

Tracing surface seawater mixing and nutrient transport by ^{222}Rn on the northern coast of Beibu Gulf, China

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Abstract

The transport and diffusion of substances in seawater are limited by the mixing motion of water bodies, while the main forms of mixing in offshore water bodies are advection and eddy diffusion. The eddy diffusion process of water indicates the possible transport direction of dissolved substances. However, the complex environment in the coastal zone makes it difficult to quantitatively assess the water diffusion process. ^{222}Rn is a useful tool to trace the diffusion process of water bodies. However, studies on the ^{222}Rn distribution and its behavior in the Beibu Gulf are scarce. In this study, the activity distribution characteristics of ^{222}Rn in surface seawater of the Guangxi shelf area of the Beibu Gulf were measured. Based on the one-dimensional, steady-state model, the vorticity diffusion coefficient of ^{222}Rn in the horizontal direction was calculated as $(0.42\text{--}2.13) \times 10^8 \text{ m}^2/\text{d}$, and the offshore fluxes of ^{222}Rn under the influence of water mixing were calculated as $2.00 \times 10^{12} \text{ Bq/d}$. Correspondingly, the horizontal transport fluxes of silicate, phosphate, nitrite and nitrate were $6.28 \times 10^{-3} \text{ mol}/(\text{m}^2\cdot\text{d})$, $0.10 \times 10^{-3} \text{ mol}/(\text{m}^2\cdot\text{d})$, $0.20 \times 10^{-3} \text{ mol}/(\text{m}^2\cdot\text{d})$ and $4.15 \times 10^{-3} \text{ mol}/(\text{m}^2\cdot\text{d})$, respectively. These results indicate that the study of eddy current diffusion in offshore marine water facilitates a deeper understanding of the water mixing process and nutrient transport and migration.

Key words: ^{222}Rn , water mixing, nutrients, vorticity diffusion coefficient, horizontal transport flux

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1 Introduction

Since the Industrial Revolution, the rapid development of society and economy has led to resource depletion and ecological destruction; thus, environmental problems have gained widespread attention (Chen, 2019). Coastal zones have convenient land and water transportation, and their urbanization is more advanced than that of other regions, making important contributions to global economic development. However, the ecosystems in these areas are fragile and easily damaged by human activities. Many current environmental problems, such as ocean acidification (Liu et al., 2021), marine eutrophication (Santos et al., 2021; Wang et al., 2021), algae bloom (Chen et al., 2020), and organic pollution of seawater, are caused by human activities in this region (McKenzie et al., 2020; Mwangi et al., 2016). Data show that the destruction of coastal ecosystems has restricted social productivity and hindered economic development in coastal areas (Wang et al., 2021). Therefore, the environmental governance of coastal areas has gained the attention of governments worldwide.

However, it is difficult to trace the source of pollutants that damage the ecological environment and assess their diffusion and migration process due to the complex hydrodynamic conditions of land-water interactions in coastal zones. These factors restrict the sustainable development of the coastal zone environment and increase the difficulty of environmental governance.

The migration and diffusion of pollutants in seawater are closely related to the mixing and exchange of water bodies. The mixing of marine water bodies is a common form of seawater movement. Previous studies have interpreted this mixing as the process of gradually homogenizing various characteristics in seawater (Su, 2013; Su et al., 2013). The whole water mixing process is divided into four forms: (1) Molecular diffusion occurs mainly via the random movement of molecules to exchange materials with adjacent seawater. The diffusion process is described by Fick's law. The intensity depends on the material gradient in space, with an order of magnitude of $10^{-5} \text{ cm}^2/\text{s}$, and the influencing factor is the properties of seawater (Su, 2013). (2) Turbulent

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diffusion carries out material exchange with adjacent seawater via the random movement of seawater microclusters (Su, 2013). The diffusion process is closely related to the movement of seawater, which is relatively complex and difficult to simulate numerically. Therefore, eddy diffusivity was introduced to describe the diffusion process and quantify the intensity of diffusion, with an order of magnitude of $10\text{--}10^8\text{ cm}^2/\text{s}$ (Su, 2013). (3) Advection carries dissolved and granular matter through the water body for migration. The migration process is determined by water flow movement and is closely related to the flow field morphology (Su, 2013). (4) Convection is the process of water exchange and material migration in the vertical direction, which depends on the difference in water density caused by heat and salt. Seawater mixing is the result of the interaction of various mixing forms, but the processes dominated by different mixing forms show different characteristics. In the diffusion-dominated process, the concentration of the source decreases with increasing time but does not change greatly in space. In the advection-dominated process, the concentration of the source does not change with time but moves with the flow in space. In a process dominated by advection and diffusion, the concentration of the source will not only decrease with time but also move spatially with the flow (Su et al., 2013). Current studies have shown that the mixing process of offshore water bodies mainly exists in the form of advection and turbulent diffusion (Blanton et al., 1994; Moore, 2000), and the effect of molecular diffusion is disregarded (Sarmiento et al., 1976). Therefore, the study of turbulent diffusion and peaceful flow has practical significance for the establishment of solute transport models in seawater, the assessment of ocean self-purification capacity, and the calculation of the ocean dilution diffusion coefficient (Su, 2013). This investigation can improve our understanding of the laws and patterns of temporal and spatial variations in dissolved substances in the ocean, especially the biogeochemical cycles near coastal zones (Moore, 2010). For example, nutrient ions and iron ions in the bottom layer are transferred to the surface by eddy current diffusion after remineralization, thus improving primary productivity (Ge et al., 2020). Horizontal water mixing may lead to the cross-shelf migration of nutrients, causing eutrophication in slope areas (Zheng et al., 2020). Vertical stratification of water may cause anoxia and affect the population structure of marine organisms (Zhang et al., 2018).

The natural radionuclide ^{222}Rn ($T_{1/2} = 3.82\text{ d}$) is a water-soluble inert gas, that is a decay product of the ^{238}U series. ^{222}Rn is chemically and particulate conservative and is not bioavailable or directly affected by geochemical conditions. Because ^{238}U ($T_{1/2} = 4.46 \times 10^9\text{ a}$) is widely distributed in soil, rock layers, minerals, and atmospheric particles, ^{222}Rn is ubiquitous. In addition, due to the special geological environment of aquifers, ^{222}Rn will be enriched in groundwater, and its activity is much higher than that of surface runoff and seawater, making it an ideal tracer for the discharge of submarine groundwater (Chen, 2019; Wang, 2020). ^{222}Rn has been widely applied to trace submarine groundwater discharge (SGD) (Chen, 2019; Chen et al., 2019; Wang, 2020; Zhang et al., 2016). In contrast, it is rarely used to evaluate horizontal eddy diffusion, which might be because ^{222}Rn is easily degassed to the atmosphere. Nevertheless, some studies have shown that correcting the fraction of ^{222}Rn escaping to the atmosphere could make it possible to utilize ^{222}Rn for horizontal eddy diffusion tracing (Wang et al., 2021). Theoretically, according to the ^{222}Rn activity, the decay law of the natural radionuclide, and the detection limit of RAD7, ^{222}Rn can still be detected after 5–6

half-lives (Moore, 2000). Thus, ^{222}Rn can trace water mixing for approximately 15 d. Since the offshore process is relatively short and changes rapidly, ^{222}Rn may also be suitable for tracing seawater mixing in coastal regions. Additionally, RAD7 is widely employed with high sensitivity and a low detection limit, and the water consumption (250 mL) is considerably less than that used to detect radium in seawater (50 L). Therefore, ^{222}Rn may be utilized instead of radium to trace water mixing when water sample allocation is limited.

In this study, the distribution of ^{222}Rn activity in the surface water of the Guangxi shelf area of the Beibu Gulf was determined in the summer of 2021 (end of May 2021). By using the one-dimensional advective diffusion model corrected for atmospheric diffusion and flow action under steady-state conditions, we estimated the horizontal eddy current diffusion and compared the spatial variation. Nutrient diffusion fluxes in the study area were further calculated by using the apparent diffusion coefficient to evaluate the influence of nutrient horizontal transport fluxes in the study area. The results of this study provide insights into the significance of water mass mixing on the distribution of nutrients in subtropical bay areas.

2 Study areas and methods

2.1 Study areas

The geographical location and sampling stations of the sea area involved in this study are shown in Fig. 1. The study area is in the Beibu Gulf area in the northwestern region of the South China Sea, bordering the Leizhou Peninsula and Hainan Island to the east, Guangxi Zhuang Autonomous Region to the north, Vietnam to the west, and the South China Sea to the south.

The Beibu Gulf is a natural semienclosed shallow bay, with a coastline length of 1 628.6 km and a sea area of $1.283 \times 10^5\text{ km}^2$. Surrounded by islands and land on three sides, the Beibu Gulf is only connected to the sea toward the south, where it projects westward and is fan-shaped. The northern coastal waters of the Beibu Gulf have numerous harbors and runoff, mainly including Tieshan Port, Beihai Bay, Qinzhou Bay, Lianzhou Bay, Fangcheng Port and Nanliu River and Dafeng River. The sea floor in the bay is flat, and the water depth ranges from 20 m to 80 m, with an average depth of 38 m (Wu, 2014). The Beibu Gulf is in tropical and subtropical regions and has a tropical monsoon climate. The annual precipitation is 1 200–2 000 mm, and the pre-

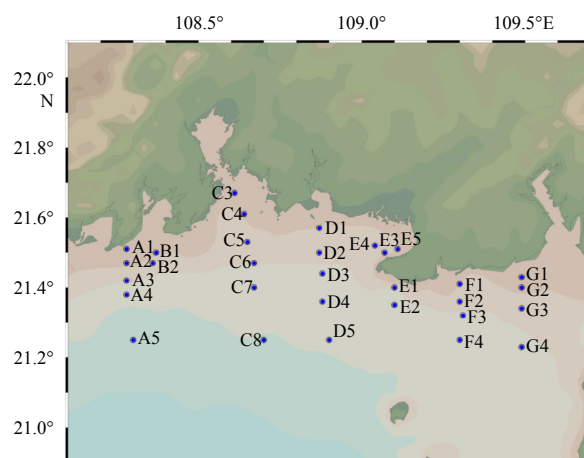


Fig. 1. Sampling stations in the study area of the Guangxi shelf in the Beibu Gulf.

precipitation is mainly concentrated from July to September, among which the precipitation along the coast of Guangxi is the highest, with uneven spatial and temporal distributions and large annual variations. The rainfall in the Beibu Gulf is affected by the monsoon circulation system. The dry and wet seasons are distinct, with high rainfall in summer and low rainfall in winter. The prevailing wind has strong seasonal changes, the winter monsoon has a long influence time and fast wind speed, and summer has the opposite effect and is susceptible to tropical cyclones (Xiong, 2019; Tang, 2011; Cao et al., 2019; Yang et al., 2006). Due to the unique topography of the Beibu Gulf, diurnal tides are obvious in the bay, and some areas have irregular diurnal tides. The tidal current is mainly reciprocating. Except for the irregular diurnal tides at Tieshan Port and Longmen Port, the remainders are regular diurnal tides. The maximum possible tidal range in most sea areas is 3–6 m, the average tidal range exceeds 2 m, and the maximum tidal range at the bay crest is greater than 6 m (Feng, 2021; Chen et al., 2020). A total of 31 stations were observed in this study, and the specific sampling stations are displayed in Fig. 1.

2.2 Methods

2.2.1 Sample collection and pretreatment

The seawater samples are collected by the plexiglass water sampler (the water samples below the water surface are controlled to be collected at 1.5–2 m during sampling). The rubber tube is inserted at the bottom of the water sampler, filled with water samples from the bottom of the bottle, seawater is slowly injected into the 250 mL glass bottle by the overflow method, and the cap is tightened to ensure that there are no bubbles in the glass bottle.

The ^{226}Ra seawater samples in this study were located at the same station as the ^{222}Rn seawater samples. At each sampling station, a pump was used to extract 50 L of surface seawater. The siphon principle was applied to make seawater flow through the water column containing manganese fibers to enrich radium in the water. Afterward, the filtered manganese fibers were cleaned with Milli-Q water to remove salt and sediment particles.

The nutrient samples were filtered through 0.45 μm cellulose acetate filters that were precleaned with hydrochloric acid, rinsed with Milli-Q water and poured into polyethylene bottles. Then, the samples were treated with saturated HgCl_2 and kept away from light until the laboratory measurement could be conducted.

2.2.2 Chemical analysis

^{222}Rn samples collected from 250 mL glass bottles were analyzed by the RAD7 Radon detector (Durrige Co., Inc., USA) and its RAD H_2O accessory at Beibu Gulf University. The measurement accuracy of RAD7 is 5% (under any humidity condition), its detection range is 4–750 000 Bq/m^3 , and the uncertainty value of the mean activity concentration of radon for a 2 h cycle was approximately $\leq 21\%$ (Diab, 2019).

For ^{226}Ra , after field pretreatment, samples were taken back to the laboratory at the Third Institute of Oceanography, Ministry of Natural Resources for follow-up treatment. First, the manganese fibers were dried, loaded into a crucible, covered and placed in a muffle furnace for ashing at 800°C for 12 h. After grinding, the powder was evenly packed into a 9 mm sample tube, which was compacted, fixed and sealed for 20 d. Then, ^{226}Ra activity was determined with a well-type, high-purity germanium γ spectrometer (Model GCW2021) by ^{214}Pb (at 295.2 keV and 351.9 keV) and ^{214}Bi (at 609.3 keV).

Phosphate and silicate concentrations were measured at Xia-

men University using a Four-channel Continuous Flow Technicon AA3 AutoAnalyzer (Dai et al., 2008; Wan et al., 2023). The nitrite and nitrate (DIN) concentrations were measured using the chemiluminescence technique (Braman and Hendrix, 1989; Zheng, 2018). All sampling records and analysis results are shown in Table 1.

2.2.3 Steady diffusion advection model

The apparent diffusion coefficient of seawater is calculated using a one-dimensional advection-diffusion model. The specific principle and method are quoted from Moore (2015).

$$dA/dt = K_h \frac{\partial^2 A}{\partial X^2} - u \frac{\partial A}{\partial X} - \lambda A \pm J, \quad (1)$$

where A is the ^{222}Rn activity concentration (Bq/m^3) at the sampling station; K_h is the average value of the eddy diffusion coefficient, h refers to the sampling depth (m) above the pycnocline layer; X is the offshore distance (km); u is the advection velocity (m/s); λ denotes the decay constant ($2.09 \times 10^{-6} \text{ s}^{-1}$) of ^{222}Rn ; and J represents other ^{222}Rn input or removal ($\text{Bq}/(\text{m}^3 \cdot \text{s})$).

Wang et al. (2021) noted that strong vertical stratification can render the J input at the bottom negligible, and for nuclides with no scavenging effect, J is omitted. At this time, the system can be regarded as a steady-state condition (Moore, 2000). The appropriate boundary condition is selected: when the offshore distance $X = 0 \text{ km}$, $A = A_0$; when the offshore distance $X \rightarrow \infty$, $A \rightarrow 0$. The calculation results are obtained from the above boundary conditions:

$$A = A_0 e^{-\frac{u - \sqrt{u^2 + 4\lambda K_h}}{2K_h} X}. \quad (2)$$

The decay of short half-life nuclides is an important loss item. If the diffusion of nuclides is dominant, the influence of advection can be disregarded.

$$A = A_0 \exp\left(-X \sqrt{\frac{\lambda}{K_h}}\right), \quad (3)$$

$$\ln A = \ln A_0 - X \sqrt{\frac{\lambda}{K_h}}. \quad (4)$$

The logarithm of ^{222}Rn activity and the offshore distance are used for linear fitting, and the slope is m .

$$m = -\sqrt{\frac{\lambda}{K_h}}. \quad (5)$$

Radon is a radioactive inert gas. Although radon will not be used by organisms or directly affected by environmental conditions, it will diffuse to the atmospheric environment, which is the main loss process of radon in the diffusion process. Therefore, atmospheric loss ($-J$) cannot be disregarded. The atmospheric diffusion of ^{222}Rn is a gap effect, which is corrected using the following formula:

$$J = \frac{F}{h}, \quad (6)$$

Table 1. Sample record and analysis results

Station	Latitude	Longitude	Temperature/ °C	Salinity	pH	DO/ (mg·L ⁻¹)	²²² Rn/ (Bq·m ⁻³)	²²⁶ Ra/ (Bq·m ⁻³)	Offshore distance/ km	Phosphate/ (μmol·L ⁻¹)	Nitrite/ (μmol·L ⁻¹)	Nitrate/ (μmol·L ⁻¹)	Silicate/ (μmol·L ⁻¹)
A1	21.51°N	108.28°E	29.08	31.78	8.29	9.32	127.7 ± 61.6	4.69 ± 0.32	3.20	0.06	0.25	6.76	10.58
A2	21.47°N	108.28°E	29.54	31.68	8.30	9.33	50.0 ± 37.2	4.41 ± 0.24	7.70	0.08	0.21	13.95	10.46
A3	21.42°N	108.28°E	29.79	31.79	8.38	9.34	117.5 ± 59.3	4.32 ± 0.35	13.50	0.03	0.03	133.69	2.70
A4	21.38°N	108.28°E	29.62	31.97	8.40	9.54	67.2 ± 44.9	3.16 ± 0.23	18.00	0.04	0.04	12.39	2.58
A5	21.25°N	108.30°E	30.62	31.41	8.21	7.90	18.4 ± 21.4	2.73 ± 0.32	32.00	0.00	0.08	2.02	1.07
B1	21.50°N	108.37°E	29.90	31.35	8.40	9.92	136.7 ± 64.7	5.15 ± 0.26	6.70	0.09	0.08	16.78	7.57
B2	21.47°N	108.36°E	29.60	31.37	8.40	9.69	100.7 ± 56.4	5.47 ± 0.33	10.10	0.09	0.06	49.42	7.59
C3	21.67°N	108.61°E	31.04	24.24	8.01	7.13	94.5 ± 54.8	5.80 ± 0.45	4.20	0.83	1.15	29.95	26.95
C4	21.61°N	108.64°E	31.93	28.28	8.12	7.72	53.5 ± 42.3	6.97 ± 0.35	8.50	0.57	1.19	16.01	20.79
C5	21.53°N	108.65°E	31.36	30.10	8.17	8.10	240.4 ± 83.3	6.39 ± 0.30	15.20	0.30	1.10	9.97	17.79
C6	21.47°N	108.67°E	31.16	30.54	8.27	9.75	422.4 ± 111.2	6.90 ± 0.29	22.10	0.13	0.19	4.05	11.81
C7	21.40°N	108.67°E	30.69	31.23	8.33	8.73	26.1 ± 26.0	4.46 ± 0.27	30.60	0.09	0.10	3.07	8.88
C8	21.25°N	108.70°E	30.51	31.16	8.15	6.70	11.8 ± 16.5	4.15 ± 0.34	52.30	0.01	0.09	3.56	5.26
D1	21.57°N	108.87°E	33.52	26.37	8.06	7.66	166.4 ± 65.7	5.45 ± 0.30	10.10	0.30	1.27	156.72	28.53
D2	21.50°N	108.87°E	33.34	28.28	8.31	9.31	263.7 ± 85.8	4.80 ± 0.24	16.30	0.09	0.33	5.69	13.02
D3	21.44°N	108.88°E	33.20	30.46	8.14	8.36	183.4 ± 76.4	5.32 ± 0.25	23.00	0.09	0.49	60.02	14.63
D4	21.36°N	108.88°E	31.53	30.95	8.34	8.79	99.8 ± 54.8	4.74 ± 0.16	32.10	0.06	0.10	5.12	9.32
D5	21.25°N	108.90°E	31.08	29.00	8.17	6.60	23.1 ± 23.2	4.09 ± 0.22	45.50	0.00	0.06	2.89	6.40
E1	21.40°N	109.10°E	31.82	31.40	8.34	8.96	444.4 ± 107.8	5.73 ± 0.33	3.00	0.08	0.03	97.50	4.31
E2	21.35°N	109.10°E	31.79	31.36	8.31	8.83	166.4 ± 65.7	3.58 ± 0.20	8.60	0.08	0.03	82.62	9.61
E3	21.50°N	109.07°E	31.79	28.46	8.24	8.29	336.0 ± 103.9	–	–	0.88	0.46	11.63	24.56
E4	21.52°N	109.04°E	32.84	28.44	8.21	8.24	221.2 ± 79.0	–	–	0.73	0.57	37.64	29.62
E5	21.51°N	109.11°E	32.14	28.24	8.26	9.20	146.7 ± 66.2	–	–	0.90	0.38	71.29	26.83
F1	21.41°N	109.30°E	36.85	30.92	8.32	8.93	252.0 ± 93.8	6.05 ± 0.28	3.20	0.02	0.09	5.08	2.44
F2	21.36°N	109.30°E	31.71	31.74	8.33	8.75	65.8 ± 48.5	4.47 ± 0.11	8.60	0.07	0.11	9.35	8.35
F3	21.32°N	109.31°E	31.24	31.64	8.32	8.69	280.9 ± 91.0	4.33 ± 0.20	12.90	0.06	0.07	12.41	7.67
F4	21.25°N	109.30°E	30.81	32.71	8.10	6.60	48.2 ± 33.7	3.13 ± 0.26	20.80	0.01	0.06	0.35	3.58
G1	21.43°N	109.49°E	31.88	30.77	8.26	8.50	262.1 ± 89.6	5.71 ± 0.19	5.00	0.05	0.13	5.49	5.62
G2	21.40°N	109.49°E	31.33	31.13	8.24	8.01	237.2 ± 66.2	5.45 ± 0.14	8.40	0.07	0.21	19.63	12.21
G3	21.34°N	109.49°E	31.56	31.90	8.30	8.23	74.3 ± 45.3	3.57 ± 0.23	15.00	0.06	0.12	4.25	8.98
G4	21.23°N	109.49°E	30.81	32.71	8.10	6.60	23.4 ± 23.5	3.00 ± 0.29	27.20	0.01	0.06	1.59	7.09

Note: The parameters of ²²²Rn and ²²⁶Ra are in activity concentrations; the parameters of phosphate, nitrite, nitrate and silicate are in concentrations. – represents no data.

where F represents the atmospheric loss fluxes (Bq/(m²·s)) of ²²²Rn at the air-sea interface, which is converted to the activity change (Bq/(m³·s)) in ²²²Rn at the air-sea interface by dividing by 2. In this study, a water sampler is employed to collect water samples, and the sampling depth is basically the same ($h = 2$ m).

The atmospheric loss flux of ²²²Rn is calculated by the following formula:

$$F = k(A - \alpha \cdot A_{\text{air}}), \quad (7a)$$

where k is the atmospheric transmission speed (m/s), which can be obtained from Eq. (7c); and A_{air} refers to the activity (Bq/m³) of ²²²Rn in the atmospheric environment, which can be directly detected by a RAD7 radon detector. The average activity of ²²²Rn in this study is 2.89 Bq/m³; the air-sea distribution coefficient α is obtained according to Eq. (7b):

$$\alpha = 0.105 + 0.405e^{-0.050 \cdot 2T}, \quad (7b)$$

$$k_{600} = 0.266 \times v^2, \quad (7c)$$

where k_{600} is the gas migration rate of carbon dioxide under standard conditions (20°C; Schmidt numbers: $S_c = 600$); v is wind speed (m/s); and T is the temperature (°C) of the surface seawater.

J is substituted into Eq. (1) to obtain the following formula:

$$\frac{dA}{dt} = K_h \frac{\partial^2 A}{\partial X^2} - u \frac{\partial A}{\partial X} - \lambda A - \frac{k(A - \alpha A_{\text{air}})}{h}. \quad (8)$$

A new boundary condition is selected. When the offshore distance $X = 0$ km, $A = A_0$. When the offshore distance $X \rightarrow \infty$, $A \rightarrow b$. The ²²²Rn activity and offshore distance are linearly fitted, and the slope is substituted with m to obtain:

$$m^2 K_h - mu = \frac{k}{h} + \lambda. \quad (9)$$

If advection u is disregarded, then

$$K_h = \frac{\frac{k}{h} + \lambda}{m^2}. \quad (10)$$

If the advection term cannot be disregarded, it is calculated according to the one-dimensional model obtained by Li and Cai (2011).

$$u = (L_1^2 \lambda_1 - L_2^2 \lambda_2) / (L_2 - L_1), \quad (11)$$

$$K_h = L_1^2 \lambda_1 + L_1 \lambda_1 = L_2^2 \lambda_2 + L_2 \lambda_2, \quad (12)$$

where L_1 and L_2 are the reciprocals obtained by linear fitting with the change in offshore distance after a logarithmic change in the corresponding nuclide activity.

$$K_h = \frac{k}{h} + \lambda + \frac{mu}{m^2}. \quad (13)$$

3 Results

3.1 Distribution of basic hydrological parameters in the Guangxi shelf area of the Beibu Gulf

The temperature ranges from 29.08°C to 36.85°C (Fig. 2a), and the average temperature is $(31.42 \pm 0.27)^\circ\text{C}$ ($n = 31$). There is a distinct horizontal gradient of the temperature with a decreasing trend toward the offshore region. The surface seawater temperature of coastal waters is relatively high, and the high value area appears near the mangroves of Jinhai Bay in Beihai City, and the estuaries of the Dafeng River and Nanliu River. Because the sampling stations are close to the offshore region, these areas are greatly affected by surface warming, coastal wetlands and upstream runoff. The salinity ranges from 24.24 to 32.71 (Fig. 2b), and the average salinity is 30.43 ± 0.34 ($n = 31$). The salinity of sea water generally increases from the estuary to the outer bay, which is also a typical characteristic of estuarine and coastal zones (Guo, 2020). Low-value waters appear near the Qinzhou Bay and Sanniang Bay because the Qinzhou River, Dafeng River and other small rivers flow into the shore. The pH range was 8.01–8.40 (Fig. 2c), with an average value of 8.25 ± 0.02 ($n = 31$).

DO concentrations vary from 6.6 mg/L to 9.92 mg/L (Fig. 2d), with an average value of 8.44 ± 0.18 ($n = 31$). The DO concentration of surface seawater in offshore waters is relatively high, and there are high value areas near the Bailong Peninsula and the Silver Beach of Beihai. The DO concentrations show a decreasing trend with increasing offshore distance.

3.2 Spatial distribution of surface seawater ^{222}Rn in the Guangxi shelf area of the Beibu Gulf

In May 2021, the surface seawater activity of ^{222}Rn in the study area of the Beibu Gulf ranged from 0 Bq/m³ to 444 Bq/m³, with an average concentration of (153 ± 61) Bq/m³ ($n = 31$) (Fig. 3a). Overall, ^{222}Rn activity decreases with increasing offshore distance, which is similar to the results of other research areas (Moore, 1998). The high value areas of ^{222}Rn activity in surface water were mainly at 21.5°N, which is located at the mouth of Qinzhou Bay and extends outward perpendicular to the shoreline ((422 ± 111) Bq/m³), and the area near the Silver Beach of Beihai ((444 ± 108) Bq/m³). The estuaries of the Dafeng River, Nanliu River and Tieshan Port of Beihai also have high ^{222}Rn activity concentrations (Figs 1 and 3). Low ^{222}Rn activity concentration (below 50 Bq/m³) is mainly distributed in the southern area at approximately 21.3°N.

The activities of ^{226}Ra in the surface seawater in the study area range from 3.00 Bq/m³ to 6.97 Bq/m³ (Fig. 3b), with an average concentration of (4.79 ± 0.22) Bq/m³ ($n = 24$).

3.3 Spatial distribution of nutrients in surface seawater in the Guangxi shelf area of the Beibu Gulf

The concentration of nitrite ranged from 0.03 µmol/L to 1.27 µmol/L (Fig. 4b), with an average concentration of (0.30 ± 0.07) µmol/L ($n = 31$). The nitrate concentration ranged from

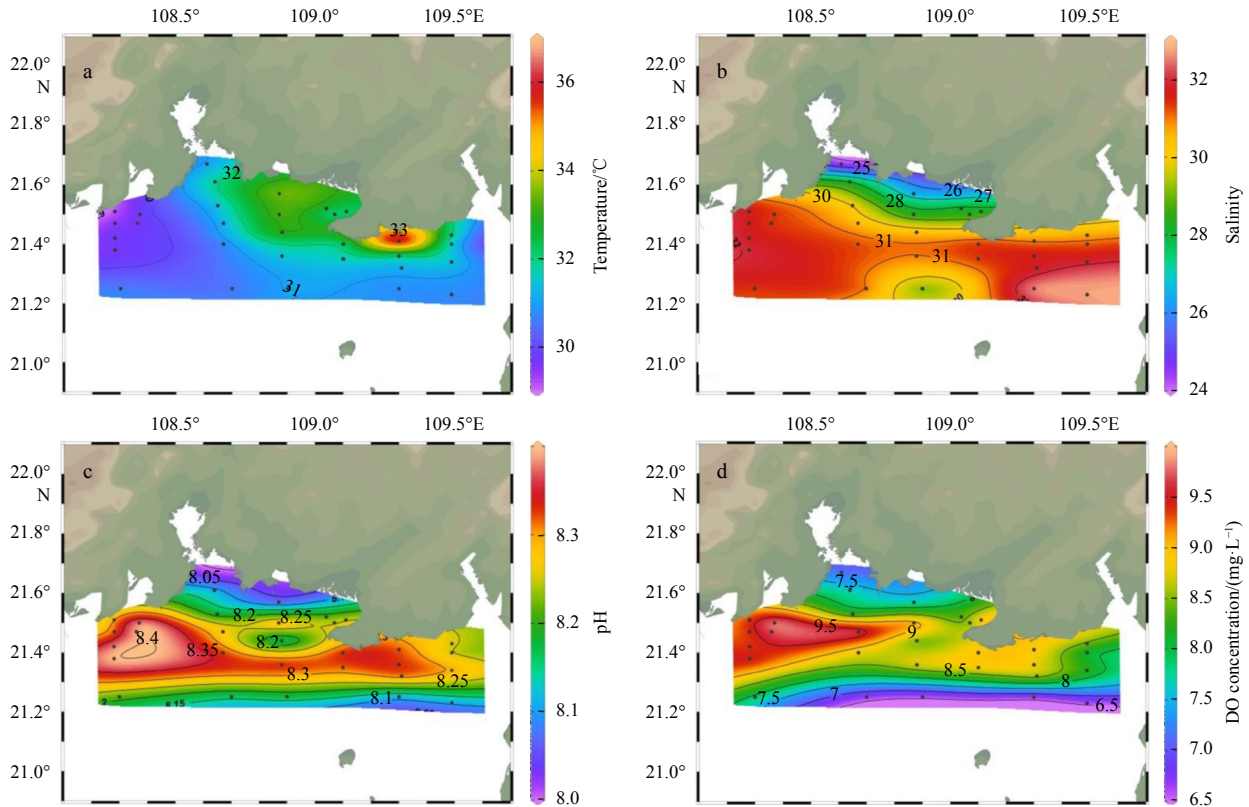


Fig. 2. Distributions of surface seawater parameters: temperature (a), salinity (b), pH (c), and DO (d) distributions in the study area of Guangxi shelf of the Beibu Gulf.

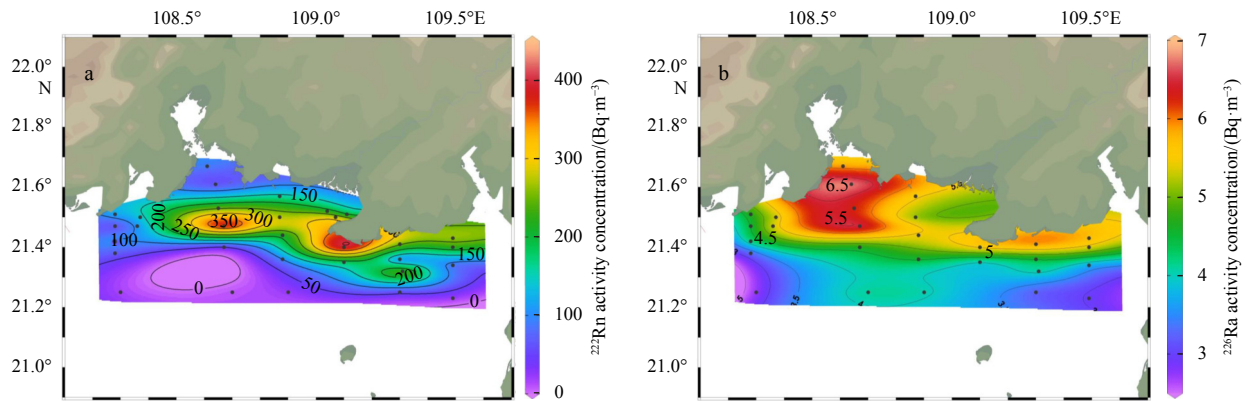


Fig. 3. Distributions of ^{222}Rn (a) and ^{226}Ra (b) in surface seawater on the Guangxi shelf of the Beibu Gulf.

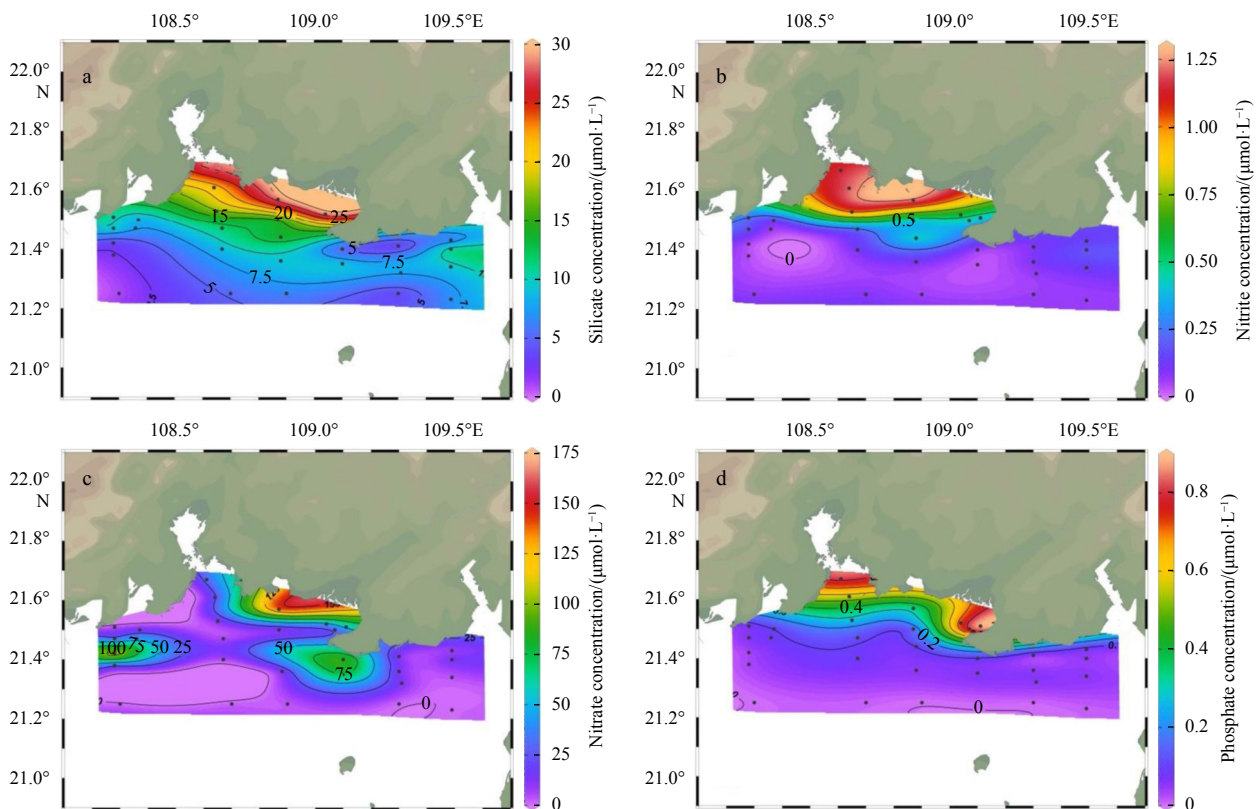


Fig. 4. Results of surface seawater testing parameters: silicate (a), nitrite (b), nitrate (c), and phosphate (d) distributions in the study area of the Guangxi shelf in the Beibu Gulf.

0.35 $\mu\text{mol/L}$ to 157 $\mu\text{mol/L}$ (Fig. 4c), with an average concentration of $(28.74 \pm 7.23) \mu\text{mol/L}$ ($n = 31$). The phosphate concentration ranged from 0.002 $\mu\text{mol/L}$ to 0.878 $\mu\text{mol/L}$ (Fig. 4d), with an average concentration of $(0.19 \pm 0.05) \mu\text{mol/L}$ ($n = 31$). The concentration of silicate ranged from 1.07 $\mu\text{mol/L}$ to 29.62 $\mu\text{mol/L}$ (Fig. 4a), and the average concentration was $(11.51 \pm 1.49) \mu\text{mol/L}$ ($n = 31$). Overall, the nutrient concentrations showed higher values in the Qinzhou Bay and Lianzhou Bay and a decreasing trend toward the offshore region. It is speculated that this finding may be related to nutrients discharged from marine fisheries (oyster culture) in local ports. In addition, the Qinzhou Bay and Lianzhou Bay have inputs from the Qinjiang River, Maoling River, Dafeng River and Nanliu River, and the nutrient concentration is similar to the variation trend in runoff (Wu, 2014). The river basin is broad, passes through the urban area and is significantly af-

ected by surrounding industrial construction and human activities. The river carries high concentrations of nutrients into the ocean, which has a significant impact on coastal waters (Li et al., 2015, 2018). In particular, the nitrate concentration in the waters near Silver Beach and Bailong Peninsula in Beihai, showed a high value area, while the silicate showed a low value area. Combined with Figs 2c and d, it was determined that the waters showed a high pH value and high DO concentration, which may be attributed to the existence of nutrient limiting factors that potentially limit the growth of phytoplankton (Wu, 2014). If phytoplankton photosynthesis is dominant, CO_2 is absorbed, resulting in an increased pH of water, and O_2 is produced, which increases DO. In general, the high nutrient concentration was mainly concentrated in the coastal sea area of the study area, and mainly distributed in the bay mouth and river estuary sea area.

4 Discussion

4.1 Influence of source and sink items on the spatial distribution characteristics of ^{222}Rn

When applying ^{222}Rn to trace the movement of water, it is necessary to identify its source-sink pattern in the study region. The sources mainly include surface runoff input, SGD, decay of ^{226}Ra , and sediment diffusion, while its loss terms mainly include its own decay, atmospheric evaporation, and mixing of seawater (Chen et al., 2018a; Colbert et al., 2008; Zhang et al., 2016). Due to the nature of escaping to the atmosphere, its own decay and other factors, ^{222}Rn usually exhibits the following order in natural aquatic systems: fresh underground water (well water) > porewater > river water > near-shore seawater > offshore seawater (Chen et al., 2018a; Zhang et al., 2016). ^{222}Rn in coastal seawater may be greatly affected by SGD and surface runoff (Chen et al., 2018a; Zhang et al., 2016).

The plot of ^{222}Rn vs. salinity (Figs 5 and 6) provides further evidence for its main sources in the study region. The ^{222}Rn activity was lowest at the offshore stations with the highest salinity, which is a typical characteristic of seawater samples. The lowest salinity samples exhibited medium ^{222}Rn activity, indicating the influence of riverine discharge. In contrast, the highest ^{222}Rn occurred in nearshore samples with salinities of 30–32. However, relatively higher ^{222}Rn activity (compared to offshore seawater) appears in the sea near the Qinzhou Bay and Beihai Silver Beach.

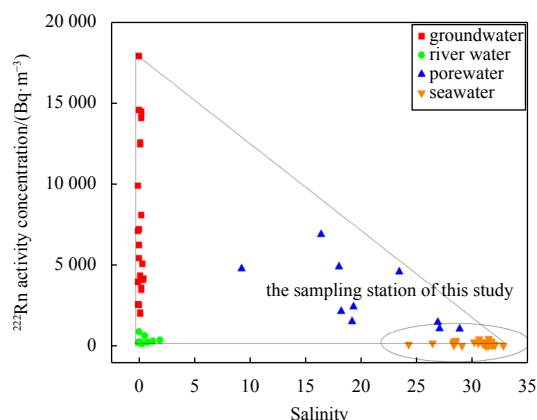


Fig. 5. Distribution of salinity- ^{222}Rn activity concentration correlation in groundwater (GW), river water (RW), porewater (PW), seawater (SW) (GW and PW data are from Wang (2020) and Chen (2019); RW and SW were sampled and tested by our team).

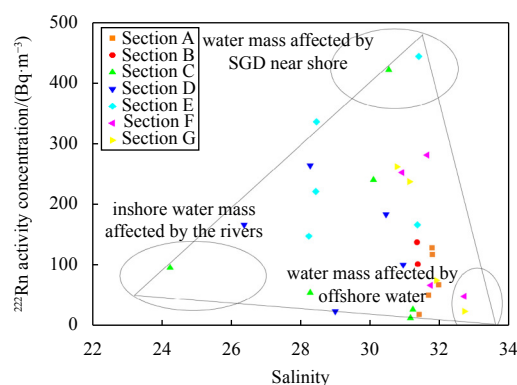


Fig. 6. Distribution of salinity- ^{222}Rn activity concentration correlation in surface seawater.

^{222}Rn activities in pore water were relatively higher ($(1.06\text{--}6.85) \times 10^3 \text{ Bq/m}^3$) along the coast of Beibu Gulf (Chen et al., 2018a, b; Wang, 2020). It is speculated that the reason for this higher value may be the input of submarine groundwater discharged from nearby coastal wetlands due to tidal rise and fall by coastal currents.

In addition, sediment diffusion and radium decay could also contribute to ^{222}Rn . ^{226}Ra , as the parent of ^{222}Rn , has particle desorption properties in saltwater environment. In subterranean estuaries, where the geochemistry is complex, the desorption process of radium also contributes to the change in ^{222}Rn activity in seawater (Zhong et al., 2023). Reportedly, the activity of ^{226}Ra in water bodies in estuaries reaches a maximum between salinities of 13 and 25, after which the activity gradually decreases due to the dilution of seawater (Zhong et al., 2023). Thus, it is possible to use Rn_{ex} activity = ^{222}Rn activity – ^{226}Ra activity to calibrate the ^{222}Rn provided by ^{226}Ra . The sediment diffusion fluctuations were steady and negligible. According to previous studies, the inventory of sediment diffusion is usually less than 1% and can be disregarded (Berelson et al., 1982; Martens et al., 1980; Zhang et al., 2016). In our study, the inventory of sediment diffusion on the northern coast of the Beibu Gulf was also disregarded.

After the introduction of a high radon water mass near shore, it further affects other sea areas by diffusion, advection and other movements. Combined with the distribution characteristics of salinity in Fig. 2b, it is observed that the salinity of nearshore surface seawater significantly changes, indicating the impact of the mixing process on the distribution of the sea water mass. The activity of ^{222}Rn in surface seawater exponentially decreases with increasing offshore distance (Fig. 7), with the most pronounced decrease within 50 km of the coastline. The activity of ^{226}Ra in the surface seawater of each section selected in this study linearly decreased with increasing offshore distance (Fig. 8). Thus, the short-lived isotopes (^{222}Rn) followed a log-linear distribution of activity, while the long-lived isotopes (^{226}Ra) followed a linear-linear distribution within 50 km of the shoreline. A similar phenomenon was also observed in other studies, while the distribution may be controlled by eddy diffusion, and offshore advection can be negligible (Su et al., 2013; Wang et al., 2021; Moore, 2000).

In addition to the sources of ^{222}Rn described above, the loss terms also affect the level distribution of ^{222}Rn and the accuracy of the calculation. The main losses of ^{222}Rn in this study are due to its own decay and atmospheric escape. ^{222}Rn diffuses from the ocean to the atmosphere through the sea-air interface, especially in the presence of more pronounced atmospheric motion. In the case of ^{222}Rn tracing seawater horizontal migration processes

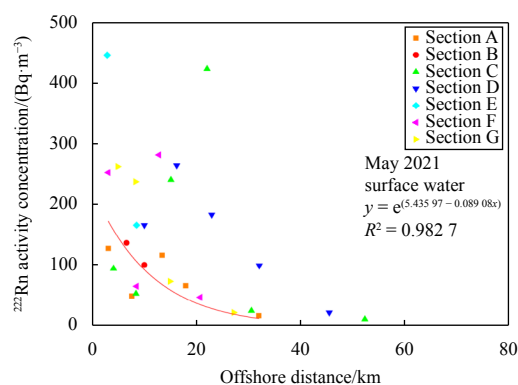


Fig. 7. Relationship between the surface ^{222}Rn activity of the Guangxi shelf area of the Beibu Gulf and offshore distance.

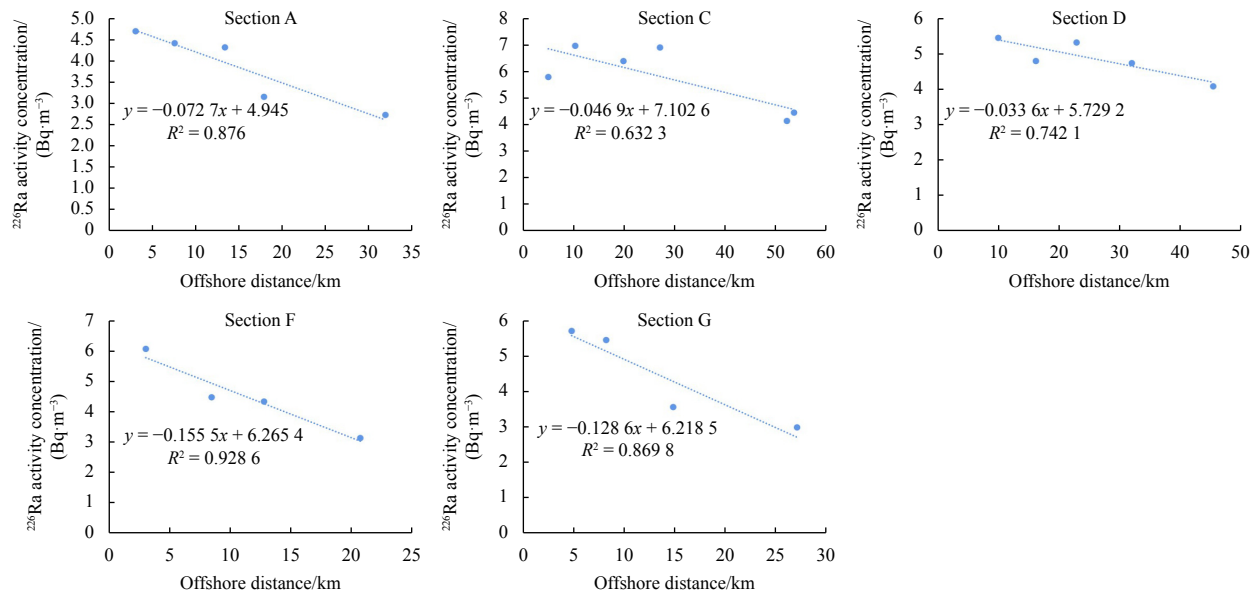


Fig. 8. Relationship between the surface ^{226}Ra activity of the Guangxi shelf area of the Beibu Gulf and offshore distance. R^2 is the linear correlation coefficient.

with large spatial and temporal scales, the atmospheric diffusion and self-decay terms cannot be disregarded, and the accuracy of the results needs to be improved by correcting these two processes with Eq. (8).

4.2 ^{222}Rn estimates the horizontal eddy diffusion coefficient

The northern bay can be regarded as a semienclosed system with possible disturbances from lateral inputs other than currents, which often limits the application of the one-dimensional model. However, ^{222}Rn shows a significant decreasing trend with increasing distance offshore, which suggests that the lateral input of ^{222}Rn from other sources to the surface seawater in the study sea is limited, especially in the sea within 50 km from the coast. Therefore, the lateral input of ^{222}Rn in this study could be disregarded. In addition to the lateral input, the ^{222}Rn of surface seawater may also have a vertical input. However, some studies have shown that the horizontal and vertical vortex diffusion coefficients differ by several orders of magnitude. Previous studies have indicated that the amount of radon transported by vertical diffusion is very small (Su et al., 2013; Wang et al., 2021). Following these studies, the effect of vertical eddy diffusion is disregarded in this study.

The ^{222}Rn -based apparent eddy diffusion coefficients of water bodies in the horizontal direction were estimated after correction of each ^{222}Rn source-sink pattern using the eddy diffusion

model. As shown in Table 2, if the influence of the atmospheric loss term and advection term in the ^{222}Rn tracer diffusion process is not considered, then the average value of the eddy diffusion coefficients of Sections A, C, D, F, and G is $(0.38 \pm 0.08) \times 10^8 \text{ m}^2/\text{d}$ according to Eq. (5). If the atmospheric loss term of the ^{222}Rn tracer diffusion process is corrected according to Eq. (10), the average value of the eddy diffusion coefficient K_h for five sections A, C, D, F and G is $(1.21 \pm 0.30) \times 10^8 \text{ m}^2/\text{d}$. These results indicated that the K_h estimated by considering atmospheric loss is 3.2 times that estimated by disregarding atmospheric loss, which reflected the importance of the atmospheric loss of ^{222}Rn .

The eddy diffusion coefficient is very sensitive to the effect of advection and is related to the advection velocity (Su et al., 2013; Wang et al., 2021; Moore, 2015; Li and Chen, 2011). Li and Cai (2011) developed a new one-dimensional advection-diffusion model to illustrate the effect of advection on diffusion: the offshore flow increases the eddy diffusion coefficient, while the on-shore flow decreases the eddy diffusion coefficient. According to Eqs (11) and (12) and by using ^{222}Rn and ^{226}Ra , the average value of the eddy diffusion coefficient K_h for Sections A, C, D, F, and G is estimated to be $(0.52 \pm 0.10) \times 10^8 \text{ m}^2/\text{d}$. The obtained advection results are substituted into Eq. (13) to correct for both atmospheric losses and the advection effects of ^{222}Rn during diffusion. Then, the average value of the eddy diffusion coefficient K_h for Sections A, C, D, F, and G is estimated to be $(1.24 \pm 0.31) \times 10^8 \text{ m}^2/\text{d}$,

Table 2. Horizontal eddy diffusion coefficients at each station in the Guangxi shelf area of the Beibu Gulf in May 2021

	^{222}Rn (considering without u and J)			Combined ^{222}Rn and ^{226}Ra		^{222}Rn (considering J)	^{222}Rn (considering u and J)
	Slope	R^2	$K_h/(10^8 \text{ m}^2 \cdot \text{d}^{-1})$	$K_h/(10^8 \text{ m}^2 \cdot \text{d}^{-1})$	$u/(\text{m} \cdot \text{d}^{-1})$	$K_h/(10^8 \text{ m}^2 \cdot \text{d}^{-1})$	$K_h/(10^8 \text{ m}^2 \cdot \text{d}^{-1})$
Section A	-0.07	0.8219	0.39	0.55	-1106	2.10	2.13
Section C	-0.05	0.4137	0.60	0.73	-743	1.69	1.72
Section D	-0.07	0.8025	0.42	0.46	-328	0.80	0.81
Section F	-0.07	0.3289	0.35	0.67	-2410	1.04	1.12
Section G	-0.12	0.9790	0.12	0.17	-518	0.41	0.42
Mean	—	—	0.38 ± 0.08	0.52 ± 0.10	—	1.21 ± 0.30	1.24 ± 0.31

Note: K_h is the average value of the eddy diffusion coefficient, h refers to the sampling depth (m) above the pycnocline layer; u is the advection velocity (m/s); J is other ^{222}Rn input or removal ($\text{Bq}/(\text{m}^3 \cdot \text{s})$); slope is the log-linear slope; R^2 is the linear correlation coefficient; — represents no data.

which is 3.3 times more than that of K_h obtained by disregarding both atmospheric losses and advection effects but is similar to that of K_h obtained by considering only atmospheric losses, indicating that advection effects have some influences on the ^{222}Rn tracer diffusion process, while the primary influence is from the atmospheric loss term.

Further, we collected the horizontal vorticity diffusion coefficients in different global sea areas, which varied by several orders of magnitude ($0.000\ 5\text{--}8.64 \times 10^8\ \text{m}^2/\text{d}$ (Table 3 and references therein). Possible reasons include the change in hydrological conditions (water depth, wind speed, and velocity) in different sea areas worldwide, the differences in sampling analysis among different research teams (sampling time and offshore distance of the transect), and the differences in tracer methods (Wang et al., 2021). The results of this study are on the same order of magnitude as those of other gulf types within the global K_h variation range.

4.3 Horizontal transport flux of ^{222}Rn

Assuming that the flux of each section represented the profile

of a section of the shoreline, and the diffusion flux of ^{222}Rn can be obtained by the ^{222}Rn activity gradients multiplied by the boundary seepage area (Moore, 1998; Colbert et al., 2008; Swarzenski and Izbicki, 2009). In this study, three sections (A, D and G) showed significant correlations between activity and distance. Assuming that the water body in the study area is evenly distributed, each section extends to the mixed layer with a length of 140 km (Google Earth) and a sampling depth of 5 m. The vorticity diffusion coefficients of the three sections (K_h) were multiplied by the concentration gradient and then multiplied by the size of the mixing layer (S) to obtain the offshore fluxes of ^{222}Rn (F_{Rn} , mol/d) under the influence of horizontal vorticity diffusion,

$$F_{\text{Rn}} = K_h \times \Delta A \times S. \quad (14)$$

The offshore fluxes of ^{222}Rn of three sections (A, D and G) were $2.98 \times 10^{12}\ \text{Bq/d}$, $2.30 \times 10^{12}\ \text{Bq/d}$ and $1.47 \times 10^{12}\ \text{Bq/d}$, respectively, with an average flux of $(2.24 \pm 0.44) \times 10^{12}\ \text{Bq/d}$ (Table 4).

To determine the primary sources of ^{222}Rn , we further estimated the average input flux of ^{222}Rn from rivers in the study area

Table 3. Horizontal eddy diffusion coefficients in major coastal areas worldwide

Study area	Methods	Season	$K_h/(10^8\ \text{m}^2\cdot\text{d}^{-1})$	Reference
Laizhou Bay	^{224}Ra	wet season	2.53	Wang et al. (2016)
East China Sea	^{224}Ra	wet season	2.93	Men et al. (2011)
		dry season	3.36	Men et al. (2011)
		dry season	2.16	Men et al. (2013)
Taiwan Strait	^{224}Ra	dry season	2.16	Men et al. (2013)
South Atlantic Bight	^{223}Ra , ^{224}Ra	wet season	0.31–0.36	Moore (2000)
Yellow Sea	^{223}Ra , ^{224}Ra , ^{226}Ra	wet season	2.53	Su et al. (2013)
Long Island Sound	^{224}Ra	wet season	0.004–0.043	Torgersen et al. (1996)
San Diego to northwest of Hawaii	^{226}Ra	wet season	0.09	Chung (1976)
Northeast Pacific	^{226}Ra , ^{228}Ra	–	0.09	Huh and Ku (1998)
		–	4.32	Huh and Ku (1998)
		wet season	0.004	Su (2013)
East China Sea	^{226}Ra , ^{228}Ra	wet season	2.22	Su (2013)
Eastern Pacific Ocean	^{226}Ra , O_2 and salinity	wet season	0.86	Ku et al. (1980)
Western Bay of Bengal	^{226}Ra , ^{228}Ra	–	0.86–8.64	Rengarajan et al. (2002)
Cross-shelf of the Bering Sea	^{228}Ra	wet season	1.90	Xing et al. (2011)
Sub-Arctic waters	^{228}Ra	–	0.43–0.86	Moore et al. (1980)
World ocean	^{228}Ra	–	0.86–8.64	Kaufman et al. (1973)
Seto Inland Sea	^{228}Ra	dry season	0.095–0.12	Kasemsupaya et al. (1993)
Western Yellow Sea	^{228}Ra	wet season	2.51	Men et al. (2006)
Southeastern Bering Sea	salt balance	wet season	0.86	Coachman and Walsh (1981)
Middle Atlantic Bight	current meter and remotely sensed data	dry season	0.026	Fischer (1980)
Western Long Island Sound	^{222}Rn	wet season	>0.04	Torgersen et al. (1997)
Catalina Harbor	^{222}Rn	wet season	0.000 5	Colbert et al. (2008)
San Nicolas Basin	^{222}Rn	wet season	0.008 6	Berelson et al. (1982)
Yellow-Bohai Sea	^{222}Rn	wet season	3.92	Wang et al. (2021)
		dry season	1.97	Wang et al. (2021)
Beibu Gulf	^{222}Rn	dry season	0.42–2.13	this study

Note: K_h is the average value of the eddy diffusion coefficient, h refers to the sampling depth (m) above the pycnocline layer; – represents no data.

Table 4. Offshore fluxes of ^{222}Rn in the Guangxi shelf area of the Beibu Gulf in May 2021

Section	R^2	$K_h/(10^8\ \text{m}^2\cdot\text{d}^{-1})$	$\Delta A/(\text{Bq}\cdot(\text{m}^3\cdot\text{m})^{-1})$	$F_{\text{Rn}}/(10^{12}\ \text{Bq}\cdot\text{d}^{-1})$
A	0.821 9	2.13	0.02	2.98
D	0.802 5	0.81	0.04	2.30
G	0.979 0	0.42	0.05	1.47
Mean	–	–	–	2.24 ± 0.44

Note: K_h is the average value of the eddy diffusion coefficient, h refers to the sampling depth (m) above the pycnocline layer; A is the ^{222}Rn activity concentration at the sampling station; F_{Rn} : the offshore fluxes of ^{222}Rn ; R^2 : the linear correlation coefficient.

Table 5. ^{222}Rn fluxes of riverine input to the Guangxi shelf area of the Beibu Gulf

River	Mean annual discharge/ (10^9 m^3)	Fresh water endmember $^{222}\text{Rn}/(\text{Bq}\cdot\text{m}^{-3})$	Average daily emission flux of $^{222}\text{Rn}/$ ($10^{10} \text{ Bq}\cdot\text{d}^{-1}$)
Beilun	29.40 ^a	$1\,859 \pm 212^c$	14.97 ± 1.71
Jiangping	7.67 ^b	640 ± 122^c	1.34 ± 0.26
Fangcheng	17.86 ^a	886 ± 149^c	4.34 ± 0.73
Maoling	16.20 ^a	234 ± 80^c	1.04 ± 0.36
Qinjiang	11.53 ^a	250 ± 80^c	0.79 ± 0.25
Dafeng	6.05 ^a	218 ± 86^c	0.36 ± 0.14
Nanliu	53.13 ^a	254 ± 74^c	3.70 ± 1.08
Total river input flux	141.84 ^a	–	26.54 ± 4.52

Note: Fresh water endmember ^{222}Rn parameter is in activity concentration. – represents no data. ^a data cited from Wu (2014); ^b data cited from Wang (2020); ^c data are from this study.

($26.54 \times 10^{10} \text{ mol/d}$) by multiplying the average annual discharge of coastal terrestrial rivers in the study area by the ^{222}Rn concentration near zero salinity (Table 5). The results indicated that the offshore fluxes of ^{222}Rn are 8.44 times that of the river input fluxes. Thus, surface runoff is not the primary source of ^{222}Rn in the coastal waters of the northern coast of the Beibu Gulf. We speculated that SGD is the most influential factor in the distribution of ^{222}Rn in the surface seawater in this study area, which is consistent with the information derived from the ^{222}Rn and salinity relationship (Fig. 5).

4.4 Horizontal transport of nutrients

Water mixing provides a pathway for the nutrient transport required by phytoplankton organisms. In this study, the concentration gradients of nutrients (ι , $\text{mol}/(\text{m}^3\cdot\text{m})$) in five sections of the study area with considerable variation were calculated and multiplied by the value of the horizontal eddy diffusion coefficient K_h to obtain the nutrient fluxes under the influence of diffusion processes, which is the diffusion flux of nutrients (F_{nutri} , $\text{mol}/(\text{m}^2\cdot\text{d})$). F_{nutri} was calculated as follows:

$$F_{\text{nutri}} = K_h \times \iota. \quad (15)$$

Then the horizontal transport fluxes of nutrients can be calculated by following formula (Su, 2013):

$$\text{Flux}(\text{mol}/(\text{m}^2 \cdot \text{d})) = F_{\text{nutri}}(\text{mol}/(\text{m}^2 \cdot \text{d})) \times \text{MLS}(\text{m}^2)/\text{SA}(\text{m}^2), \quad (16)$$

where MLS represents the size of the mixing layer (m^2), SA is the size of the entire study area (m^2). The horizontal eddy diffusion is assumed to extend to the nearshore mixed layer of approximately 140 km in length and 5 m in depth. Assuming that the hori-

zontal transport of nutrients is uniformly distributed throughout the study area (area of approximately $5.85 \times 10^9 \text{ m}^2$, Google Earth). The nutrient fluxes are $6.28 \times 10^{-3} \text{ mol}/(\text{m}^2\cdot\text{d})$ (silicate), $0.10 \times 10^{-3} \text{ mol}/(\text{m}^2\cdot\text{d})$ (phosphate), $0.20 \times 10^{-3} \text{ mol}/(\text{m}^2\cdot\text{d})$ (nitrite), and $4.15 \times 10^{-3} \text{ mol}/(\text{m}^2\cdot\text{d})$ (nitrate) (Table 6). The horizontal transport fluxes of nutrients may be overestimated because the biological uptake and removal effects of sinking particles on nutrients were not considered.

The variation in marine primary productivity in summer in the nearshore waters of Beibu Gulf, ranged from $212 \text{ mg}/(\text{m}^2\cdot\text{d})$ to $2\,160 \text{ mg}/(\text{m}^2\cdot\text{d})$ (in terms of carbon). Using the maximum value and combined with the Redfield ratio (C:N:P=106:16:1), the amounts of DIN and phosphate required to meet the growth of phytoplankton under ideal conditions were $27.19 \times 10^{-3} \text{ mol}/(\text{m}^2\cdot\text{d})$ and $1.70 \times 10^{-3} \text{ mol}/(\text{m}^2\cdot\text{d})$, respectively. Accordingly, the horizontal eddy diffusion process in this study accounted for only 7.35% of DIN and 3.52% of phosphate. The reason for this large discrepancy could be the existence of other transport pathways for nutrients. First, the SGD in the near-shore waters of the Beibu Gulf transports $50.8 \times 10^6 \text{ mol/d}$ DIN, $0.61 \times 10^6 \text{ mol/d}$ DIP, and $70.7 \times 10^6 \text{ mol/d}$ silicate, which is 5–10 times the total river nutrient input (Wang, 2020; Guo, 2020; Chen et al., 2019). In addition, the dry and wet deposition fluxes of atmospheric nitrogen in summer in this study area are $0.18 \text{ mmol}/(\text{m}^2\cdot\text{d})$ and $0.3 \text{ mmol}/(\text{m}^2\cdot\text{d})$, respectively (Guo, 2020). Furthermore, marine aquaculture wastewater discharge can supply approximately 1 478 t of ammonia nitrogen and 195 t of phosphate (Guo, 2020).

5 Conclusions

Surface runoff and SGD are the main sources of ^{222}Rn in nearshore surface seawater. ^{222}Rn can trace not only the SGD process but also the seawater mixing process. Based on the variation in ^{222}Rn activity with distance in offshore surface seawater, the vorticity diffusion coefficient in the horizontal direction of

Table 6. Horizontal transport fluxes of nutrients in the Guangxi shelf area of the Beibu Gulf

	$K_h/(10^8 \text{ m}^2\cdot\text{d}^{-1})$	Silicate $F_{\text{nutri}}/$ ($\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)	Phosphate $F_{\text{nutri}}/$ ($\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)	Nitrite $F_{\text{nutri}}/$ ($\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)	Nitrate $F_{\text{nutri}}/$ ($\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)
Section A	2.13	70.51	0.46	1.31	35.11
Section C	1.72	77.53	2.91	3.77	94.32
Section D	0.81	50.77	0.67	2.79	6.61
Section F	1.12	43.96	0.09	0.19	30.19
Section G	0.42	11.29	0.08	0.13	7.30
Mean	1.24 ± 0.31	50.81 ± 11.64	0.83 ± 0.53	1.64 ± 0.72	34.71 ± 15.99
Mixed layer area/ m^2	7.00×10^5	7.00×10^5	7.00×10^5	7.00×10^5	7.00×10^5
Study area/ m^2	5.85×10^9	5.85×10^9	5.85×10^9	5.85×10^9	5.8×10^9
Flux	–	6.28×10^{-3}	0.10×10^{-3}	0.20×10^{-3}	4.15×10^{-3}

Note: F_{nutri} diffusion flux of nutrients; – represents no data.

different sections was estimated, and then, the offshore fluxes of ^{222}Rn and the corresponding nutrient fluxes that were horizontally transported were also estimated.

By comparing the offshore fluxes of ^{222}Rn with the input fluxes of rivers, it is determined that the offshore fluxes are 7.54 times the input fluxes of rivers, which may be influenced by the input of SGD from the Guangxi coastal zone. In addition, by comparing the horizontal transport fluxes of nutrients and the content of nutrients required by phytoplankton growth in the study area under ideal conditions, we discovered that the horizontal transport of nutrients only provided 7.35% N and 3.52% P, which was insufficient to meet the material basis required by phytoplankton growth. This result shows that mixed water transport is not the only route for nutrient intake in the study area.

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