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Seasonal changes in the radium-226 distribution on the southeastern USA continental shelf: implications for changing submarine groundwater discharge

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Abstract Enrichments of radium isotopes in coastal waters have served as indicators of submarine groundwater discharge (SGD). Because coastal waters exchange with the open ocean on a time scale of weeks to months, seasonal patterns of radium isotope distribution may be used to indicate changes in SGD through the year. Here I report the seasonal distributions of ^{226}Ra measured in surface waters of the continental shelf of southeastern USA. The study area encompassed most of the South Atlantic Bight. Activities of ^{226}Ra were highest off the coast of Georgia. In summer, these high activities extended throughout the study area; but during spring and winter they decreased markedly off the coast of South Carolina. The primary source of excess ^{226}Ra (that is activities in excess of open ocean values) is SGD. Because the activities of ^{226}Ra in SGD vary little with season, the lower excess activities off South Carolina imply lower rates of SGD during the spring and winter.
Key words submarine groundwater discharge; radium; coastal ocean; nutrients

INTRODUCTION

We now recognize that submarine groundwater discharge (SGD) is an important component of the hydrological cycle because it transfers nutrients, metals and carbon to the coastal ocean (Valiela *et al*., 1990; Paeril, 1997; Cai *et al*., 2003; Windom *et al*., 2006). Recent studies have found that SGD provides a major source of nutrients to salt marshes, estuaries and other communities on the continental shelf. For example, it is estimated that the fluxes of nitrogen and phosphorus to the shelf of South Carolina and Georgia, USA, from submarine groundwater discharge exceeded fluxes from local rivers (Krest *et al*., 2000; Moore *et al*., 2002). Because nutrient concentrations in coastal groundwater may be several orders of magnitude greater than in surface waters, groundwater input may be a significant factor in the eutrophication of coastal waters.

Material fluxes from the coastal to open ocean are difficult to quantify because small scale temporal and spatial variability make these systems exceedingly complex. Chemical tracers offer promise but few techniques have been developed and tested to study this complex region. Moore (2000a,b) developed new methods based on four radium isotopes, which enable oceanographers to quantify SGD and determine fluxes of dissolved components across the continental shelf. These early studies were in July 1994, primarily along the coast of South Carolina (Moore, 1996). In this paper I investigate the distributions of ^{226}Ra across the continental shelf of the South Atlantic

Bight from Cape Fear, North Carolina, to St Augustine, Florida. The present study includes measurements during September–October 1998, April 1999, and February 2000.

EXPERIMENTAL METHODS

Samples were collected and processed using standard methods (Moore, 1976). Radium isotope measurements followed Moore (1984).

RESULTS

The results are presented in Figs 1–4, with different time periods shown on different figures. The first cruise (PW) was divided into two legs: leg 1, 6–20 September 1998 (Fig. 1), and leg 2, 22 September–3 October 1998 (Fig. 2). Cruise AW was from 9–18 April 1999 (Fig. 3); cruise FW was from 8–17 February 2000 (Fig. 4).

Surface waters in the open Atlantic Ocean contain 7–8 dpm ^{226}Ra/100L with little spatial variation (Broecker *et al*., 1976; Key *et al*., 1985). Higher activities measured in coastal waters indicate a local source. These sources include riverine input (both dissolved and desorbed from particles), regeneration and release from marine sediments, erosion of old terrestrial sediments, and submarine groundwater discharge (SGD).

Moore (1987) reported much higher near-shore ^{226}Ra and ^{228}Ra activities for samples collected in February and April compared to September–October. The station closest to shore had activities almost double the values measured at this station during the other cruises. For samples collected in July 1994, Moore (1996) reported ^{226}Ra activities on the South Carolina inner shelf in the range 15–28 dpm/100L. Activities of 10–15 dpm/100L were present between the inner shelf and the shelf break. These activities are similar to values measured in September–October 1982 (Moore, 1987) and in September 1998, leg (Fig. 1). Moore (1996) demonstrated that such high activities could not be supported by riverine or sedimentary inputs; they must result primarily from SGD.

The present study extends the temporal ^{226}Ra data set to autumn, winter and spring and the spatial data from the coast of central North Carolina to the northern Florida coast, about 80 km south of Jacksonville. The pattern during 6–20 September 1998 from Cape Fear to Crescent Beach, Florida, (Fig. 1) was similar to the July distribution along the South Carolina coast reported by Moore (1996) with activities >20 dpm/100L on the inner shelf and >9 dpm/100L over the remainder of the shelf. By late September the pattern changed significantly. The 9 dpm/100L contour was much closer to shore and near-shore activities in Long Bay (between Winyah Bay and Cape Fear) decreased from 13–18 dpm/100L to 7–8 dpm/100L (Fig. 2). These lower values are equal to the average ^{226}Ra activity in the open North Atlantic, thus there was essentially no enrichment of ^{226}Ra in near-shore Long Bay during the late September sampling period. The same was true in April 1999 when activities in the entire northern half of the study area again were not significantly enriched over the open North Atlantic with the exception of a few samples on the inner shelf (Fig. 3). The distribution off southern Georgia and northern Florida during this period were similar to the distribution in

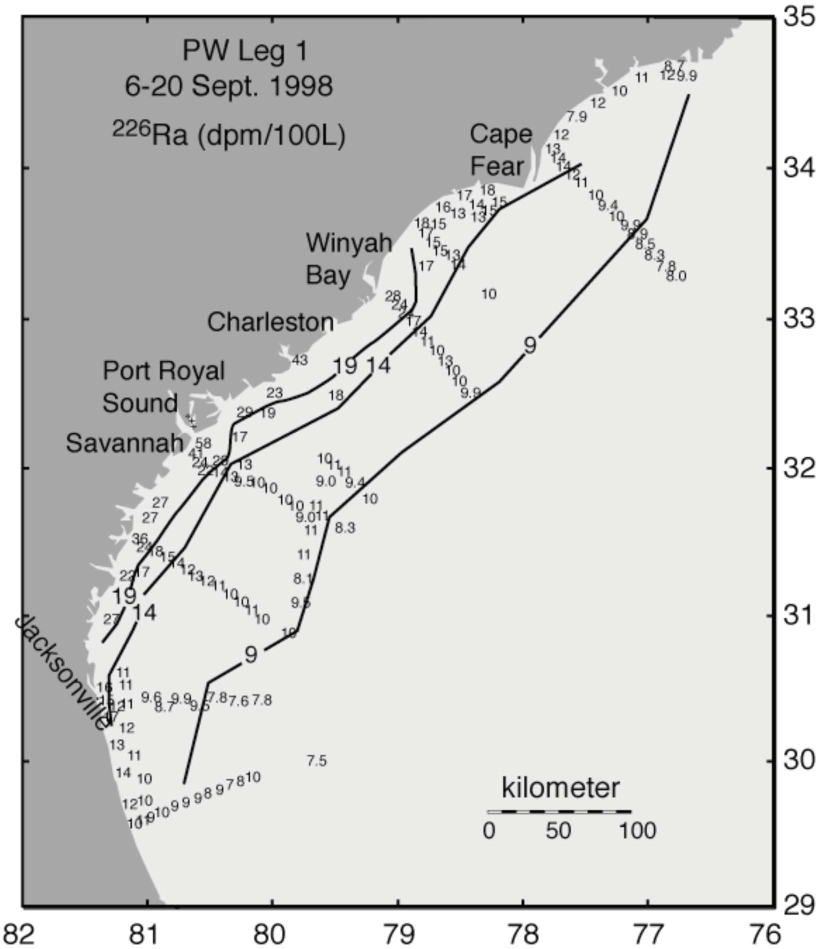

Fig. 1 The seasonal distribution of ^{226}Ra in South Atlantic Bight surface waters during early September was similar to prior studies in the summer with high enrichments throughout the inner shelf.

September–October 1998. Samples from February 2000 followed a pattern similar to April 1999, a slight enrichment in the northern half of the study area and higher enrichments in the southern half (Fig. 4).

DISCUSSION

Spatial distribution

The Georgia Bight between Port Royal Sound and Jacksonville clearly has higher activities of ^{226}Ra compared to Long Bay and Onslow Bay and Crescent Beach. Although this region has higher river runoff than the rest of the SAB, Moore & Shaw (2007) concluded that activities of ^{226}Ra in the estuaries of the major rivers of the SAB could not be explained by input from the rivers. They considered these river mouths to be "marsh-dominated", where chemical fluxes are strongly augmented by interactions with marsh pore waters.

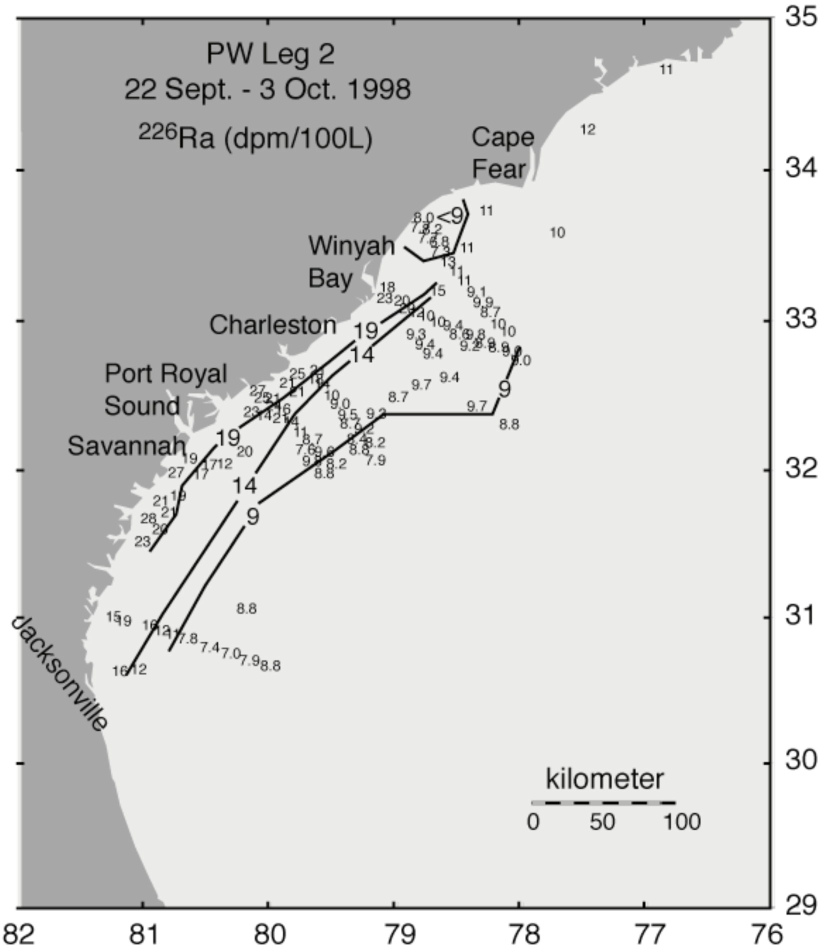

Fig. 2 By late September the high ^{226}Ra activities measured in Long Bay (between Cape Fear and Winyah Bay) had diminished to open ocean values. High activities were present off the coast of Georgia.

The tide range increases from the coast of North Carolina (average ~1 m) to the Georgia Bight, where it reaches an average of ~2 m. This leads to a much greater exchange of salty water across the estuaries and coastal marshes of the Georgia Bight compared to Long Bay, Onslow Bay, and the northern coast of Florida. Studies in these salt marshes (Rama & Moore, 1996; Krest *et al*, 2000; Crotwell & Moore, 2003; Moore *et al*., 2006; Moore & Shaw, 2007) reveal that circulation of sea water through coastal aquifers underlying the salt marshes strongly enriches the resulting SGD in radium as well as nutrients and carbon. Near shore SGD certainly is an important source of radium isotopes to the coastal waters.

Coastal marshes are not the only source of excess radium to the SAB. Moore *et al*. (2002) and Moore & Wilson (2005) demonstrated that SGD leaking from limestone on the inner shelf is another source of radium and nutrients. These studies showed that tidal pumping, storms, and buoyancy are important factors in supplying radium to overlying waters. Thus, higher tidal ranges in the Georgia Bight may increase offshore additions of radium.

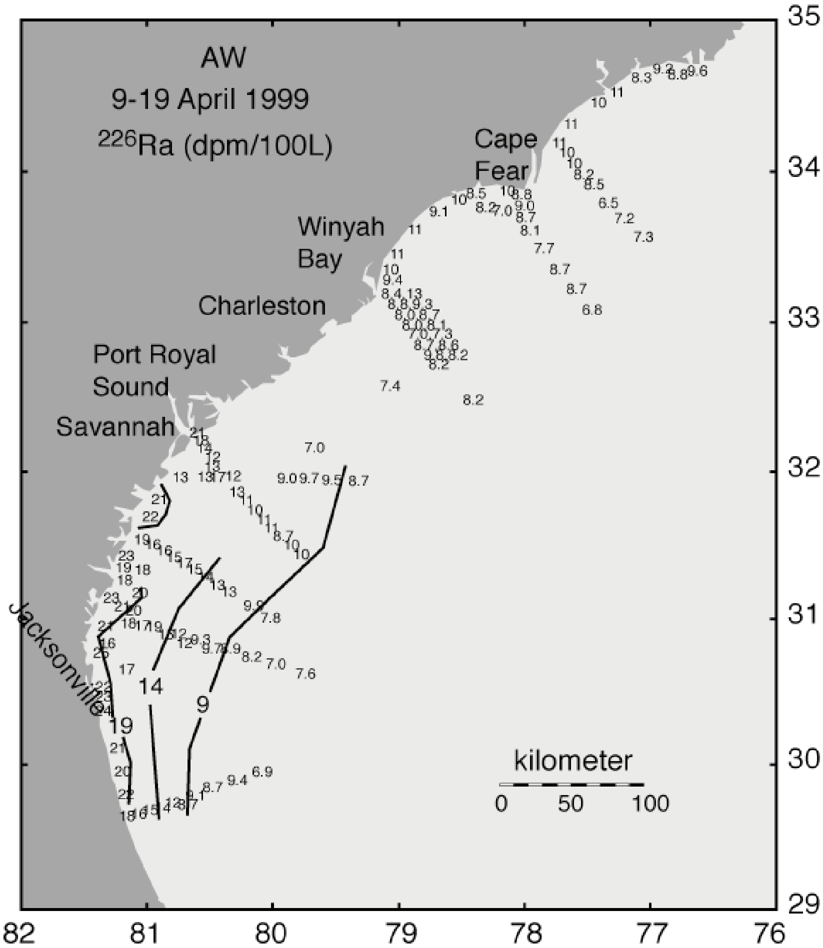

Fig. 3 In April the ^{226}Ra distribution in South Atlantic Bight surface waters was similar to late September.

Temporal changes

The most dramatic temporal changes in ^{226}Ra activity occurred between legs 1 (6–20 September) and 2 (22 September–3 October) of the 1998 cruise. In less than four weeks the inshore surface water in Long Bay (<39 km from shore) decreased in ^{226}Ra by a factor of 2 (Figs 1 and 2). During the second leg of this cruise, offshore activities of ^{226}Ra in this region were similar to those measured on leg 1. The leg 2 samples with low activity were from stations where the pycnocline had disappeared. However, the decrease in the surface activity cannot be explained by an increased mixing depth (i.e. dilution by mixing with bottom water) because deep samples from this region collected on leg 1 had activities similar to those measured in surface waters. The low leg 2 values represent a reduction in the total inventory of ^{226}Ra in Long Bay. The lower ^{226}Ra values cannot be explained by simple intrusion of low ^{226}Ra waters from offshore. The salinity of the inshore waters was lower than open ocean water and only slightly higher than salinity during leg 1. The low activity samples are lower in ^{226}Ra than samples of similar salinity collected on leg 1. There was a significant change in temperature, with leg 2 samples being up to 5° colder.

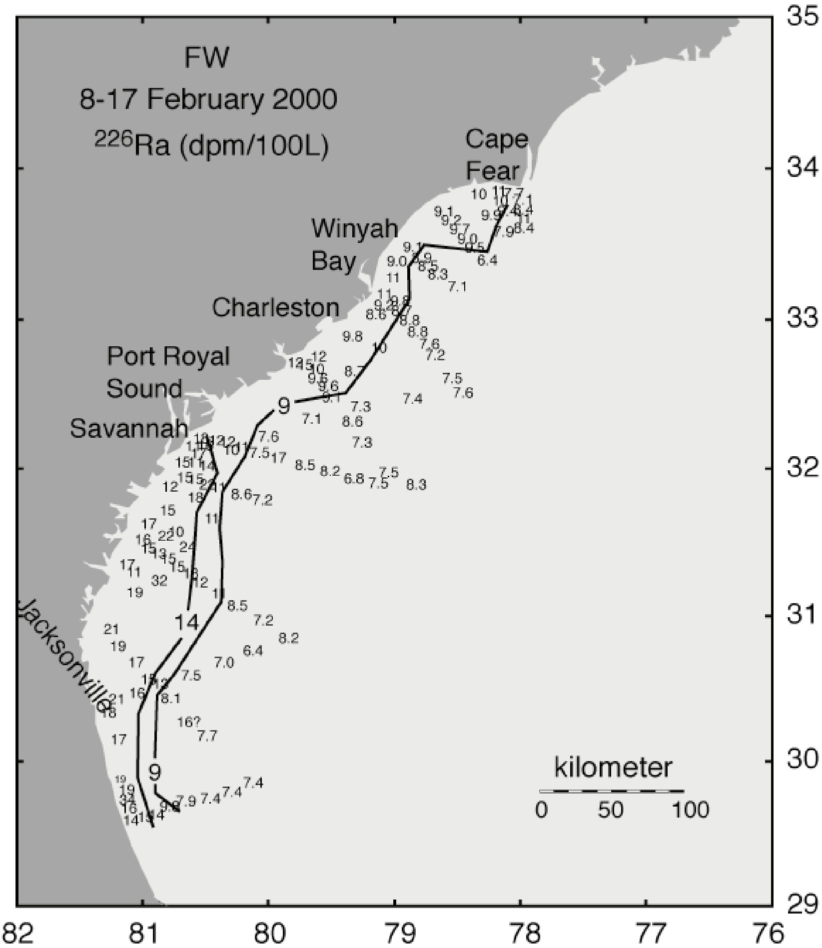

Fig. 4 A pattern similar to late September and April was present in February, with low ^{226}Ra activities in Long Bay and higher activities off the coast of Georgia.

Two processes are required to explain the data. First there must have been an exchange event that flushed the inshore water with water from the open ocean. Secondly, there must have been a reduction or cessation in SGD between the flushing event and the collection of the leg 2 samples. During this interval the salinity of the water derived from the offshore intrusion was measurably diluted by surface runoff that contained low ^{226}Ra activity. Although there are no significant rivers entering this portion of Long Bay, there are inlets to the Intracoastal Waterway that could supply the freshened water. In addition longshore drift of water leaving Winyah Bay may enter Long Bay.

In April 1999 the ^{226}Ra activity throughout Long Bay and extending to the region off Winyah Bay was considerably lower than in September–October 1998. Few values were greater than typical open ocean activities of 8 dpm/100L. Nevertheless, the salinity during each sampling was significantly lower than open ocean values. This means that the residence time of water in the area was long enough to reflect dilution with river water. The Winyah Bay transect was sampled at the start and end of the cruise; results from each transect were similar. These results imply that there must have been a reduction in SGD lasting at least a month before the cruise.

These new data reinforce the hypothesis that SGD is the primary source of the ^{226}Ra enrichment in these coastal waters. The other source functions should operate throughout the year. Indeed, rivers were flowing well and frequent storms re-suspended coastal sediments and eroded subareal sediments during the late September 1998, April 1999, and February 2000 sampling periods. The lower ^{226}Ra activities measured in the northern part of the study area during these periods indicate either a substantial reduction of SGD or a much lower activity of ^{226}Ra in the discharging fluids. Our measurements of ^{226}Ra in groundwater monitoring wells along the coast and offshore show no consistent changes with season (Moore & Wilson, 2005; Moore *et al*., 2006). Thus, the lower ^{226}Ra activities must be due to reduction of SGD.

CONCLUSIONS

The offshore excess inventories of ^{226}Ra in the South Atlantic Bight are supplied almost entirely by SGD. These inputs vary with location and time of year. Radium enrichments are considerably greater in the Georgia Bight relative to the remainder of the study area. This is especially evident in the spring and winter when activities of ^{226}Ra off the South Carolina coast are similar to open ocean activities, implying low inputs of SGD to the SC coast during these periods. Why this pattern occurs is unknown. It could be a terrestrial effect as lags between seasons of high precipitation and SGD have been reported (Michael *et al*., 2005). Or it could be a marine effect as sea level is generally higher in the summer (http://ibis.grdl.noaa.gov/SAT/hist/tp_products/topex.html), resulting in greater infiltration of sea water into aquifers.

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