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Advective flow through the upper continental shelf driven by storms, buoyancy, and submarine groundwater discharge

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Abstract

Data from monitoring wells on the Carolina, USA, continental shelf require a reevaluation of pore water exchange across the seafloor. Temperature, salinity, and ^{226}Ra data from 3 offshore wells require rapid and frequent pore water exchange to depths of several meters through sands and other permeable sediments. The exchange is driven by tidal pumping, storms, buoyancy, and submarine groundwater discharge. Tidal pumping causes semidiurnal temperature cycles in one well that can only be explained by rapid fluid flow. The effect of large storms is evident in sudden temperature changes 2–4 m below the seabed in two wells. These changes require considerable pore water exchange. Sudden cooling of the ocean may cause pore waters to become buoyant with respect to the ocean and trigger pore water convection to several meters depth as observed in one well. The wells also display frequent large (factor of ten) changes in ^{226}Ra activity. This requires a substantial input of ^{226}Ra-enriched fluids to replace ^{226}Ra that is lost during exchange events. These data support a fourth flow process, which is groundwater seeping from the underlying limestone. The pore spaces in the overlying sand provide a temporary reservoir for these fluids. We conclude that pore water residence times in 2–4 m thick sands on this continental margin are on the order of a few months or less.

Keywords: submarine groundwater discharge; pore water advection; thermal simulation; South Atlantic Bight; Radium

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1. Introduction

Water moves through permeable rocks and sediments in response to pressure and density gradients. At the continent–ocean margin, these gradients may be generated locally, e.g. hydrothermal vents, or induced from the land, e.g. coastal submarine springs. These are two examples of visible, sometimes spectacular, discharge into the sea. More subtle exchange through permeable materials occurs in response to weaker, often fluctuating, pressure and density gradients. Although such exchange may not be as obvious, the effect on the ocean may be much greater [1].

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Numerous workers [2–6] have shown that ocean currents and waves induce flow through the upper (1–10 cm) layers of permeable sands on the continental shelf. Huettel et al. [4] used flume experiments to demonstrate that fluctuating boundary flows caused rapid exchange of dissolved metals and nutrients at sediment depths up to 10 cm. Jahnke et al. [7] measured high rates of benthic primary productivity on the Georgia continental shelf that required considerable non-diffusive pore water transport of nutrients. These studies, and many more, have established that pore water in the upper 10 cm of sandy sediments exchanges rapidly with the ocean.

Others have shown that tidal pumping exchanges seawater with deeper (2–4 m) semi-confined aquifers on the continental shelf [8]. The effects of tidal pumping have even been recognized in sealed boreholes deep in the ocean crust established by the Ocean Drilling Program [9]. Models have also established that tides affect seawater–groundwater exchange in coastal aquifers [10–12].

There has been less attention to storm-driven flow through deep layers of permeable sediments. Considerations of the effects of storms on the seabed usually focus on suspension and redistribution of bottom sediments.

Density differences provide another driving force for seawater–porewater exchange. Kohout [13] invoked large-scale geothermal convection to explain anomalous temperature profiles through the Florida platform. He reasoned that geothermal heating was causing fluids in the central platform to rise. Along the deep margins of the platform, cold seawater was being drawn into the platform to replace the rising water. Wilson [14] simulated this effect on continental shelves and concluded that deep geothermally-driven fluid flow is likely widespread on passive margins. Small scale buoyancy-induced flow through permeable sediments has not been widely recognized. In one of the few papers on the subject, Webster et al. [15] demonstrated water exchange through sandy sediments in an estuary occurs in response to salinity variations in the overlying waters. Grigg et al. [16] found through experiments and models that pore water samplers called peepers may deplete major ion concentrations adjacent to the face of the sampler. This depletion occurs because ions diffuse into the chamber, inducing a salinity gradient that drives convection.

In this paper we document the effects of storms on the exchange of fluids from semi-confined permeable zones several meters below the sea bed. We also provide additional evidence of the role of tidal pumping in deep exchange. We show that exchange of pore waters in sandy sediments may be driven by sudden temperature changes in the overlying ocean that cause the pore waters to become less dense than the overlying ocean water. Finally, we present model results and ^{226}Ra data that require leakage of groundwater from the underlying limestone.

2. Study site

For this study we used 3 monitoring wells set through sandy sediments to limestone basement about 20 km offshore of Holden Beach, N.C. (Fig. 1). The stratigraphy at each well site is different. Two of these wells (1 and A) have a clay confining layer between the sand and limestone. One of these wells (well 1) was described earlier [8]. At well 1 sediments consist of 1 m of sand/shell overlying a 1 m thick clay confining layer. Between the confining layer and the limestone is a high porosity zone, which may be an active karst surface. Evans and Lizarralde [17] have described the area as a region of subsurface karst formation. Their seismic profiles clearly show the confining layer encountered at well 1 and nearby breaches in the layer. They conclude that the limestone in this area is an offshore extension of the Castle Hayne aquifer, the most productive aquifer of coastal North Carolina.

Well A is about 3.5 km NW of well 1. Here the limestone is closer to the surface and the high permeability zone is much thinner than well 1. Well 2 is 6 km west of well A. Unlike wells 1 and A, well 2 does not have a thick confining layer or a high porosity zone above the limestone. Clay stringers were encountered during installation of well 2, but no compact confining layer was encountered. Thus well 2 provides an example of a breach in the offshore clay confining layer where direct exchange between the limestone aquifer and overlying ocean is inhibited only by permeable sands. Fig. 2 is a hypothetical cross section approximately west to east across wells 2, A, and 1. We recognize that this figure is a highly simplistic representation of a geologically complex