011):113–122

Prakash A (1996) Remote sensing-GIS based geoenvironmental studies in Jharia Coalfield, India. With special reference to coalmine fires. Ph.D. thesis

Prakash A, Gens R (2010) Remote sensing of coal fires. In: Stracher GB, Prakash A, Sokol EV (eds) Coal and peat fires: a global perspective, vol 1., Coal—combustion and geologyElsevier, Oxford, pp 231–253

Prakash A, Gupta RP (1999) Surface fires in Jharia Coalfield, India—their distribution and estimation of area and temperature from TM data. Int J Remote Sens 20(10):1935–1946

Prakash A, Saraf AK, Gupta RP, Dutta M, Sundaram RM (1995) Surface thermal anomalies associated with underground fires in Jharia Coal Mine, India. Int J Remote Sens 16(12):2105–2109

Prakash A, Gupta RP, Saraf AK (1997) A Landsat TM based comparative study of surface and subsurface fires in the Jharia Coalfield, India. Int J Remote Sens 18:2463–2469

Raju A, Gupta RP, Prakash A (2012) Delineation of coalfield surface fires by thresholding Landsat TM-7 day-time image data. Geocarto Int. doi:10.1080/10106049.2012.710651

Reddy CSS, Srivastav SK, Bhattacharya A (1993) Application of thematic mapper short wavelength infrared data for the detection and monitoring of high temperature related geoenvironmental features. Int J Remote Sens 14:3125–3132

Rosema A, Guan H, van Genderen JL, Veld H, Vekerdy Z, Ten Katen AM, Prakash A (1999) Manual of coal fire detection and monitoring. Report of the Project 'Development and implementation of a coal fire monitoring and fighting system in China'. Netherlands Institute of Applied Geoscience, Utrecht, NITG 99-221-C. ISBN 90-6743-640-2

Schmal D (1987) A model for the spontaneous heating of stored coal. Ph.D. thesis, Delft University of Technology

Sinha PR (1986) Mine fires in Indian coalfields. Energy 1–12:1147–1154

Stracher GB, Taylor TP (2004) Coal fires burning out of control around the world: thermodynamic recipe for environmental catastrophe. Int J Coal Geol 59:7–18

van Dijk P, Zhang J, Wun J, Kuenzer C, Wolf K-K (2011) Assessment of the contribution of in situ combustion of coal to greenhouse gas emission; based on a comparison of Chinese mining information to previous remote sensing estimates. Int J Coal Geol 86(2011):108–119

van Genderen JL, Cassels CJS, Xiangmin Z (1996) The synergetic use of remotely sensed data for the detection of underground coal fires. Int Arch Photogramm Remote Sens 31:722–727

Whitehouse AE, Mulyana AAS (2004) Coal fires in Indonesia. Int J Coal Geol 59:91–97

USGS LP DAAC (Land Processes Distributed Active Archive Centre) archive. https://lpdaac.usgs.gov/data_access

Zhang J, Wagner W, Prakash A, Mehl H, Voigt S (2004) Detecting coal fires using remote sensing techniques. Int J Remote Sens 25(16):3193–3220