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Seepage rate variability in Florida Bay driven by Atlantic tidal height

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Abstract. Atlantic tidal fluctuations drive pressure head variations in shallow offshore wells drilled into the limestone subsurface on both the Florida Bay and Atlantic sides of Key Largo, Florida, USA. We tested the hypothesis that these pressure head variations influence groundwater flow and that flux rate variability is associated with tidal variability. We used an automated Rn monitor to make continuous measurements of ^{222}Rn, a natural tracer of groundwater discharge, in Florida Bay waters. We also deployed three types of seepage meters, including an automated heat pulse meter to collect a continuous record of seepage from the sediments. Drum type seepage meters inserted into soft sediments and fiberglass meters cemented to the rocky bay floor were utilized with pre-filled 4-l bag collectors, and monitored on an hourly basis. Maximum Rn inventories in Florida Bay waters were associated with high tide on the Atlantic side of the island. Modeling of the Rn variation indicated variable groundwater discharge rates with maximum flux occurring at high Atlantic tide. Seepage meter results in Florida Bay were consistent with ^{222}Rn modeling. Florida Bay seepage meter rates showed positive correlation with Atlantic tide, meter 1, $r = 0.63$, $n = 12$, $p < 0.025$ and meter 2, $r = 0.67$, $n = 12$, $p < 0.025$. A seepage meter offshore of the Atlantic side of Key Largo exhibited rates that were inversely correlated with Atlantic tide ($r = 0.87$, $n = 9$, $p < 0.005$) showing negative rates when the tide was high, and positive rates when the tide was low. Overall, our results are consistent with the hypothesis of Reich et al. (2002), that pressure head variations driven by Atlantic tide influence groundwater seepage rate variability in Florida Bay off Key Largo. Effectively, as proposed by Reich et al. (2002), Key Largo functions as a semi-permeable dam separating Florida Bay and the Atlantic Ocean.

Introduction

Recent declines in water quality and the health of seagrass beds in Florida Bay and the coral reefs in the Florida Keys National Marine Sanctuary have focused attention on sources of nutrients to these systems. One possibility is that submarine groundwater discharge (SGD) plays a role in delivering excess nutrients. We follow the definition of Burnett et al. (this issue), that is, SGD is any flow of water up across the sea floor regardless of driving force or salinity. Groundwaters in the shallow subsurface contain dissolved nutrients from both organic materials disseminated within the matrix (Sansone et al. 1990) and are further contaminated from on-site sewage disposal systems. Sewage in the Florida Keys is discharged into more than 600 disposal wells that penetrate the permeable Key Largo Limestone to depths of 10–30 m. Additionally there are an estimated 24,000 septic tanks and 5000 cess pits on the islands (US-EPA 1996). Natural tracers, including ^{15}N of seagrass tissue, have indicated that the greatest impact of groundwater discharge is along the shore of the Florida Bay side of the upper Keys (Corbett et al. 1999).

Groundwater on Key Largo is mostly saline (Shinn et al. 1994) due to the high hydraulic conductivity of the Key Largo limestone, one of the regions most permeable. Meteoric freshwater lenses exist on some of the lower Keys due to the lower permeability of the Miami Oolite compared to the Key Largo Limestone of the upper Keys (Vacher et al. 1992). On Key Largo a 1–2 m thick brackish lens (13 ppt) has been observed in the center of the island (Reich et al. 2002), similar to lenses observed on some other of the upper Keys (Silveira et al. 1987). Studies employing viral and chemical tracers have documented horizontal and vertical transport rates of meters per day for water flow in the subsurface (Lapointe et al. 1990; Paul et al. 1995, 1997, 2000; Dillon et al. 1999, 2000; Reich et al. 2002). Hydraulic conductivity in the Key Largo limestone ranges between 1400 and 38,000 m per day (Fish and Stewart 1990; Vasher et al. 1992; Dillon et al. 1999). The porous nature of the Key Largo Limestone was demonstrated by Dillon et al. (1999) who followed the water table height as a function of Atlantic tide in a well onshore on Key Largo. In this well, the groundwater table oscillated with Atlantic tide with only a 1.4 h lag between Atlantic high tide and the highest water level in the well (Dillon et al. 1999). There was a 60% damping of the tidal amplitude as the pressure wave moved through the carbonate rock.

On an average basis the water level in Florida Bay is several centimeters higher than the water level in the Atlantic (Reich et al. 2002). However, the Atlantic has a tidal range of 0.8 m, while water levels in Florida Bay are relatively constant over daily time scales. Therefore, during a high Atlantic tide the ocean level is higher than the Bay water surface, so there is pressure differential pushing water from the Atlantic towards Florida Bay. In contrast, when the Atlantic tide is low, the situation is reversed, and there is pressure differential pushing water from Florida Bay towards the Atlantic (Halley et al. 1997; Reich et al. 2002) (Figure 1).

Reich (1996) developed an underwater manometer for measuring head pressures relative to the sea surface on underwater wells. Well pressure heads of roughly ± 10 cm water height were measured relative to the bay/sea surface on both sides of Key Largo. Changes in these pressures were driven by variations in Atlantic tide. Due to these observations, Shinn et al. (2002) hypothesized that they should observe variations in seepage rate associated with variations in the Atlantic tide in a large number of seepage meters cemented onto the limestone surface on both sides of Key Largo. However, they failed to observe negative seepage rates, aquifer recharge, even when well head pressures were lower than the surface of Florida Bay or the Atlantic. They attributed the lack of measurable recharge to seepage meter artifacts associated with wave and current activity. Shinn et al. suggested that the persistent positive flows that they observed in seepage meters were due to a Bernoulli type effect that caused pumping of shallow pore fluids out of the sea floor

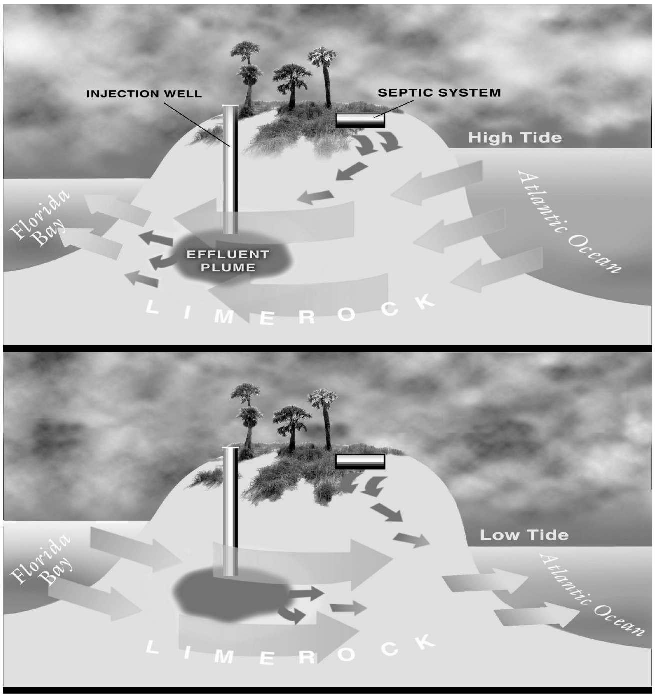

Figure 1. Model of Reich et al. (2002). Variations in Atlantic tide control subsurface head pressures. When Atlantic tide is high, there is a pressure force pushing water towards Florida Bay, which has relatively constant water level. When Atlantic tide is low, there is a pressure force from Florida Bay towards the Atlantic. From FSU Research in Review, Frank Stephenson, ed., used with permission.

(Huettel and Gust 1992; Huettel et al. 1996, 1998). Current flow effects on seepage meter measurements have also been discussed by Libelo and MacIntyre (1994).

The objective of our study was to test the hypothesis that groundwater seepage on the Florida Bay side of Key Largo is influenced by Atlantic tidal variations that are known to drive pressure fluctuations in the subsurface. We tested the hypothesis that pressure head fluctuations observed in shallow wells drilled into the limestone expressed themselves in groundwater flux rate variability. Because the upper 1.5 m of limestone underlying Florida Bay is significantly less porous and permeable than the underlying rock (Shinn et al. 1994), groundwater flux driven by tidal height fluctuations may be retarded or not expressed (Shinn et al. 2002). Impermeable caliche layers often cap the limestone in the Keys. We used a new automated Radon monitor (Burnett et al. 2001) to make continuous measurements of ^{222}Rn, a natural tracer of groundwater discharge (Cable et al. 1996a,b; Corbett et al. 1999, 2000), in the waters of Florida Bay and modeled its variation to calculate variations in groundwater seepage. We also deployed two automated heat pulse seepage meters (Taniguchi and Fukuo 1993) to collect a continuous record of seepage in the sediments and attempted to evaluate possible wave and wind artifacts by placing one of these meters over a plastic barrier covered with sand to act as a control. Drum and fiberglass type seepage meters were also deployed with pre-filled bag collectors (Cable et al. 1997), and monitored on an hourly basis.

Methods

In August 1996, hydrostatic pressure was measured in two submerged 6-m wells on both the Atlantic and Florida Bay sides of Key Largo (locations 3 and 4, Figure 2(A)). Measurements were made as a function of Atlantic tide using the methods of Reich (1996). Well head elevation were determined relative to Atlantic sea level on the Atlantic side of Key Largo and relative to Florida Bay level on the Bay side of the Key. Simultaneously seepage was measured in four fiberglass meters that had been cemented to the rocky sea floor on either side of the island (Shinn et al. 2002). The wells and seepage meters were roughly 10 m offshore in water a meter deep. Drum-style seepage meters (Cable et al. 1997) were deployed in October 1995 offshore of Hammer Point in peaty sediments (site 5, Figure 2(B)) along the Florida Bay side of Key Largo. Water flux in both types of manual meters was measured on an hourly basis with 4-l plastic bags pre-filled with 1 l of seawater. Negative water flux (into the bay-bed) could be determined if the collector bags lost water.

Two Taniguchi-style automated heat pulse seepage meters (Taniguchi and Fukuo 1993), connected to chambers made from 15-cm top or bottom sections of 55-gallon drums, were deployed about 50 m offshore (site 2) in April 2001. One meter was pushed into a sandy portion of the bay bottom while the other meter was implanted into sand, which was placed into a child's plastic swimming pool. This experiment served as a control, assuming that the plastic would prevent any seepage from entering the automated meter.

At the same time (April 2001), two automated radon monitors (Burnett et al. 2001) were deployed at the seaward ends of docks at two private houses on Florida Bay about 7 km apart (sites 1 and 2, Figure 2(B)). In both cases these docks extended about 50 m offshore with a water depth at the seaward end of ~ 1.5 m. A submersible pump was set about 50 cm over the bottom at each location. The seawater, at a flow rate of $\sim 2 \mathrm{l/min}$, was continually supplied to an air–water exchanger where it was mixed with a circulating stream of air which was directed to and analyzed by an atmospheric radon monitor. We also monitored continuously the water level, air and water temperature at each location. Wind speed was obtained from a NOAA buoy (Molasses Reef) about 10 km to the south of our stations.

Variations in the continuous radon record were then used to calculate rates of groundwater seepage by preparing a dynamic water column radon budget with the unknown term being radon supplied by seepage (c.f. Corbett et al. 2000). At steady state, the Rn mass balance can be expressed as

$$J_{\mathrm{benthic}} + \lambda N_{\mathrm{Ra}} - J_{\mathrm{atm}} - \lambda N_{\mathrm{Rn}} \pm J_{\mathrm{hor}} = 0.$$

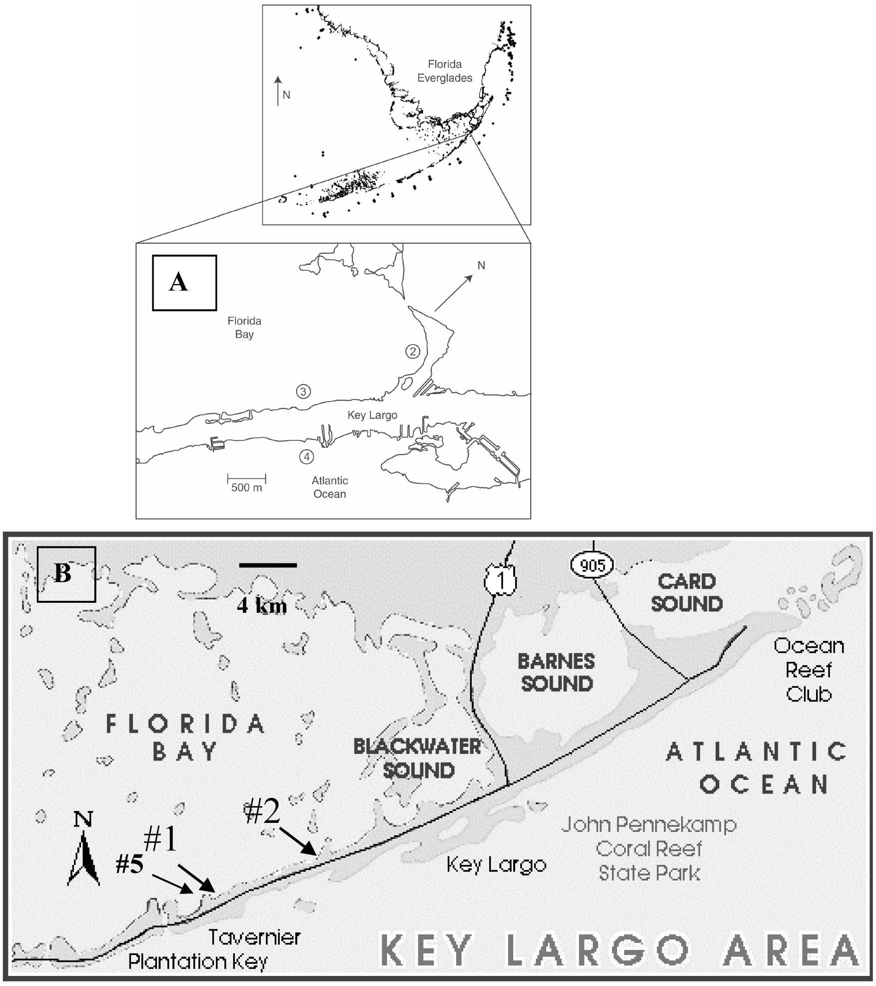

Figure 2. Upper panel (A) is an expanded map showing the location of intensive sites where well and seepage meters were cemented to the seafloor (sites 3 and 4). The automated seepage meters and Rn detector were at site 2. A larger area map (lower panel, B) shows the location of site 2 again and also site 1 where a second continuous Rn detector was placed. Site 5, Hammer Point, is where drum type meters were placed.

The term $J_{benthic}$ represents the combined advective (J_{seep}) and diffusive (J_{diff}) flux of Rn to the overlying water column, λ is the decay constant of ^{226}Ra or ^{222}Rn and λN_{Ra} and λN_{Rn} account for the production and decay of radon in the water column, respectively. J_{atm} is the flux of Rn to the atmosphere, and J_{hor} is the horizontal mixing of Rn into or out of the study area.

We made allowances for losses due to atmospheric evasion, diffusive flux from the sediments and mixing with lower concentration waters offshore. Our procedure for estimating groundwater fluxes from continuous radon measurements in the coastal zone may be summarized by the following steps:

(1) ^{222}Rn inventories were calculated for each hourly measurement by multiplying the excess ^{222}Rn activity (dpm/m^3) by the water depth (m) = (dpm/m^2). Excess ^{222}Rn (total ^{222}Rn minus ^{226}Ra) activities in the water column were estimated from spot measurements of ^{226}Ra using the Rn in-growth method (Cable et al. 1996a,b). We considered loss by radioactive decay negligible because of the short duration between the time steps in our measurements, that is, 1 h. Since tidal level did not vary significantly in Florida Bay over the experiment, inventory changes were driven by concentration changes.
(2) Inventories were corrected for atmospheric evasion losses during each measurement interval. The total flux across the air–water interface depends on the molecular diffusion produced by the concentration gradient across this interface and turbulent transfer, which is dependent on physical processes, primarily governed by wind speed. We used equations presented by Macintyre et al. (1995) that relate gas exchange across the sea–air interface to the gradient in radon concentration, temperature, and wind speed. All relevant parameters to assess atmospheric exchange were either measured or acquired including continuous measurements of the atmospheric radon concentration (ranged from <30–170 dpm/m^3 during this study). The ^{222}Rn activity in the coastal waters, is assumed to be well mixed in these shallow coastal waters so the activity at the surface is assumed to be the same as that measured by the radon monitor.
(3) Diffusive flux from the sediment was estimated by a one dimensional vertical advection–diffusion model following and using the parameters of Corbett et al. (2000).
(4) Horizontal mixing losses were not measured directly but estimates were made based on inspection of the change in the measured inventories (corrected for atmospheric loss) over time. These 'net' ^{222}Rn fluxes were determined by evaluating the change in inventories (dpm/m^2) over each 1-h time interval. Calculation of the net fluxes of radon in the study domain without consideration of the mixing losses shows major positive spikes in the data about 24 h apart and occasional negative fluxes. We assume that these apparent negative fluxes are due to mixing processes with lower concentration waters offshore. We estimated these losses for different periods based on the maximum absolute values of the negative fluxes. These estimates should thus represent conservative (lower) estimates of the mixing losses as they are based on measurements of remaining radon inventories present at any one time. Higher losses could be compensated for by higher input fluxes at the same time. These estimated losses are then added to the measured net fluxes to derive total input fluxes to the study domain. Burnett and Dulaiova (2003) recently showed that mixing losses estimated in this manner agreed closely with independently assessed offshore fluxes based on the distribution of radon and short-lived radium isotopes in a coastal setting in the northeast Gulf of Mexico.

(5) To convert radon flux estimates to water flux, we simply divide by the radon pore water concentration. This concentration was determined by use of sediment equilibration measurements (Corbett et al. 1998) and direct measurements from shallow wells in the Key Largo area (Corbett et al. 1999). Fortunately, these estimates showed that ^{222}Rn was very uniform in the shallow groundwater (398 ± 24 dpm/l, $n = 73$; Corbett et al. 1999) as well in the Florida Bay sediments based on sediment equilibration (400 ± 120 dpm/l; Corbett et al. 2000). A more complete description (including a listing of equations) of the calculations and corrections for estimating SGD rates based on continuous radon measurements may be found in Lambert and Burnett (2003) and Burnett and Dulaiova (2003).

Results and discussion

Hydrostatic pressure in two 6 m deep wells in 1 m deep water on both sides of Key Largo varied with Atlantic tide (Figure 3) as was also observed by Reich et al. (2002). When Atlantic tide was high, there was hydrostatic pressure forcing water from the Atlantic towards Florida Bay. Atlantic side well head pressures were lower than the level of the Atlantic surface indicating recharge. Simultaneously, Florida Bay well head pressures were greater than the bay surface level indicating discharge. When Atlantic tide was low, pressure was from Florida Bay towards the Atlantic. Atlantic well pressure was above the surface water level indicating discharge while Florida Bay wells had water levels below the bay surface level indicating recharge. Seepage meters located adjacent to the Florida Bay wellhead responded to the head pressure in a direct fashion, although negative rates were not observed here. Both Florida Bay seepage meter rates showed positive correlation with Atlantic tide, meter 1, $r = 0.63$, $n = 12$, $p < 0.025$ and meter 2, $r = 0.67$, $n = 12$, $p < 0.025$. A seepage meter offshore of the Atlantic side of Key Largo exhibited rates that were inversely correlated with Atlantic tide ($r = 0.87$, $n = 9$, $p < 0.005$) showing negative rates (recharge) when the tide was high, and positive rates (discharge) when the tide was low. A second seepage meter on the Atlantic side showed uniform slightly positive rates over the tidal cycle with no correlation with tide. Presumably the second meter was located over a dead impermeable spot. Seepage meters located at Hammer Point (site 5, Figure 2) showed positive and negative seepage rates corresponding to the tides, with positive seepage occurring with high Atlantic tide and negative rates with low Atlantic tide (Figure 4).

Both the radon in Florida Bay water at site 1 and 2 showed generally increasing concentrations during the experimental period with a definite 24-h periodicity in the data (Figure 5). Frequency analysis using the Fourier Analysis program in Matlab (a product of the Mathworks, Boston, MA, http://www.mathworks.com), indicated that the power in the record was concentrated near 24 and 12 h in both the tide and Rn data, although the power at 24 h was stronger in the Rn data. The concentrations of ^{222}Rn ranged from about 2–10 dpm/l at site 1 and were considerably higher at 8–16 dpm/l at site 2. The inventories of radon (concentration times water depth)

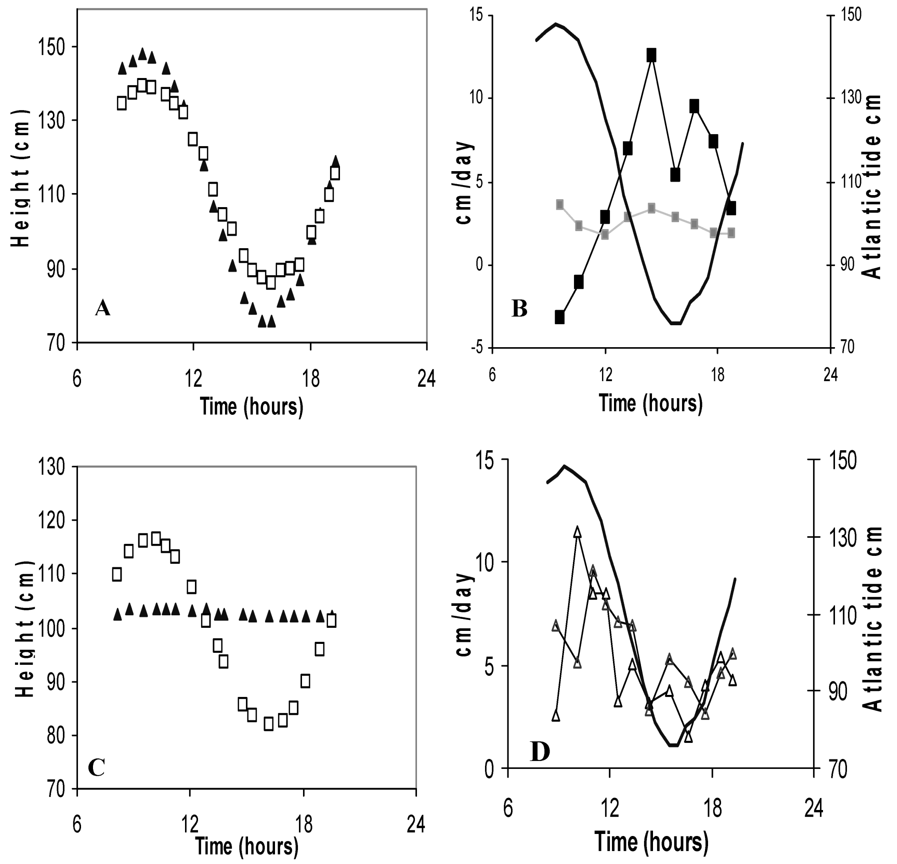

Figure 3. Panel A: Atlantic water depth (solid triangles), and Atlantic well head pressure (open squares) at site 4. Note that well pressure is below the surface of the Atlantic at high tide, indicating recharge and above it at low tide, indicating discharge. Panel B: Seepage rate (cm/day) at 2 meters at site 4, Atlantic side of the Key. Negative rates indicate downward water flux, recharge, while positive rates indicate upward flux, discharge. The Atlantic tide (water level) is shown for reference as a line. Panel C: Florida Bay water level (solid triangles) and Florida Bay well head pressure (open squares) site 3. Florida Bay well head pressures were in phase with the Atlantic tide. Panel D: Seepage rate (cm/day) at 2 meters at site 3, Florida Bay side of the Key (open triangles). Atlantic tide (water level) is shown for reference as a line. Both Florida Bay seepage meter rates showed positive correlation with Atlantic tide, $r = 0.63$, $n = 12$, $p < 0.025$ and $r = 0.67$, $n = 12$, $p < 0.025$. Atlantic side rates (Panel B, darker squares) were inversely correlated with Atlantic tide ($r = 0.87$, $n = 9$, $p < 0.005$).

showed essentially the same pattern as the concentrations since the water depth changes very little in this area of Florida Bay (Figure 6). The trend of increasing Rn concentrations at both sites over the study period could have been due to an increase in the maximum Atlantic tidal height (Figures 6 and 7). Higher tidal heights would create greater hydrostatic pressure to drive more groundwater (and thus more Rn) through the subsurface into the Bay.

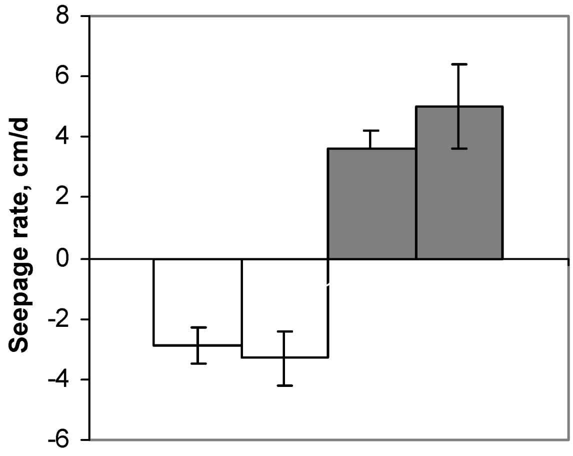

Figure 4. Florida Bay mean seepage rates determined from drum type meters at Hammer Point (site 5, Figure 2(B)) with pre-filled plastic bag water collectors checked hourly. Open bars were measurements conducted during low Atlantic tide while dark bars were conducted during high Atlantic tide. Error bars represent standard deviation of replicate measurements. Negative seepage rates indicate recharge, while positive rates indicate discharge.

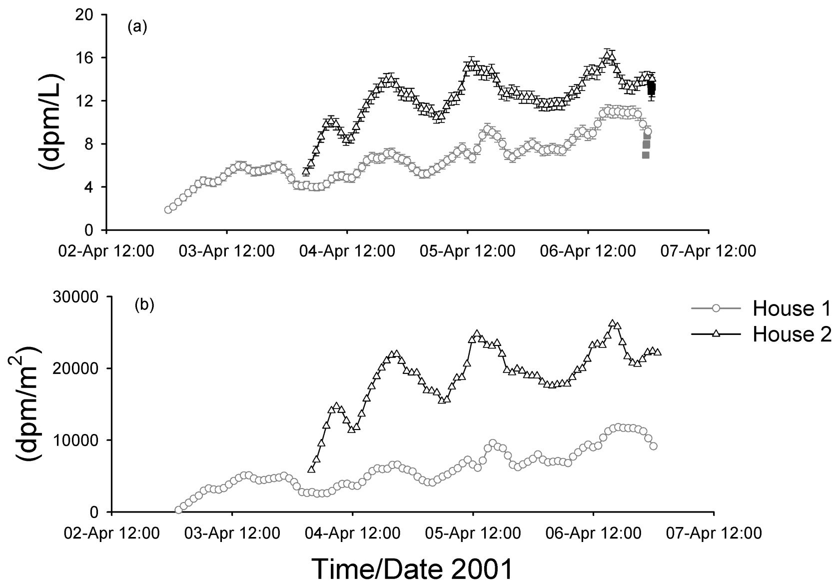

Figure 5. (a) Concentrations (3-point smooth) of ^{222}Rn in Florida Bay waters at site 1 and 2; and (b) Inventories of ^{222}Rn from the same two locations. Note the strong concordance between the two sites. The two sites are approximately 7 km apart. The black and gray filled squares in 'a' refer to grab sample analyses of radon in the nearshore waters at sites 1 and 2, respectively. Error bars in Figure 5(a) represent $\pm 1\sigma$ counting errors.

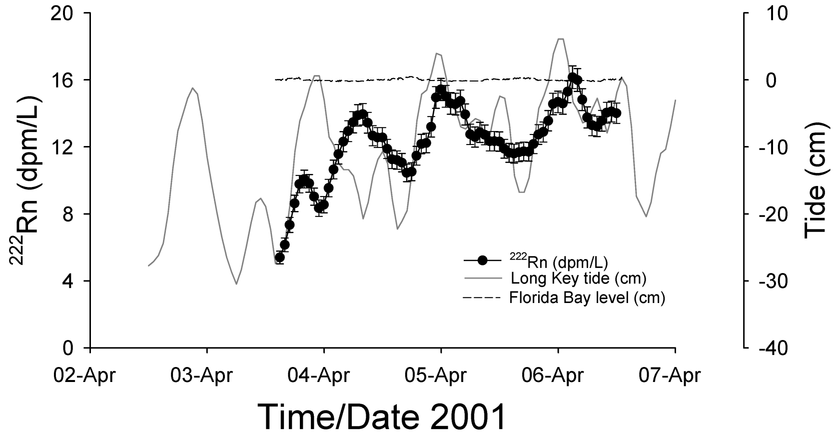

Figure 6. Concentrations of ^{222}Rn in Florida Bay waters, site 2 (left-hand scale) and the water levels in Florida Bay and the Atlantic, off Long Key (right-hand scale). The Atlantic tidal data are relative to mean sea level (downloaded from NOAA's National Ocean Service web page, http://www.ndbc.noaa.gov/Maps/Florida.shtml) while the Florida Bay water level is simply relative to its own mean value during the measurement period. The two water levels are not tied to a single reference level.

Rn concentrations in Bay waters appear to be responding to periodic inputs of subsurface waters, which contain elevated radon concentrations. According to measurements made in several wells throughout Florida Bay as well as on land, the saline subsurface waters average 398 ± 24 dpm/l ($n = 73$) in ^{222}Rn (Corbett et al. 1999). The periodicity in the radon signal appeared to be related to the tidal pattern on the ocean side of the keys. While the tides are mixed and semi-diurnal, rather than diurnal, the higher high tide was clearly dominant throughout the period investigated (Figure 6).

It is clear that Florida Bay shows almost no tidal fluctuation while the tidal oscillation approachs ~ 80 cm in the Atlantic (Figure 6). While the different references prevent the two water-level records from being compared directly on an absolute basis, it is clear that there are periods when sea level would be higher on the Atlantic side of Key Largo than the Florida Bay side. Unfortunately, we were unable to have a survey completed to tie the two records to a common datum. The diurnal difference in water level between the Atlantic Ocean and Florida Bay suggests the possibility that a hydraulic gradient could be set up across the island resulting in flow into and out of Florida Bay through the permeable limestone at periodic intervals. Such flow is consistent with the observations of Dillon et al. (1999) who noted that the back and forth movement of SF_6 laden groundwater plumes in the Key Largo subsurface appeared to be driven by Atlantic tide. The surface of the groundwater table clearly oscillated with Atlantic tide (Dillon et al. 1999). The question as to how much of the SGD is recirculated surface water and how much of it is directly released groundwater is difficult to answer, and depends

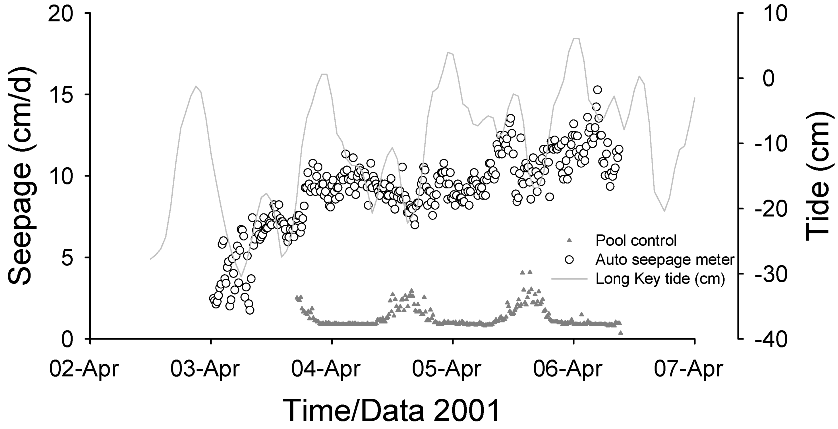

Figure 7. Variation of seepage as recorded by two automatic seepage meters at site 2 (left-hand scale) and the water levels in the Atlantic, off Long Key (right-hand scale). The 'control' was an automatic seepage meter placed into a sand-filled plastic swimming pool on the seabed a short distance from the meter emplaced directly into the sand.

upon the mixing of seawater and groundwater within the aquifer. In a sense, as soon as seawater is advected into the aquifer, it becomes groundwater, and as the subsurface water in Key Largo is saline, it all originated as seawater. As discussed by Reich et al. (2002), tidal pumping will lead to mixing and dispersion rather than to advection. However, higher Rn and CH_4 concentrations near the Keys relative to other portions of Florida Bay, and the more ^{15}N enriched seagrass tissue found there (Corbett et al. 1999) are all consistent with the delivery of nutrients to the surface waters through exchange of groundwaters and surface waters.

The wavelength between successive peaks in the Florida Bay radon record is very close to the spacing between each of the higher high tides in the Atlantic. We assume that the offset of a few hours between the occurrence of an Atlantic high tide and the radon peak in Florida Bay represents the time required for the driving force to propagate from the Atlantic side of Key Largo to the Florida Bay side. Unfortunately, the tidal record shown is from Long Key, about 25 miles to the southwest. While we suspect that the general shape and trend would be much the same at Key Largo, there is likely some offset in the timing between the two locations. It is clear that the radon record displays a much better concordance with the Atlantic tide than the water level in Florida Bay.

The automatic seepage meter deployed directly in the seabed showed a trend of generally increasing seepage throughout the period, in much the same manner as the radon concentrations and the maximum water level in the Atlantic increased during the measurement period (Figure 7). Negative seepage rates were not observed at this location. The seepage meter record showed initial values of 2–3 cm/day and increased slowly to about 10 cm/day by 4th April and then rose further to $\sim$15 cm/day by the end of the experiment. The control meter, in the plastic swimming pool, showed consistently low base values (<1.0 cm/day) with

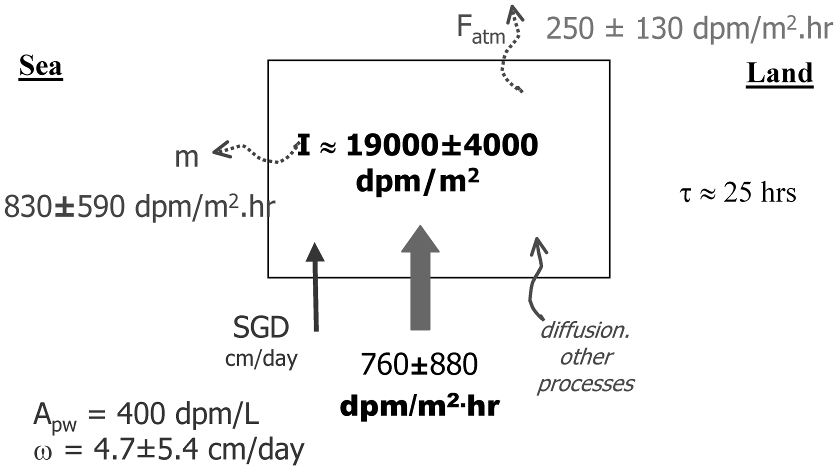

Figure 8. Box model showing mass balance of radon in the coastal waters at site 2, Key Largo. Estimates shown are averages and standard deviations over the course of the experiment. Based on the measured inventory, calculated atmospheric losses (F_{atm}), and estimates of mixing losses (m), a total radon flux is calculated in a dynamic process. The fluxes illustrated are mean values but the budget is balanced hourly. Based on an assumed ^{222}Rn concentration in the discharging fluids and the change in the corrected inventory from one measurement period to the next (1-h integration periods used), the radon record can be converted to a water flux record. The variables τ, A_{pw} and ω represent the average residence time, activity of ^{222}Rn in the pore waters, and upwelling velocity (SGD rate), respectively.

spikes up to about 2.5 cm/day about 24 h apart. We are not sure what caused these apparent seepage spikes although we acknowledge that it seems improbable that the 24-h period is a complete coincidence. One possibility is that the increased wind that tends to come up in the afternoons when these spikes occurred, induced flow through the sand and into the seepage chamber above the plastic barrier. We suggest that these spikes represent the so-called 'Bernoulli's Revenge' of Shinn et al. (2002). Whatever the reason, the generally very low values (thought to be near the limit of detection) in the control meter provide confidence that the other meter is actually recording seepage rather than responding to some external forcing.

We can estimate the total radon flux into the nearshore bay waters required to support the amount of radon observed using the trends in the measured radon inventories together with estimates of losses to the atmosphere and to mixing with lower concentration Florida Bay waters (Figure 8). The average inventory of radon was $19{,}000 \pm 4{,}000$ dpm/m^2, a very high inventory for a water depth of only 1.8 m. Since the radon monitors were in fixed locations in shallow water during generally calm conditions (average wind speed 2.6 m/s) with almost no tidal currents, the 'sphere of influence' for the measurements was likely limited to the area in close proximity to our sampling point (probably less than $\sim$100 m radius). Radium analyses of the bottom sediment collected from this site showed that the ^{226}Ra concentration was $\sim$1.5–2.0 dpm/g. Based upon an advection diffusion model

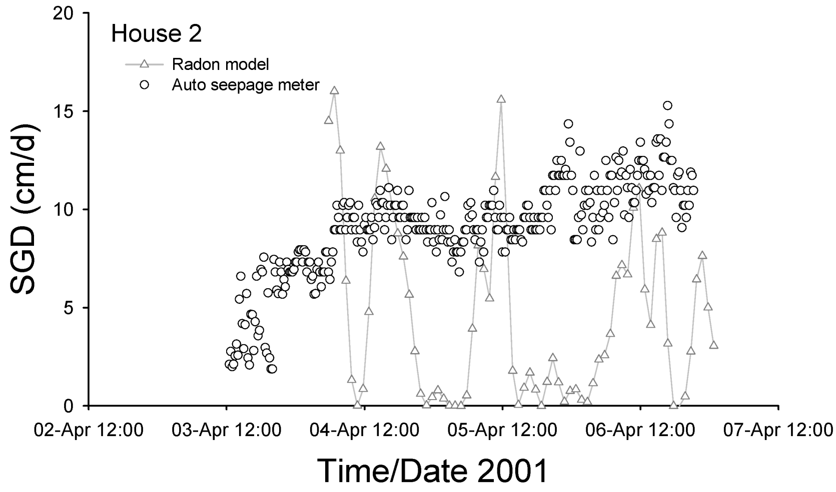

Figure 9. SGD flux rates based on radon modeling (triangles) together with the SGD record measured by an automatic seepage meter over the same time period.

(Corbett et al. 2000; Burnett et al. 2003b), we estimate that the Rn flux via diffusion only from this sediment would be $\sim 40\,\mathrm{dpm/m^2\,h}$, about 5% of the total flux required to support the observed inventory. Similar diffusive flux estimates were reported within this area (Corbett et al. 2000). The box model also indicates that ^{222}Rn must have a residence time of only about 25 h in this system. This compares to a much longer 5.5-day mean life ($1/\lambda$, where $\lambda =$ decay constant of ^{222}Rn, 0.181 day^{-1}) of ^{222}Rn based on its decay.

Using a determined value of 400 dpm/l for the radon concentration of the subsurface fluids flowing into these waters, we converted the radon flux to an estimate of water fluxes. The flux rates calculated in this manner show a much more obvious diurnal pattern than the single set of seepage meter results (Figure 9). The actual flux rates, however, are similar with a range from $\sim$2–15 cm/day determined by the automatic seepage meter while the radon modeling results varies from 0 to 15 cm/day throughout the experimental period. The seepage meter, of course, is only looking at a very small portion of the sea floor ($\sim 0.25\,\mathrm{m^2}$) while the radon modeling is based on measurements made in the overlying water column that would generally smooth out smaller scale variations. The greater variability indicated by the radon model in this case is likely the result of the type of seepage present in this area. Unlike disseminated seepage through sandy sediments where radon modeling and seepage meters have shown excellent agreement (Burnett et al. 2002; Lambert and Burnett 2003), groundwater inputs in the keys may be largely from seeps in exposed limestone in Florida Bay. If this is the case, then the radon model is likely providing a more realistic picture of fluid inputs than the one seepage meter emplaced into an isolated patch of sediments. Corbett et al. (2000) estimated seepage rates of 0.2–4.2 cm/day for larger sections of Florida Bay using mean water column

Rn activities. The Rn model shows decreasing maximum seepage rates over the study period while the maximum Rn concentrations were increasing. The increase in Rn concentration over the study period may have been due to the greater height of the Atlantic tidal maximum. The apparently lower SGD rates in the later part of the experiment may have been due to over-estimated mixing losses, the most uncertain part of the radon mass balance. Since we used the maximum observed negative net fluxes for the mixing term, the lowest calculated SGD rate based on the Rn model will be zero. In fact, these mixing losses, and thus SGD rates, could be higher.

The uncertainties in the SGD estimates made by the radon model are difficult to quantify. The mixing term is clearly a significant source of uncertainty because it can be a significant fraction of the total flux into the system and was not measured directly. Atmospheric losses also involve additional uncertainties although likely not as important in this case because of low exchange rates during this period of relatively calm winds. Lambert and Burnett (2003) estimated the uncertainty in calculated SGD rates in a similar study by use of a sensitivity test to determine the response of the Rn model to large changes in two parameters, mixing and tide normalization (not important in this case because of the very low amplitude tides in Florida Bay). While keeping all other parameters constant, the mixing and tidal parameters were varied by increasing the values by 100% (2×) and reducing by 50%. This resulted in the estimated SGD rates changing by about ±25%.

Overall, seepage meter and ^{222}Rn results present a consistent picture that the pressure head variations driven by Atlantic tides observed in groundwater wells result in seepage rate variability in Florida Bay off of Key Largo. A similar mechanism of tidal oscillation driving nearshore seepage has also been described by Bokuniewicz and Pavlik (1990) for the sandy sediments on the backside of Fire Island, New York. Our results are consistent with the seepage model proposed by Reich et al. (2002). At all three sites investigated, seepage rate varied with Atlantic tide, which controlled the wellhead pressure. It is not clear why we did not observe negative rates at every site. Possibly the reversal in hydraulic gradient only occurs in regions of greatest hydraulic conductivity. Alternatively, it is possible that there is a small water table mound beneath parts of Key Largo that maintains a water table elevation that is higher than both the Atlantic and Florida Bay. Persistent brackish water lenses (around 13 ppt) do occur on the island (Reich et al. 2002). The lack of negative SGD in some areas would support this suggestion. While it is clear that there are tidal influences on pressure heads and the magnitude of SGD, it is not clear that tides always cause hydraulic gradient and SGD reversals. Future work on Key Largo should couple continuous hydraulic head measurements along a transect of wells installed across the island with continuous monitoring of seepage rate and radon concentrations.

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