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Infrared measurements to evaluate groundwater discharge in the coastal zone

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Abstract Infrared images of surface temperature obtained from a remotely-controlled helicopter were compared with data measured *in situ* by optical fibre cables and thermometers for evaluating the groundwater discharge into the ocean. Soil surface temperature measured *in situ* at the transect line with thermister thermometers and optical fibre cable agreed well with the infrared thermal data. The electrical conductivity of the submarine groundwater discharge decreases with decreasing surface temperature, indicating that the infrared measurement can tell us the change in fresh component of submarine groundwater discharge. Therefore, the remotely-controlled infrared method is a good tool for monitoring the coastal environment including groundwater discharge into the coastal zone.

Key words fibre optics cable; groundwater seepage; infrared images; remotely controlled measurements; submarine groundwater discharge; surface temperature

INTRODUCTION

Direct groundwater discharge in the coastal zone is now recognized as an important pathway for water and dissolved minerals from the land to the ocean. There are several methods to evaluate the magnitude of the groundwater discharge rates. However, methods evaluating spatial distribution of direct groundwater discharge have not yet been established. There are some indirect methods such as radon measurements (Moore, 1996; Burnett *et al.*, 2001), resistivity measurements (Taniguchi *et al.*, 2006), and seepage meter measurements (Taniguchi *et al.*, 2002), although these methods always require intensive field measurements.

Evaluation of submarine groundwater discharge (SGD) at regional-scales by using infrared sensors to measure temperature signals, has been used in several studies (Fischer *et al.*, 1964; Roxburgh, 1985; Bogle & Loy, 1995; Banks *et al.*, 1996). However, submarine groundwater discharge rates were not quantitatively evaluated, although the locations of SGD were evaluated. These detectable locations are attributed to the spatial and temporal variation of both seawater and groundwater temperatures, which requires intensive field calibration.

In this study, infrared images of surface temperature obtained from a remotely-controlled helicopter are compared with data measured *in situ* by optical fibre cables and thermometers in order to evaluate the processes of direct groundwater discharge into the ocean.

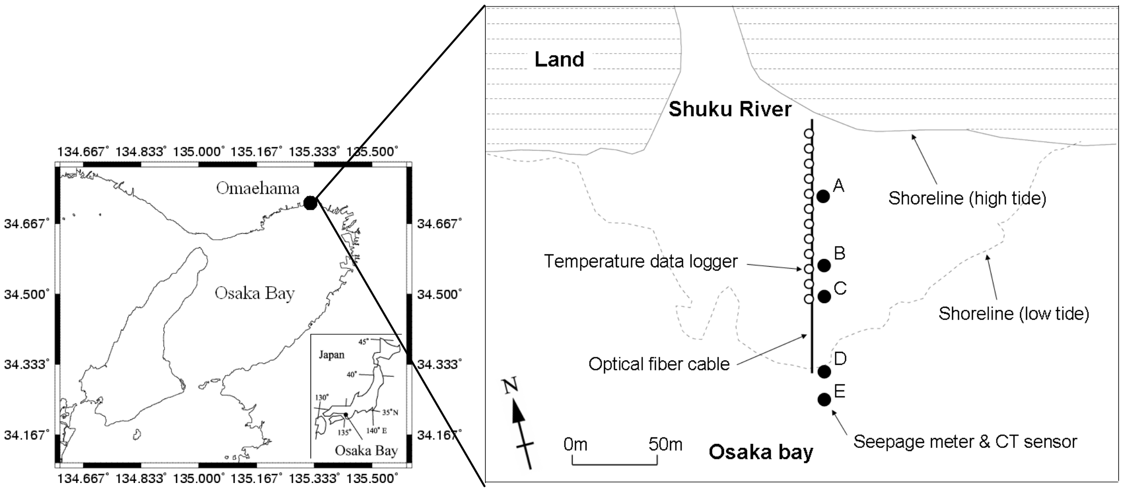

Fig. 1 Location of the study area and equipment.

METHODS

Infrared measurements were made on 23 August 2006 with a Thermo-tracer TS7302 (NEC-SanEi Co.) to obtain the surface temperature for evaluating groundwater discharge into the coastal waters of Omaehama, Kobe, Japan (Fig. 1). Measurements were made in the 8–14 μm window, with a spatial resolution of 100 cm (from a height of 300 m, and with an accuracy of ±2%. In addition, *in situ* temperature measurements on the seabed and coastal land surface were made from 21–24 August 2006 with a fibre optics cable (Hitachi Co., Ltd.) to evaluate the change in temperature of the pore water from groundwater discharge. Temperature measurements under the seabed (5 cm depth under the seabed) were also made with temperature data loggers ("tidbit" HOBO Co., Ltd.). Instrument locations are shown in Fig. 1.

The seepage meter method (Lee, 1977) was applied to evaluate the groundwater discharge rates from the seabed. Instruments were deployed in inter-tidal zone (A, B and C), and measurements were made at each high and low tide. Continuous heat flow type seepage meters (Taniguchi & Iwakawa, 2001) were used in the subtidal zone (D and E), with measurements every minute. Conductivity measurements of groundwater discharge, to evaluate the amount of terrestrial groundwater in groundwater discharge, were made with conductivity-temperature sensors ("Compact-CT", Alec Electronics) in the chamber of the seepage meter. Further, measurements of tidal change were also made with Diver sensors (Daiki-Rikakogyo Co.). Measurements were made every 5 mins from 06:30 h to 18:30 h and every 1 min from 13:00 h to 18:30 h on the 23 August.

RESULTS AND DISCUSSION

Results of infrared measurements made at 12:50 h on 23 August 2006 are shown in Fig. 2. The beach in the study area is easily identified by the white colour, corresponding to higher temperatures. A cool spot is visible to the south of the Shuku River mouth, and active groundwater seepage was found at this location. The white

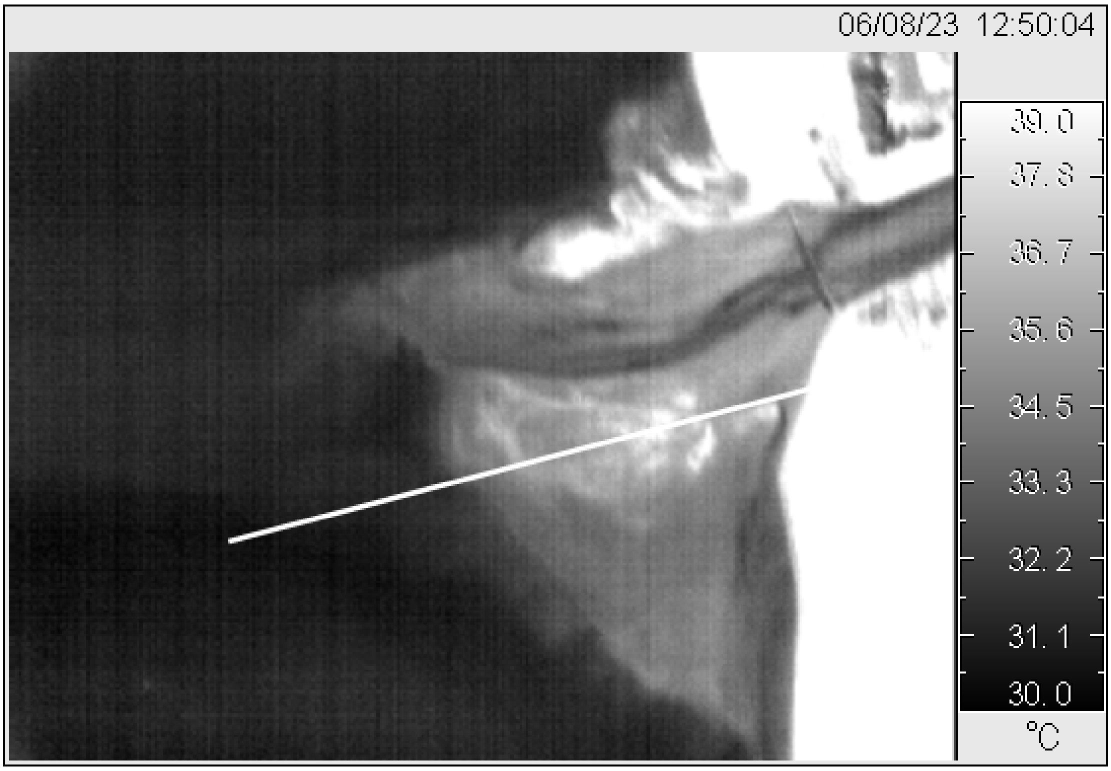

Fig. 2 Infrared images in the study area. Warmer temperatures correspond to lighter colours.

line shows the transect line of the fibre optic cable (Fig. 1). As can be seen from Fig. 2, infrared imagery from a remotely-controlled helicopter can tell us the heterogeneity of the surface temperature, which may show the condition of the groundwater discharge.

In order to compare the temperatures obtained from infrared measurements, the fibre optics cable, and from the thermister thermometer, the relationships between temperature and the distance from the coast are shown in Fig. 3. The temperature data was obtained from Fig. 2 every 1 m distance along the transect line with 0.01°C resolution. As can be seen from Fig. 3, the trend of the change in temperature obtained by infrared measurement is the same as the one measured by fibre optic cable along the transect line, although the temperature itself is different between the infrared measurement and fibre optics cable. Therefore, the infrared image from the remotely-controlled helicopter is useful for evaluating spatial variation of the surface temperature in the coastal zone.

To evaluate the relationship between groundwater discharge from seabed and surface temperature obtained from infrared images, the electrical conductivity of the groundwater discharged into the chamber of the seepage meter is plotted against the surface temperature obtained from infrared measurements (Fig. 4). It is observed that the electrical conductivity of the seepage groundwater increases with increasing surface temperature, and is attributed to the magnitude of the terrestrial groundwater discharge, which is cooler than seawater on the seabed during the summer.

Figure 5 shows the time series of fresh component of the groundwater discharge (at locations D and E) which is separated by use of a conductivity sensor in the

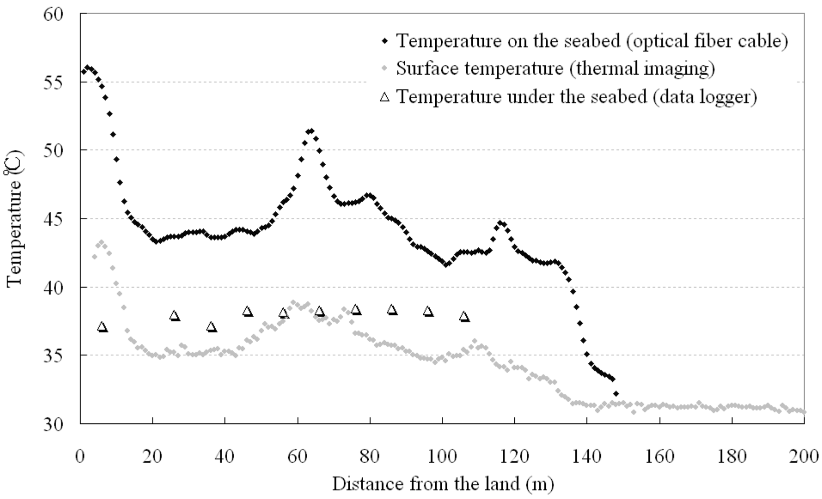

Fig. 3 Temperature against the distance from the coast.

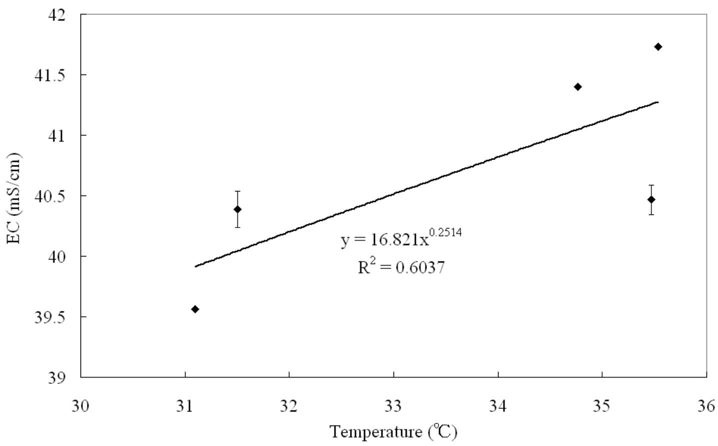

Fig. 4 Relationships between surface temperature obtained from infrared measurement and electric conductivity of the seepage groundwater.

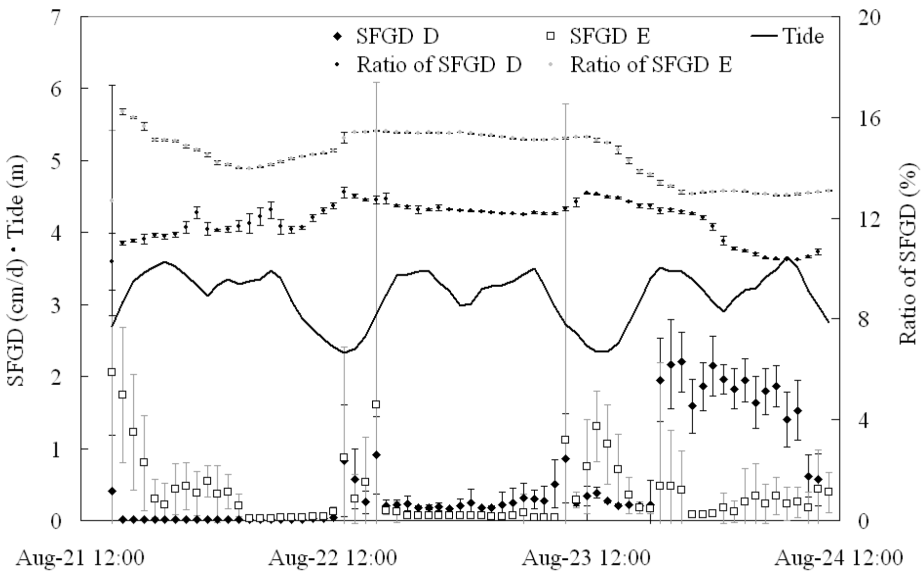

Fig. 5 Changes in fresh component of submarine groundwater discharge (SFGD), tide, and ratio of SFGD at locations D and E.

chamber of the seepage meter and two end-members, seawater and groundwater, as well as tidal change, and the ratio of fresh component of submarine groundwater discharge to total groundwater discharge. It is observed that the fresh component of submarine groundwater discharge (SFGD) and the ratio of SFGD increases with the decreasing tide, because of the hydrological connection between terrestrial groundwater and seawater. The lower electric conductivity of groundwater discharged from the seabed in Fig. 4 corresponds to the higher groundwater discharge rate, indicating that the lower surface temperature may be responding to the increased fresh groundwater discharge. The infrared imagery from remotely controlled helicopter may therefore be useful for monitoring the changes in groundwater discharge into the coastal zone.

CONCLUSION

Distribution of surface temperatures obtained from infrared measurements by thermo-tracers agreed well with *in situ* data measured by fibre optic cable and thermister thermometers. Strong correlations were found between surface temperatures obtained by thermo-tracer and the electric conductivity of the submarine groundwater discharge, indicating that remotely sensed infrared measurements may be able to tell us the magnitude of the fresh component of submarine groundwater discharge. The use of remote sensing technologies to identify and quantify submarine groundwater discharge is clearly an area for future research.

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