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Seasonal Variation of the ^{222}Rn Concentration in the Central Part of the Seto Inland Sea, Japan

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Abstract—We confirmed the seasonal variation of radon-222 (^{222}Rn) concentration in seawater of the Hiuchi-Nada, a small bay located in central part of the Seto Inland Sea to estimate the contribution of groundwater. The relation between the salinity and ^{222}Rn concentration in the seawater indicates that the bottom seawater would be significantly influenced by the deep groundwater discharge in the July 2010 which is the stratified period, while the signal of groundwater discharge is not clear in the November because of the vertical mixing. However, the ^{222}Rn concentration was totally high in the November compared with that in the July. The result suggests the seasonal variation of groundwater discharge to the study area.

Keywords: submarine groundwater discharge (SGD), seasonal variation, Seto Inland Sea, Radon-222 (^{222}Rn)

INTRODUCTION

Submarine groundwater discharge (SGD) represents all direct discharge of subsurface fluids across the land-ocean interface (Taniguchi *et al.*, 2002). Recent studies have revealed that SGD is one of the important pathways for nutrients and the other dissolved materials such as carbon and trace metals from terrestrial area to the marine environment (Moore, 2010). On the global scale, Zektser and Loaiciga (1993) estimated that the amount of dissolved material load by direct groundwater discharge is more than 50% of that from rivers. Accordingly, the effect of groundwater cannot be negligible in considering nutrient environment of coastal area.

Based on the conceptual figure shown by Taniguchi *et al.* (2002), submarine fresh groundwater discharge (SFGD) includes shallow (unconfined) groundwater

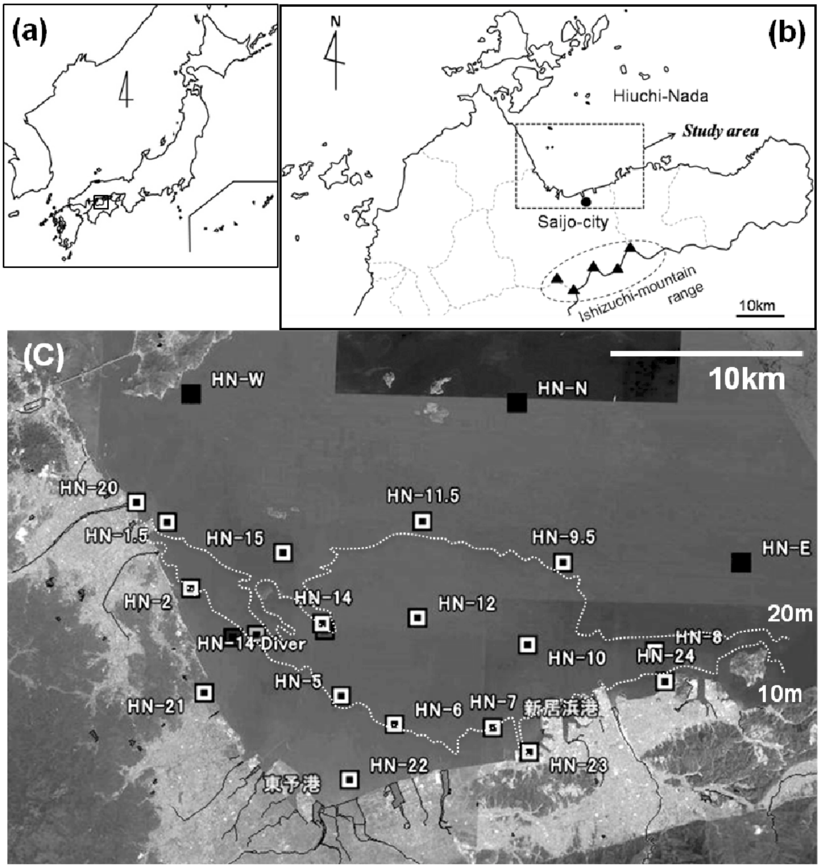

Fig. 1. Study area (a, b: location of the study area and c: sampling stations).

and deep (confined) groundwater. In addition, shallow groundwater generally discharges near the coast line, while deep groundwater would discharges from the seabed of offshore area because it has higher water pressure than shallow groundwater. However, in the previous studies, discharge area and its flux of the deep groundwater in the coastal areas were not well evaluated.

Seto Inland Sea is the largest semi-enclosed coastal sea in Japan. Recently, some researchers tried to evaluate SGD at the specific area of the Seto Inland Sea. For example, Taniguchi and Iwakawa (2004) evaluated shallow groundwater discharge in the Osaka Bay using seepage meters. Onodera *et al.* (2007) examined shallow groundwater discharge and derived nutrient transport in a small tidal flat located on an island. Shimizu *et al.* (2009) estimated the shallow groundwater discharge along the coast line of Bisan-Seto using topographic model. Nevertheless, deep groundwater discharge was not evaluated in these studies.

The objective of the study is to confirm the seasonal variation of ^{222}Rn

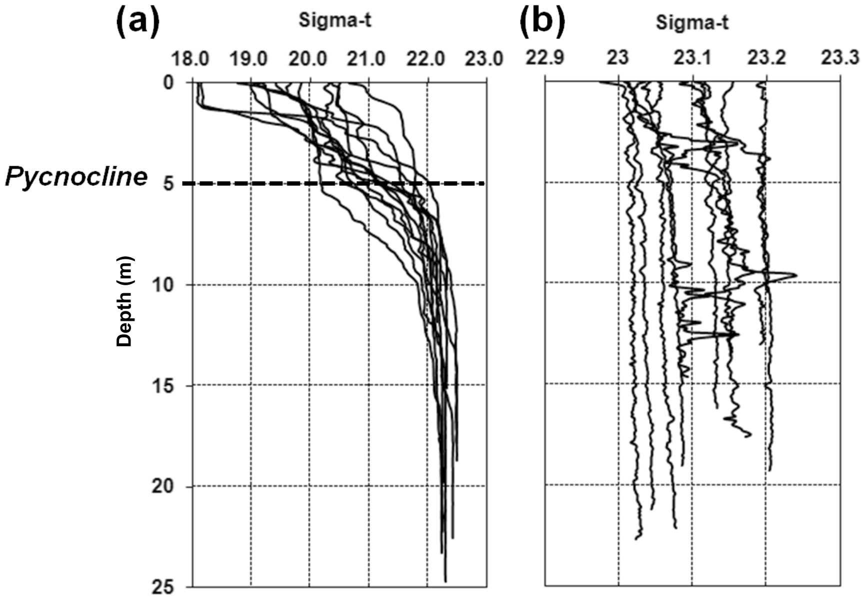

Fig. 2. Vertical profiles of sigma-t in (a) July 2010 and (b) November 2010 measured at all stations.

concentration in the seawater to evaluate the contribution of SGD at the Hiuchi-Nada in the Seto Inland Sea.

STUDY AREA

The Hiuchi-Nada is a semi-enclosed bay in the central part of the Seto Inland Sea. The bay has a size of about 50 km × 30 km and an average depth of approximately 20 m. Kurushima Strait, a narrow and deep strait (>50 m), is located at its western side, and Bisan Strait, a wide and shallow strait, at its eastern side.

The study area (Fig. 1) is southwestern part of the Hiuchi-Nada and has a size of approximately 30 km × 13 km. Based on the horizontal distribution of residual current in the Hiuchi-Nada (Guo *et al*., 2004), we know that dominant dub-tidal current flows from east to west along coastal line. Only some small rivers (Kamo River, Nakayama River etc.) flow into the study area, whereas the terrestrial area is characterized by abundant volume of groundwater recharged in the catchment of mount Ishizuchi, which is the highest mountain (max. 1982 m amsl.) in western Japan.

METHOD

We conducted the measurement of vertical profiles in salinity, water temperature and chlorophyll and sampling of sea water at intervals of 5 m from

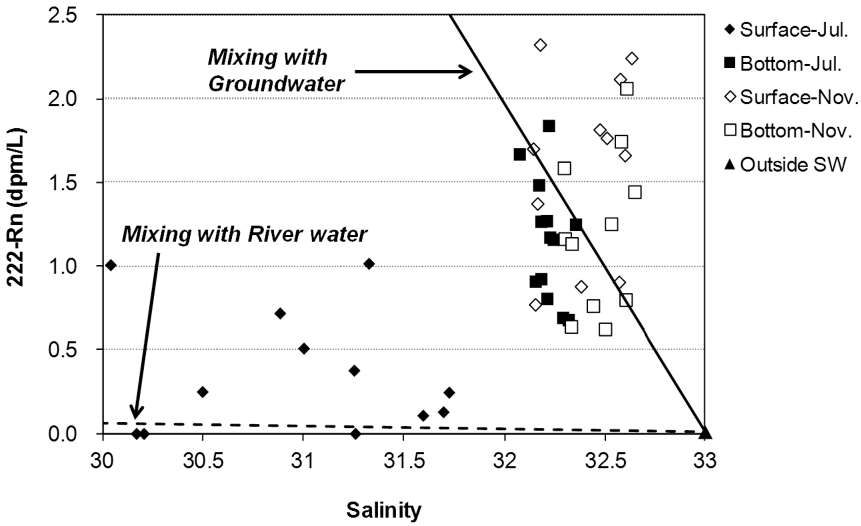

Fig. 3. Relation between salinity and ^{222}Rn in the seawater, groundwater and river water.

the surface to the bottom at about 20 stations with depth of from 10 m to 25 m in July and November 2010 (Fig. 1). River water samples and terrestrial groundwater samples were collected around the study area. Radon-222 (^{222}Rn) concentration was measured at surface and bottom layers of the sampling station using electronic radon detector (RAD7, Durridge Co.).

^{222}Rn is one of the radioactive isotopes of radon in the uranium-238 (^{238}U) series. It is unreactive in nature with short half-life ($t_{1/2}$ = 3.83 d). Burnett *et al.* (1996) pointed out that the Radon-222 (^{222}Rn) is a useful tracer of SGD because groundwater has extremely high concentration in ^{222}Rn compared with river water and seawater. Therefore, relatively high ^{222}Rn concentration in seawater suggests groundwater discharge area.

RESULTS AND DISCUSSION

Figure 2 summarized vertical profiles of sigma-t in (a) July and (b) November 2010, respectively. Sigma-t was relatively low at the upper layer in July, and it indicate the presence of significant stratification with a pycnocline at depth of about 5 m. While it was completely mixed vertically in November.

Figure 3 shows the relation between salinity and ^{222}Rn concentration in the surface and bottom seawater. Here, we hypothesized that the seawater in the study area is composed of simple binary mixing between outside seawater and terrestrial water (river water or groundwater). The outside seawater (Outside SW) means the seawater flowing into the study area, and it was assumed to be the mean value of the bottom seawater at stations of HN-W, HN-N and HN-E (Fig. 1c). The broken line and solid line represent the mixing between the outside seawater and the river water or that between the outside seawater and the groundwater, respectively. In July, the bottom seawater is situated near the mixing line between the outside seawater and the groundwater. This result suggests that the bottom seawater would be influenced by the deep groundwater discharge from the seafloor. While surface seawater was characterized by lower salinity and ^{222}Rn concentration than bottom seawater. It suggests that the surface seawater would be influenced by the inflow of river water with low ^{222}Rn concentration or the loss of ^{222}Rn to the atmosphere. On the other hands, in November, both of the surface seawater and the bottom seawater showed the similar salinity and ^{222}Rn concentration due to the vertical mixing. However, the ^{222}Rn concentration was totally higher in the November than that in the July. Besides, both of the surface seawater and the bottom seawater are situated near the mixing line between the outside seawater and the groundwater. These results suggest that the contribution of SGD to the study area was larger in the November than the July.

CONCLUDING REMARKS

To estimate the contribution of groundwater in the Hiuchi-Nada, we have confirmed the seasonal variation of salinity and radon-222 (^{222}Rn) concentration in the surface and bottom seawater during the stratification period (July 2010) and the vertically mixed period (November 2010). The relation between the salinity and ^{222}Rn concentration in the seawater indicates that the bottom seawater would be significantly influenced by the deep groundwater discharge in the July, while the signal of groundwater discharge is not clear in the November because of the vertical mixing. However, ^{222}Rn concentration was totally high in November compared with that in the July. The result suggests the contribution of SGD was larger in the November than the July.

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REFERENCES

Burnett, W. C., J. E. Cable, D. R. Corbett and J. P. Chanton (1996): Tracing groundwater flow into surface waters using natural ^{222}Rn. p. 22–28. In *Groundwater Discharge in the Coastal Zone*, ed. by R. W. Buddemeier, LOICZ, Texel, The Netherlands.

Guo, X., A. Futamura and H. Takeoka (2004): Residual currents in a semi-enclosed bay of the Seto Inland Sea, Japan. *J. Geophys. Res.*, **109**, C12008, doi:10.1029/2003JC002203.

Moore, W. S. (2010): The effect of submarine groundwater discharge on the ocean. *Annu. Rev. Mar. Sci.*, **2**, 59–88.

Onodera, S., M. Saito, M. Hayashi and M. Sawano (2007): Nutrient dynamics with groundwater-seawater interactions in a beach slope of a steep island, western Japan. *IAHS Publ.*, **312**, 150–158.

Shimizu, Y., S. Onodera and M. Saito (2009): Estimation of spatial variation in submarine groundwater discharges from a coastal grid 50 m square, using a topographic model: an example of the application to the middle of the Seto Inland Sea. *Japanese J. Limnol.*, **70**, 129–139 (in Japanese).

Taniguchi, M. and H. Iwakawa (2004): Submarine groundwater discharge in Osaka bay, Japan. *Limnology*, **5**, 25–32.

Taniguchi, M., W. C. Burnett, J. E. Cable and J. V. Turner (2002): Investigation of submarine groundwater discharge. *Hydrol. Proc.*, **16**, 2115–2129.

Zektser, I. S. and H. G. Loaiciga (1993): Groundwater fluxes in the global hydrologic cycle: past, present and future. *J. Hydrol.*, **144**, 405–427.

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