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Monitoring heat flow before and after eruption of Kuju fumaroles in 1995 using Landsat TIR images

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Abstract The Kuju fumaroles in central Kyushu, Japan began to erupt as phreatic in nature on 11 October 1995. To infer the thermal activity, main objectives were to monitor the radiative heat flux (RHF) before and after eruption of Kuju fumaroles in 1995 using 4 sets of Landsat TM thermal infrared data from 1990 to 1996; and to calculate and monitor the heat discharge rate (HDR) after multiplying RHF using a relationship coefficient between RHF and HDR, derived from two previous studies. The RHF was estimated by using the Stefan–Boltzmann equation for heat flow where we applied satellite image-derived spectral emissivity and land surface temperature. An increasing trend of total radiant heat flux was obtained of about 22–39 MW before the Kuju fumaroles eruption from 1990 to 1994 and a declining trend total RHF of about 37–11 MW after eruption from 1995 to 1996. RHF was strongly correlated with land surface temperature (LST) above ambient in our study. Spatial distribution of RHF also showed a similar trend of total RHF. After using this relationship coefficient, we obtained the HDR from our study area about 144.64, 249.74, 239.67 and 68.54 MW in 1990, 1994, 1995 and 1996, respectively. The HDR was much higher before eruption in October 11, 1995 than that of after the eruption in our study. Fumaroles area also showed an abrupt increase of bared land and no vegetation just after eruption within the thematic map in 1995. Statistics of LST and RHF also showed evidences of heat loss activity before and after eruption in 1995. In conclusion, we infer from this study that Landsat TM thermal infrared images are fully competent to monitor thermal activity from any active volcano fumaroles for future eruption.

Keywords Landsat TM TIR data · Radiant heat flux · Heat discharge rates · Kuju fumaroles

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1 Introduction

Monitoring of active fumaroles using remote sensing is an essential part of volcanology now a day. Hazards relating fumarolic eruption could happen with unpredictable measures to surrounding habitats of a potentially active volcano. If it is possible to monitor active volcano continuously, then, the surroundings could prevent from thermal, ash, lava flows like hazards. Remote measurement using satellite image data could be the best solution for spatial analysis of entire volcanic zone and to avoid the limitation of ground based monitoring for heat flow or thermal activity due to unstable ground in many volcano fumaroles. The uses of Landsat TM/ETM+ has a long history for thermal feature studies of volcano around the world (Harris et al. 2009; Savage et al. 2010; Mia et al. 2012a, b). Landsat image is now freely available with good spatial resolution of thermal band (30 meter) upon request from the USGS archives. Landsat TM has a single thermal band with 30m in resolution (after 25 February 2010, thermal infrared band used to process 30 m instead of 60 m). There are three ways of heat flow from any thermal ground i.e., conductive, convective and radiative heat flux (RHF). Satellite sensor like Landsat, could only detect radiative portion of total heat loss directly and it would require to multiply estimated radiative heat flux (RHF) using the discovered relationship coefficient between radiative heat loss and total heat loss from two geothermal or fumarolic areas to estimate total heat flow or heat discharge rate (HDR) (Mia et al. 2012b; Harris et al. 2009). Basically, HDR from any thermal ground or fumarole is the summation of convective, conductive and radiative heat losses without solar heat load. RHF is the radiative portion of total heat loss that passes through atmosphere via electromagnetic waves from thermal field or volcano. Radiative geothermal heat flux ($\mathrm{GHF_R}$) is the heat that passes through to satellite sensor from subsurface without direct or indirect effect of solar or diffuse convective steaming part of heat via electromagnetic radiation. Recently, there are some studies for detecting and quantifying thermal anomalies as well as heat losses due to volcanic eruption activity (Mia et al. 2012a; Harris et al. 2009; Savage et al. 2010). In this paper, we demonstrated the applicability of Landsat TM thermal infrared data for heat flow monitoring in an active volcano in Japan to infer the recent eruption activity.

Our study area, Kuju fumaroles, lies in the active center of Hohi volcanic zone on central Kyushu in Japan (Fig. 1). Kuju is one of the most active hazardous volcanos in Japan, started eruption recently in 11 October 1995 after at least 133 years dormancy (Kamata and Kobayashi 1997). Kuju volcano had been erupted steam and ashes in phreatic nature on 11 October 1995 by opening several new craters. It had erupted again in the middle of December of the same year in second time (Ehara et al. 2005). Ehara (1992) calculated total heat discharges rate about 104.7 MW from the Kuju fumaroles by using reservoir simulation.

Geologically, Kuju is a typical andesitic island-arc volcano, consists of 20 lava domes and cones (Nakaboh et al. 2003). The rock type is hornblende andesite in and around this volcano. A wide alteration zone is exposed in the fumaroles where three different types of alteration zones are associated such as alunite, kaolin, and montmorillonite (Yamasaki et al. 1970; Mia and Fujimitsu 2012). The first thermal activity of this volcano was initiated about 0.3 Ma years ago (Kamata and Kobayashi 1997). There is an active fumarolic field in the central part of this volcano, from where only phreatic eruptions occurred in the past, at intervals of several tens to one hundred years. The geothermal activity of this volcano is most intense after 1990s. Many faults are trending mostly in the direction of north–west and nearly east–west, of them the north–west fault is important main breeding fault in this region (Yamasaki et al. 1970). There are close relations of these faults and accompanying sub-faults, joints and fissures with the hot springs, steam fumaroles and altered zones of this voncanic region, which could be easily identified on the surface manifestations or the

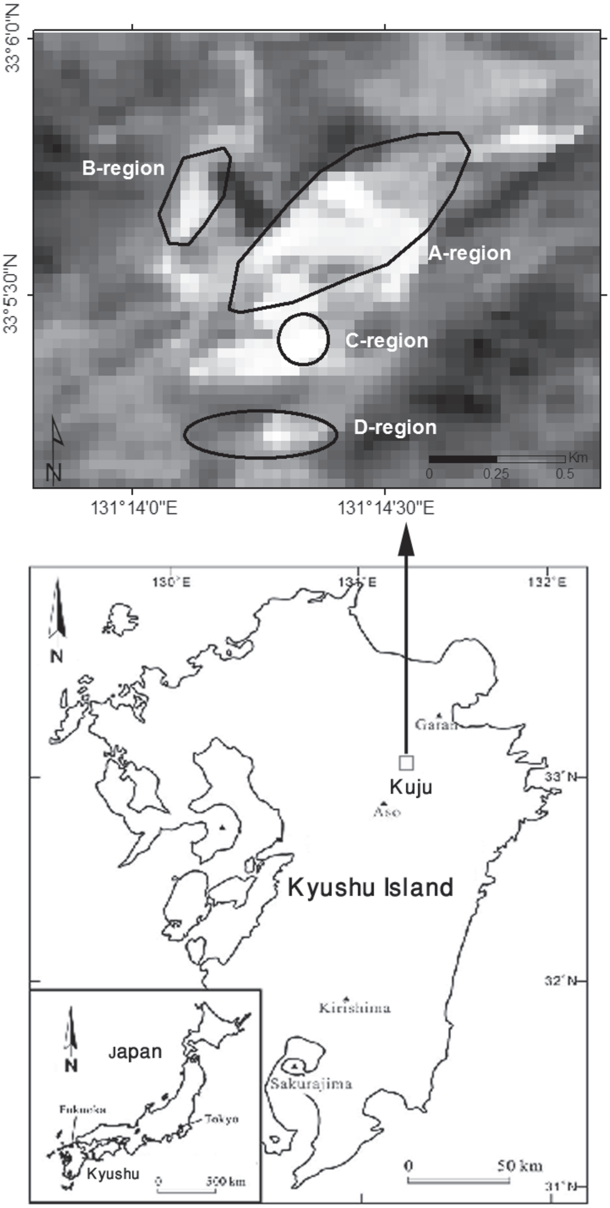

Fig. 1 Location map of our study area—*A*, *B*, *C*, *D* active regions within the Kuju fumaroles (modified after Mia and Fujimitsu 2013)

passages for geothermal fluids. The prime objectives of our study are (a) to estimate radiant component of heat flux in the year of 1990, 1994, 1995 and 1996 by using 4 sets of Landsat TM thermal infrared data, (b) to monitor the heat flow before and after eruption of Kuju fumaroles in October 11, 1995. Intended at this, the paper is organized as follows. The first section presents introduction about motivation, study area, previous study and objectives, the second step presents about materials and methodology used in this study. In the third section, we discussed the outcome of this study in details. Finally, we draw conclusion in the fourth section of this paper.

2 Materials and methods

Landsat thematic mapper (TM) images were used for this study (path/row: 112/37). The Landsat sensor bearing satellite passed through this study region from 09:47 to 10:07 am of our acquired images. We obtained four sets of Landsat TM images from the USGS Earth Resource Observation Systems Data Center upon request, which were both radiometrically and geometrically corrected. Landsat image has eight multi-spectral bands, including: four VNIR, two SWIR (Shortwave infrared) and one TIR (thermal infrared). The imageries were acquired during summer or end of summer season on 21 September 1990, 14 July 1994, 22 November 1995 and 05 September respectively. As the last eruption of Kuju fumaroles was started on 11 October 1995, we selected two images each before and after eruption in our study considering availability and good quality for monitoring the thermal activity just before and after the eruption activity of Kuju fumaroles in this study. The Landsat TM image has a single channel of thermal infrared at 30 meter resampled resolution. Local meteorological air temperature data was obtained from the AMEDAS website using the nearest Kusu station. We assumed atmospheric transmissivity 90 % at the time of image acquisition as the complex calculation and good quality of all our images (Fig. 2).

The flow chart was followed of our image processing steps for radiative heat flux estimation using Landsat TM images (Fig. 1). Initially, we analyzed all images for atmospheric correction, where we had applied the dark object subtraction method for atmospheric correction process. Then, in second steps, we applied the formula for calculating reflectance value for each band with band specific information from the header file and Landsat user handbooks by using the ERDAS imagine 9.3 models (NASA 2009). In the third steps, we estimated a vegetation index (NDVI) which is a process for calculating the vegetation index of any region, that is the ratio of reflectance value of red (b3) and near infrared (b4) region of electromagnetic spectrum (Mia and Fujimitsu 2011) i.e., $\mathrm{NDVI} = (\mathrm{b4} - \mathrm{b3})/(\mathrm{b4} + \mathrm{b3})$. The NDVI value ranges from -1 to $+1$, higher than the value of 0.5 indicated the vegetated region and lower the value of 0.2 is the bared region. In the fourth steps, spectral emissivity was estimated using the NDVI based emissivity calculation method of Valor and Caselles (1996). Normally, the emissivity value ranges from 0.7 to 0.99 for the real earth surface. The fifth step was land surface temperature estimation where we applied the mono-window algorithm because the Landsat TM has only one band of thermal infrared band (Qin et al. 2001; Mia and Fujimitsu 2011). Finally, according to the Stefan–Boltzmann's law, the radiative heat flux (RHF) was estimated by using the following equation (Mia et al. 2012a).

$$\mathrm{Q_r} = \tau\, \sigma\, \varepsilon\, \left(\mathrm{T_s^4} - \mathrm{T_a^4}\right)$$

where $\mathrm{Q_r}$ is the radiative heat flux ($\mathrm{W/m^2}$), τ is the atmospheric transmissivity, σ is the Stefan–Boltzmann constant, ε is the emissivity, $\mathrm{T_s}$ is the land surface temperature (LST) (K) and Ta is the ambient temperature (K). We used the ambient temperature from Kuju meteorological station's hourly data. We estimated total heat discharge rate for each year data set from our study area after multiplying the above total radiative heat flux by using the average value of the relationship coefficient ($\sim$6.46) of RHF and HDR, obtained from two volcano fumaroles studies (Mia et al. 2012b; Harris et al. 2009).

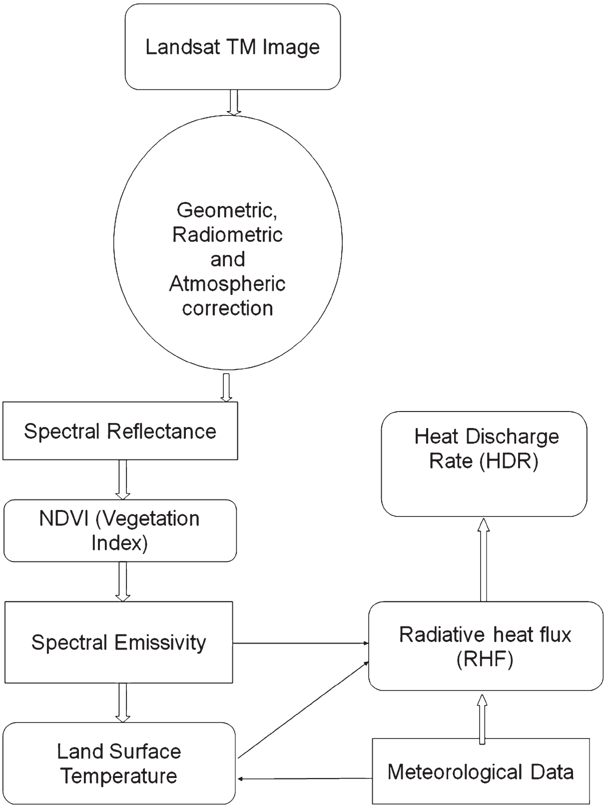

Fig. 2 Flow chart of image processing (modified after Mia and Fujimitsu 2013)

3 Results and discussions

Based on the primary objective of heat loss estimation using Stefan–Boltzmann equation, we processed the Landsat TM images for creating the thematic maps of emissivity for our study area using NDVI method. The NDVI values were also used to map land-cover into three different types of Kuju fumaroles i.e., vegetated land (NDVI $>$ 0.5), mixed land (NDVI $= 0.2 - 0.5$) and bared land (NDVI < 0.2) (Fig. 3). We obtained that the vegetated lands were increased from 1990 to 1994 before eruption of Kuju fumaroles in 1995 about 0.08 sq km but in the thematic map of 1995 just 40 days after first eruption in October 11, 1995 we did not obtain any vegetation covered area in our study region that is because of volcano ashes were covered vegetation leaves in and around the fumaroles (Table 1). The vegetated land lost about 0.02 sq km in 1996 from 1994 because of 1995 fumaroles eruption. Bared land areas were more or less similar before eruption but these were surprisingly found as double in 1995 as before just after the eruption and then again reduced in 1996 as before eruption. The decreased trend of mixed land areas before eruption was obtained an increasing trend significantly after eruption. We estimated the spatially distributed spectral emissivity of our study area by using NDVI method as our desire to use satellite image information as much as possible in our study. We obtained emissivity value in the ranges from 0.95 to

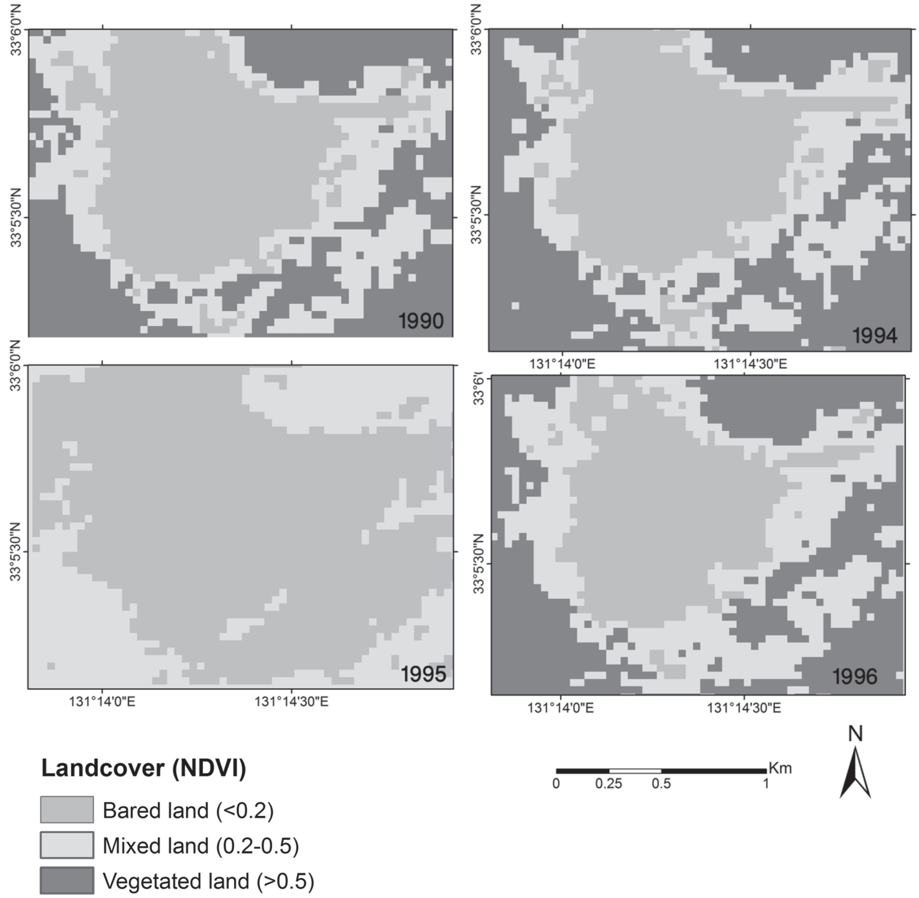

Fig. 3 Land-covers of our study area based on NDVI

0.99 in our all thematic maps of emissivity (Fig. 4). The higher value of emissivity indicates vegetation and lower is the bared land of our study area (Table 1).

Land surface temperature (LST) was estimated using mono-window algorithm as single band of thermal infrared data of landsat TM images of our study. Result showed that LST anomaly area above ambient was obtained an increasing trend from 1990 to 1995 gradually, and then it decreased in 1996. The LST anomaly area obtained about 1.1 sq km, 1.27 sq km, 1.68 sq km and 0.68 sq km in 1990, 1994, 1995 and 1996 respectively. The highest maximum LST above ambient was about 16 °C in the year of 1995 and lowest maximum was about 8 °C in 1996 (Table 1) (Fig. 5). The LST values almost always showed lower than the actual temperature of the thermal features in pixel that reflect the thermal mixing with cold background materials associated with 30 × 30 m pixel scale.

Radiative heat flux (RHF) was estimated by using Stefan–Boltzmann equation. The highest maximum RHF was obtained before eruption about 104 W/m^2 in 1994 and lowest maximum was obtained after eruption about 80 W/m^2 in 1996. The highest RHF anomaly area above zero W/m^2 was attained about 1.64 sq km in 1995 and lowest about 0.64 sq km in 1996 (Fig. 6). We found an increased RHF anomalous area from 1990 to 1995 about

Table 1 Summary results of our study

Year	Area of landcover (sq km)			Ambient temperature (°C)	Emissivity	Land surface temperature above ambient (°C)			Radiant heat flux (W/m^2)			Total radiant heat flow (MW)	Total geothermal heat flow (MW)
	Bared land (NDVI < 0.2)	Mixed land (NDVI = 0.2-0.5)	Vegetated (NDVI > 0.5)			Max	Mean	Min	Max	Mean	Min		
1990	0.81	0.72	0.82	293.95	0.95–0.99	16.17	3.68	−8.81	96.25	23.76	−48.73	22.39	144.64
1994	0.80	0.65	0.90	303.90	0.95–0.99	15.83	4.63	−6.56	103.72	31.41	−40.90	38.66	249.74
1995	1.61	0.74	0.00	275.55	0.95–0.99	15.11	6.33	−2.45	74.19	31.18	−11.82	37.1	239.67
1996	0.69	0.78	0.88	298.05	0.95–0.99	8.36	0.17	−8.02	79.51	−9.97	−46.54	10.61	68.54

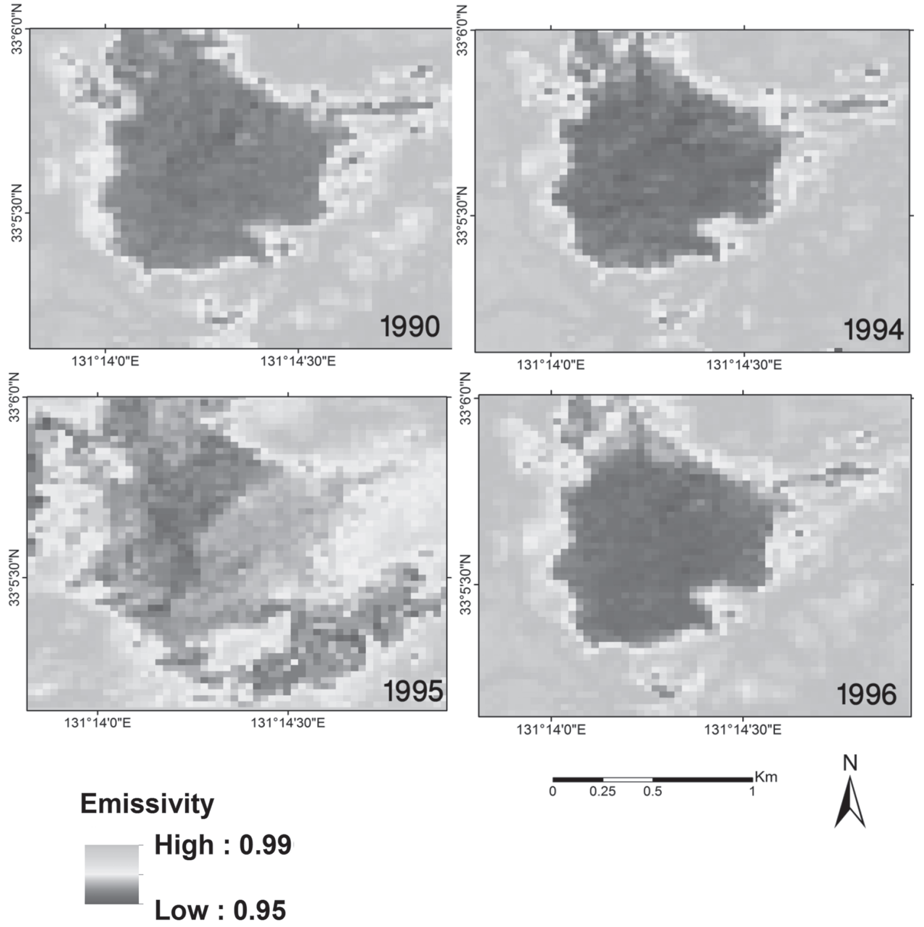

Fig. 4 Spatially distributed spectral emissivity in our study area

0.58 sq km and decreased from 1995 to 1996 about 0.98 sq km in our study area. We obtained the expected strong correlation between RHF and LST above ambient from random samples from our study area as LST is one our input parameter in the heat flux equation. The spatial distribution of random point samples of RHF showed that an increasing trend before eruption period from 1990 to 1994 and a decreasing trend from 1995 to 1996 in our study (Fig. 7). Total radiant heat flow before eruption was obtained about 22 and 39 MW respectively in 1990 and 1994. After eruption period of our study, we obtained about 37 and 11 MW total radiant heat flow respectively in 1995 and 1996 (Table 1). We found the relationship correlation of radiant component of heat flow with total about 15 % from two previous studies in volcano fumaroles. After using this relationship coefficient, we obtained the total geothermal heat flow from our study area about 144.64, 249.74, 239.67, 68.54 MW respectively in 1990, 1994, 1995 and 1996. The total heat flow had much higher before eruption in October 11, 1995 than our result in 1995 that was after 40 days of eruption.

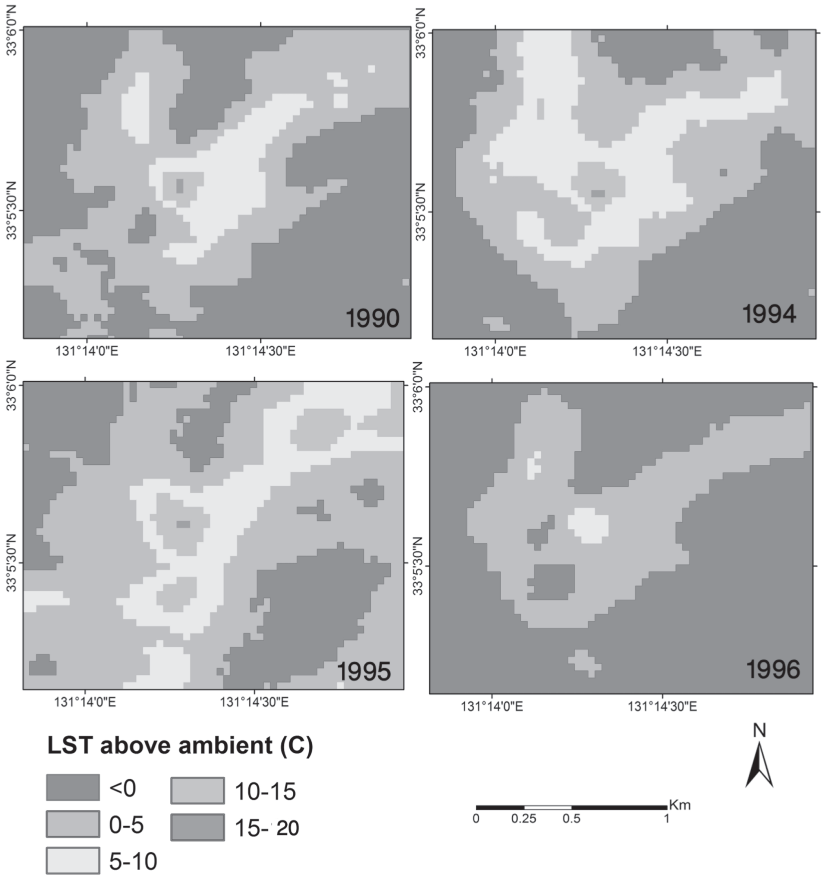

Fig. 5 Land surface temperature above ambient in our study

4 Conclusions

An augmented trend of anomalous area of both LST and RHF was obtained before 1995 eruption from 1990 and then declined from 1995 to 1996 in our study area. In case of total radiant geothermal heat flow, we found an increasing trend before the eruption and a declining trend after the eruption in Kuju fumaroles. The radiant heat flux was strongly correlated with LST above ambient in our study. Spatial distribution of RHF also showed a similar trend of total RHF. Fumaroles area showed an abrupt increase of bared land and no vegetation just after eruption within the thematic map in 1995 in our study. Statistics of LST and RHF also showed clear evidences of heat loss activity before and after eruption in 1995. Here, we only used two sets of Landsat images before the eruption because of availability of good quality images and we observed from this study that RHF abruptly increased just before eruption in 1994 than 1990. From this study, we might be suggested for the continuous monitoring of RHF using Landsat TM thermal infrared images which are fully able to predict the future volcano fumaroles eruption in any active volcano in the world.

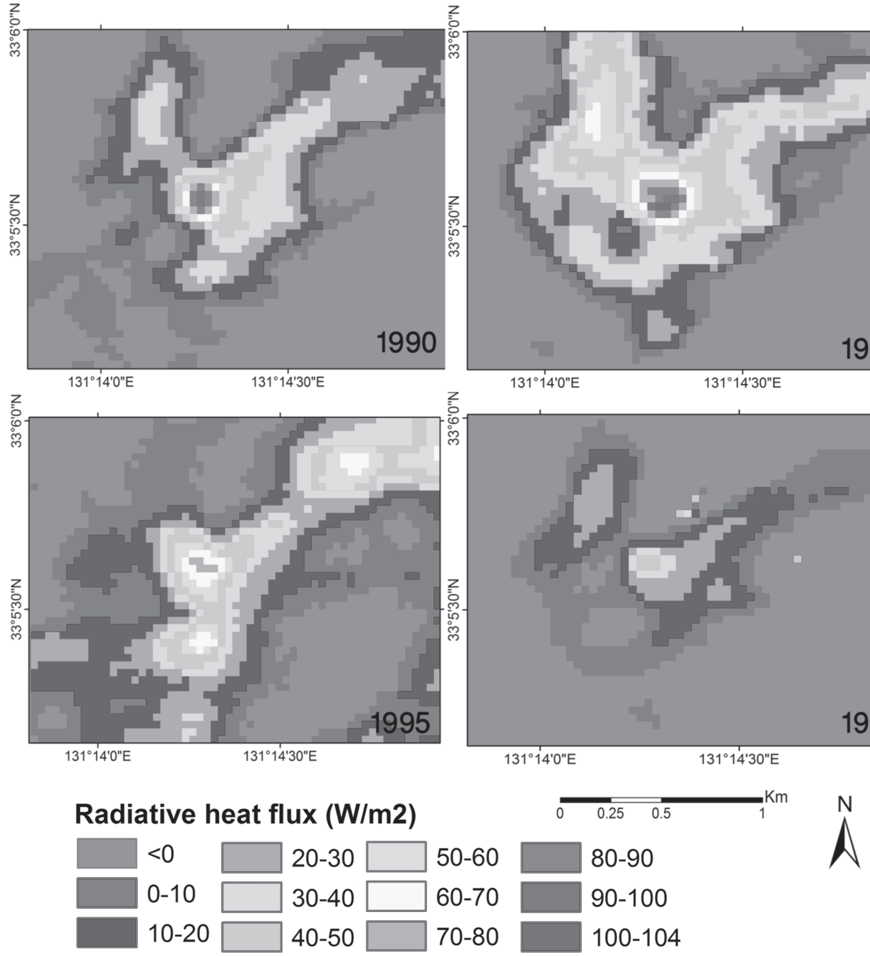

Fig. 6 Radiant geothermal heat flow in our study area

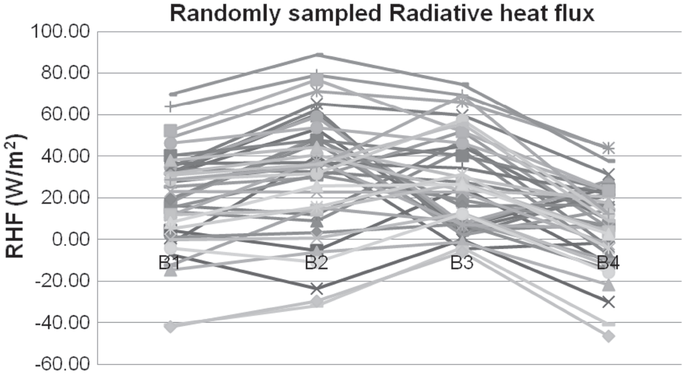

Fig. 7 Spatial distribution of randomly sampled RHF during our study period

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