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Climate-driven sea level anomalies modulate coastal groundwater dynamics and discharge

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[1] To better understand the physical drivers of submarine groundwater discharge (SGD) in the coastal ocean, we conducted a detailed field and modeling study within an unconfined coastal aquifer system. We monitored the hydraulic gradient across the coastal aquifer and movement of the mixing zone over multiple years. At our study site, sea level dominated over groundwater head as the largest contributor to variability in the hydraulic gradient and therefore SGD. Model results indicate the seawater recirculation component of SGD was enhanced during summer while the terrestrial component dominated during winter due to seasonal changes in sea level driven by a combination of long period solar tides, temperature and winds. In one year, sea level remained elevated year round due to a combination of ENSO and NAO climate modes. Hence, predicted changes in regional climate variability driven sea level may impact future rates of SGD and biogeochemical cycling within coastal aquifers. **Citation:** Gonneea, M. E., A. E. Mulligan, and M. A. Charette (2013), Climate-driven sea level anomalies modulate coastal groundwater dynamics and discharge, *Geophys. Res. Lett.*, *40*, 2701–2706, doi:10.1002/grl.50192.

1. Introduction

[2] Unconfined coastal aquifers contain two interacting water masses: terrestrial and marine groundwater [*Moore*, 1999]. The former is supplied by inland recharge and overlies a salt wedge comprised of marine groundwater, with dispersive mixing occurring at the interface [*Cooper*, 1959] (Fig. 1). In addition, an upper saline plume associated with tidal and wave driven circulation occurs in the shallow intertidal region [*Li et al.*, 2008; *Li et al.*, 2009; *Robinson et al.*, 2007; *Xin et al.*, 2010]. Circulation and surface water exchange within these systems is driven by the hydraulic gradient between the aquifer and sea level (i.e $dh/dl = (h_g - h_s)/l$, where h_g is the groundwater hydraulic head, h_s is sea level, both corrected for variable density according to *Post et al.*, 2007, and l is the horizontal distance over which the gradient is calculated) [*Michael et al.*, 2005; *Mulligan and Charette*, 2006; *Robinson et al.*, 2006].

[3] In many locations, groundwater discharge across the ocean-aquifer interface represents a significant water flux carrying terrestrially-derived dissolved constituents [*Moore*, 2010]. However, uncertainty remains concerning the total water and chemical flux via SGD on local to global scales, due in part to the presence of hydrodynamically complex and chemically dynamic coastal aquifers where sharp redox and salinity gradients lead to active biogeochemical cycling of nutrients [*Kroeger and Charette*, 2008; *Slomp and Van Cappellen*, 2004], trace metals [*Beck et al.*, 2007; *Charette and Sholkovitz*, 2006; *Gonneea et al.*, 2008; *Santos et al.*, 2011] and anthropogenically-sourced contaminants [*Bone et al.*, 2006; *Bone et al.*, 2007; *Lee et al.*, 2011]. Field studies and hydrologic modeling of coastal aquifers have largely focused on flow driven by short-time scale tides and waves, while little is known about the spatial and temporal response of the deeper mixing zone (hereafter referred to as the "mixing zone") to hydraulic gradient perturbations caused by groundwater and sea level oscillations.

[4] To address this dearth of knowledge, we established a time series within a coastal aquifer mixing zone between terrestrial and marine groundwater to observe changes in regional scale mixing over multiple years. To do this we monitored groundwater salinity within the coastal aquifer concurrently with groundwater levels at various distances inland and sea level. The goal of this study was to observe how the mixing zone of the coastal aquifer responded to terrestrial and marine forcings on monthly to interannual time scales. Lastly, we utilized a hydrologic model to simulate mixing within the coastal aquifer and subsequent groundwater discharge to the ocean either driven by terrestrial or terrestrial plus marine forcing over these same time scales.

2. Methods and Study Site

[5] Waquoit Bay is a shallow estuary on the southern shore of Cape Cod, MA, USA. Within the coastal aquifer there is a well-defined region of mixing between terrestrial and marine groundwater (Figs. 1 and S1 and supporting information). A variety of chemical processes, including ion exchange (adsorption/desorption reactions) and redox cycling, are active within the salinity interface [*Charette and Sholkovitz*, 2006]. A series of wells with a 2.5 cm screened interval were installed at eight depths across the mixing zone of the coastal aquifer ranging from 2.2 to 5.2 m below mean sea level (MSL) (Fig. 1). Salinity was sampled every month from Oct. 2004 to Oct. 2007 and June 2009 to June 2010 during the same tidal cycle and phase (4 hours past high tide, ~3 days before the monthly spring tide) to reduce the potential variability associated with tidal fluctuations (which we determined to be minimal based on an hourly time series over the course of a falling tide, Fig. S2). Salinity samples were collected after pumping approximately 1 L (6 to 13 well volumes) and measured with a Guideline AutoSal instrument. Groundwater levels

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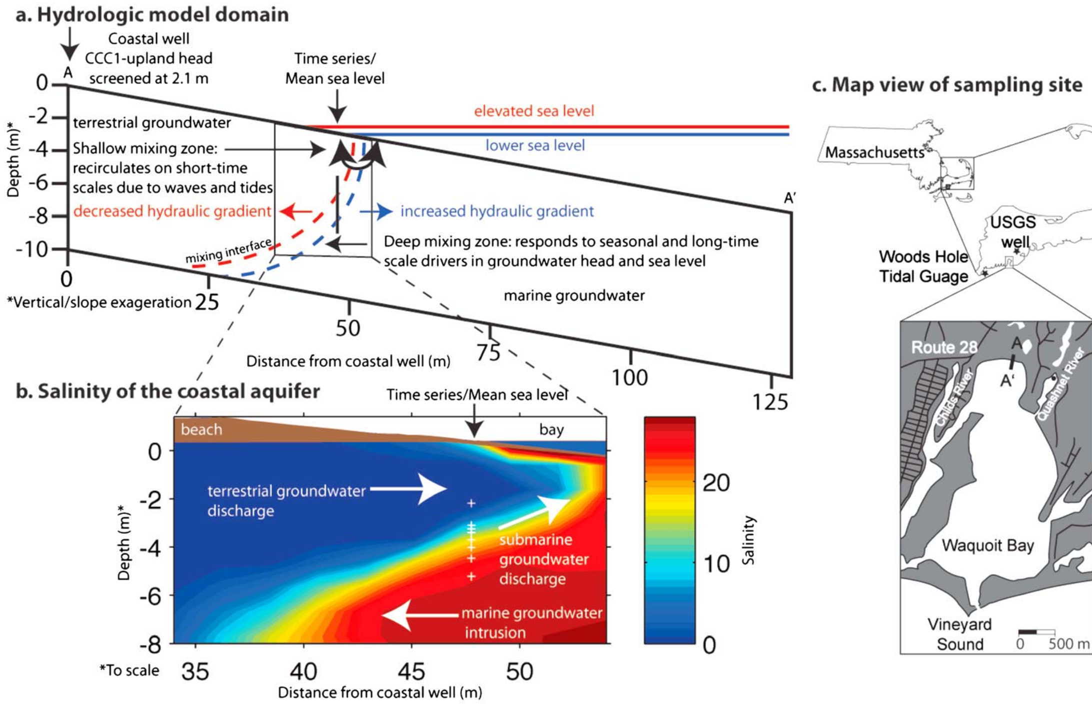

Figure 1. Hydrologic model domain and salinity cross-section of the Waquoit Bay coastal aquifer, Cape Cod, MA, USA in June 2004. The hydrologic model (a) extends from the coastal well seaward 130 m. In June 2004, a 2-D transect of the coastal aquifer (b) revealed that terrestrial groundwater overlaid marine groundwater, with the mixing region between the two marked by dynamic chemical alteration of groundwater discharging to the coastal ocean. Seasonal movement of the deep interface between terrestrial and marine groundwater was monitored monthly in wells 2.2 to 5.2 m below MSL (black line in (a) and white crosses in (b)) placed below the depth of shallow mixing induced by tidal and wave influence. The hydraulic gradient was calculated between CCC1 (screened at 2.1 m) and the location of MSL. Map overview of study site is shown in (c). Note vertical/slope exaggeration in (a).

were monitored at a nearshore well (CCC1; 46 m from MSL) and averaged over the monthly sampling resolution of the salinity time series; monthly measurements were made of inland groundwater levels (USGS #413525070291904; 10 km from MSL). Sea level was measured at NOAA's Woods Hole sea level station (#8447930) and monthly average sea level anomaly is used here for comparison with time series data.

[6] We utilized a numerical simulation model constructed with the USGS SEAWAT code [*Langevin et al*., 2008] that was designed to represent conditions within coastal permeable sand aquifers such as at Waquoit Bay. This model is a 2D vertical cross-section that simulates an unconfined aquifer and variable-density flow with vertical and horizontal gradients with additional details available in *Mulligan et al*., 2011. The simulator was not fully calibrated to field data because the intent was not to exactly reproduce the full salinity time series but rather to simulate the effect of sea level on SGD from a typical unconfined coastal aquifer. The simulation model is a two-dimensional cross section of a homogeneous unconfined aquifer below a sloping beach (0.08 m/m) where the simulated domain measures 130 m long and 10 m deep. No recharge was simulated and therefore a no flow condition was applied along the top boundary on the landward side, as well as along the bottom and seaward edge of the domain. General heads and drains are used to represent the top boundary on the bay side. Transport boundary conditions were restricted to relative concentrations of C = 1 (density of 1024 kg m^{-3}) within the bay and C = 0 (density of 999 kg m^{-3}) for terrestrial groundwater. Mixing between these waters results in variable density flow. The head at the upland boundary was allowed to vary according to the measured record at the nearshore monitoring well (CCC1); head data from different depths within the surficial aquifer at this location indicate there is no vertical gradient. The marine boundary was simulated in one of two ways: as a constant value of mean sea level (0 m), or using average monthly sea level from NOAA's Woods Hole tidal station (data available at http://tidesandcurrents.noaa.gov). Within each 15-day stress period, tidal and upland boundary conditions remain constant, but these values can vary from one stress period to the next. Due to computational demand, neither model incorporated short-time scale sea level oscillations (i.e. tides). Groundwater discharge to the ocean and marine water intrusion into the aquifer were calculated across the entire model domain. Simulations were established to run for the equivalent of Jan. 2005 to June 2007.

3. Results

[7] At this site, over an average seasonal cycle, sea level is at a minimum during winter and maximum during summer/fall due to both the annual solar tide component and thermosteric sea level variability resulting from seasonal temperature and wind dynamics [*Tsimplis and Woodworth*, 1994] (Fig. S4). The period from 2009-2010 was marked by a positive sea level anomaly, whereby sea level was elevated for an entire year, without the typical winter low

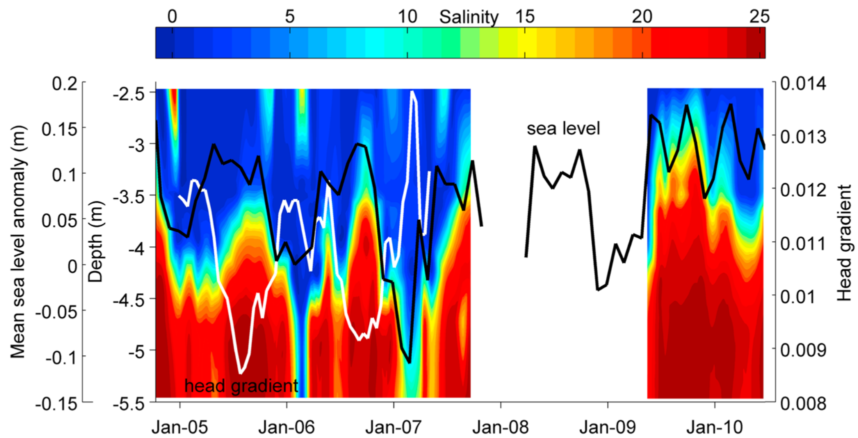

Figure 2. Salinity, the corresponding head gradient of the coastal aquifer and the mean sea level anomaly. The salinity peaks in the summer from 2004 to 2007, however it remains elevated from June 2009 through June 2010 (no data between Nov. 2007 and May 2009). The coastal hydraulic gradient (white line, right axis) was calculated between the coastal well groundwater level (CCC1) and sea level (black line, left most axis) corrected for variable density. Salinity excursions within the upper fresh portion of the aquifer (<2.5 m) were observed periodically and likely resulted from infiltration of bay water due to tidal and wave pumping. Data contoured with a MATLAB cubic interpolation.

sea level. In Waquoit Bay, coastal groundwater levels did not display a consistent seasonal signal from 2004-07. The amplitude of variability in coastal groundwater levels (10 cm, Fig. S3b) was smaller than the seasonal sea level anomaly (20 cm, Fig. S3c). Since head gradient is calculated as the difference between groundwater and sea level, adjusted for variable density, if one of these varies to a greater degree than the other, it is possible for that parameter to have a disproportionate control on the magnitude of the head gradient. A time series cross correlation between hydraulic gradient and sea level, coastal and inland groundwater levels (for 2004-07) revealed that the highest correlation with sea level (r = -0.66; 95% confidence level) occurred at zero lag. In contrast, coastal groundwater levels were not significantly correlated to the hydraulic gradient (Fig. S5).

[8] The position of the mixing zone in the coastal aquifer was monitored for 4 years (Fig. 1). The monitoring wells were ideally positioned to capture vertical and lateral movement of the mixing zone, since the slope of the mixing zone boundary at this location is stable (Fig. S1). In addition, the salinity of the monitoring wells did not respond to changes in sea level driven by tides (Fig. S2). Hence, we expect the wells to capture movement of the mixing zone in response to changes in the hydraulic gradient on longer time scales (greater than hours).

[9] The mixing zone oscillated vertically between high and low salinity with a period of approximately one year for the first three years of measurement (Fig. 2). Landward intrusion of marine groundwater typically occurred in the summer and fall, with the exception of the period between June 2009 and June 2010, when salinity remained elevated year-round signaling a prolonged intrusion of marine groundwater. To better understand the mechanisms driving seasonal mixing dynamics in the coastal aquifer, we performed a time series cross correlation of groundwater salinity and: (1) the coastal hydraulic gradient, (2) groundwater head 46 m inland of MSL (CCC1), (3) groundwater head 10 km inland of MSL (USGS well) and (4) local MSL (Fig. S7). We found that the maximum correlation between salinity and both hydraulic gradient (r = -0.49) and sea level (r = 0.56) occurred at zero lag. An increase in hydraulic gradient will lead to a decrease in salinity, thus be negatively correlated, while an increase in sea level should lower the hydraulic gradient and increase salinity, leading to a positive correlation. Notably, there was no significant correlation between coastal (46 m from MSL) groundwater head and salinity (Fig. S7). Rather, the salinity of the mixing zone was negatively correlated with inland groundwater levels (r = -0.54) with a 60-day lag. Based on this analysis, we suggest that the position of the mixing zone responds on time scales of days to weeks to sea level fluctuations and is largely controlled by the amplitude of seasonal sea level oscillations.

[10] To explore the potential impact of sea level on groundwater flow to the ocean, we constructed a numerical model of groundwater flow and salt transport in an unconfined coastal aquifer using the USGS code SEAWAT [*Langevin et al.*, 2008; *Mulligan et al.*, 2011]; we used the model to run two separate simulations. In the first simulation, the marine boundary was held constant at MSL, while in the second the marine boundary was specified as the monthly average sea level from the Woods Hole tidal gauge. In both simulations, the monthly average head data from a coastal well (CCC1, Fig. 1) was used as the transient upland fresh water boundary. The choice of these two simulations allows us to separate and evaluate the effects of oscillating groundwater head and sea level on both mixing in the coastal aquifer and subsequent groundwater discharge.

[11] In the simulation with static sea level, the salinity of SGD was low and there was minimal temporal variability in the fluid flux (Fig. 3a). In the simulation that incorporated the observed sea level record, there was a dynamic seasonal response in both the magnitude and salinity of SGD due mainly to a wider range in the hydraulic gradient (Fig. 3b). Total SGD (terrestrial plus marine groundwater) peaked in summer/fall, as previously observed [*Michael et al.*, 2003, 2005], while the terrestrial component was greatest in the winter. One of the most striking differences between the two models was the amount of marine groundwater intrusion

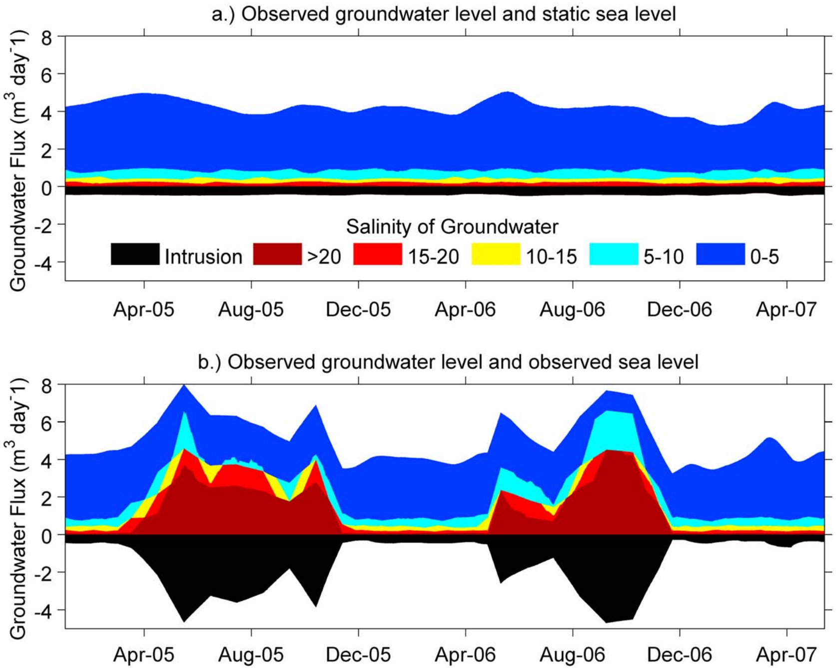

Figure 3. Hydrodynamic models of groundwater discharge and salinity across a sandy coastal aquifer. The groundwater discharge results were integrated over the 130 m study domain and binned into five different groups based on the salinity of the discharging water (represented by separate colors) and intrusion of bay water into the aquifer (black). The width of each color corresponds to the fraction of total SGD within each salinity range. The upland freshwater boundary in both models is the groundwater level at CCC1, 46 m from mean sea level. The marine boundary in (a) is static while in (b) the marine boundary was driven by the Woods Hole sea level record. The magnitude of fresh discharge was similar between the two models; however allowing the marine boundary to vary with sea level induced greater intrusion of marine groundwater. This led to increased mixing between terrestrial and marine groundwater and discharge of this mixed salinity water. In the model with the observed sea level record, total SGD peaked in summer and fall, while terrestrial SGD peaked during winter and spring, when there was relatively less marine SGD.

and subsequent mixing and discharge that occurred once the hydraulic gradient included variability in sea level. Marine groundwater cycled rapidly through the coastal aquifer, resulting in minimal lag between intrusion and discharge with enhanced mixing between terrestrial and marine groundwater.

4. Discussion

[12] In Waquoit Bay, the salinity distribution of the coastal aquifer can be directly attributed to changes in the monthly-averaged hydraulic gradient between the nearshore groundwater head and sea level. An increase in hydraulic gradient led to an overall seaward movement of the interface, resulting in lower salinity groundwater, while a decrease in gradient led to landward movement of the interface and higher salinity groundwater at this location. Previously, oscillations in inland groundwater levels driven by groundwater recharge were proposed to drive fluctuations of the hydraulic gradient across the coastal aquifer on seasonal time scales [*Anderson and Emanuel*, 2008; 2010; *Michael et al*., 2005].

[13] Throughout the four-year record, positive sea level anomalies coincided with periods of high salinity within the aquifer (Fig. 2). In 2009 to 2010, the sea level anomaly was positive and the seasonal signal was dampened resulting in prolonged marine groundwater intrusion for over a year. This positive sea level anomaly was observed at tide gauges from Maine to New York (Fig. S4a), thus had the potential to impact coastal groundwater dynamics on a regional scale [*Sweet and Zervas*, 2011]. While we did not measure groundwater head at the coast during this period, the response of the mixing zone is consistent with sea level as the dominant forcing of the hydraulic gradient. The hydraulic gradient in turn modulates SGD from unconfined aquifers as observed in the simulations. Given these results, in regions similar to Waquoit Bay (low relief, sandy unconfined aquifer), the future hydrologic response of coastal aquifers may be dependent on the sensitivity of sea level to climate change. The U.S. East Coast average annual sea level cycle results in a winter minimum and summer/fall maximum with tidal stations along the entire U.S. East Coast demonstrating coherent sea level records (Fig. S4a). The yearly period of this signal is in phase with the solar annual tidal component for the 2004-2008 portion of the record (Fig. S3b), though the actual mean sea level was higher than the predicted long period component, and the periodicity broke down during 2009-2010.

[14] This deviation from a seasonal cycle and recent trends in sea level increase have been attributed in part to changes in the North Atlantic Oscillation (NAO) [*Llovel et al*., 2011] and El Niño Southern Oscillation (ENSO) [*Sweet and Zervas*, 2011] through changes in sea surface temperatures and wind intensity and direction. El Niño and the NAO are naturally occurring modes of atmospheric variability that can affect ocean heat content, circulation, and salinity [*Hurrell and*

Deser, 2009; *Kolker and Hameed*, 2007]. The location and intensity of these atmospheric centers of action vary on seasonal and interannual time scales [*Hurrell and Deser*, 2009]. *Sweet and Zervas*, 2011 suggest that our 2009 to 2010 record overlapped with a very strong El Niño phase of ENSO, which was marked by increased northeasterly winds over the Gulf of Maine region, leading to increased coastal set up resulting in elevated positive sea level anomalies. During the same time period, the phase of the NAO, which is anti-correlated to sea level in this region, was negative [*Kolker and Hameed*, 2007; *Llovel et al*., 2011]. In a cross correlation regression between Woods Hole MSL and the NAO index for the past 30 years (1980-2011), the highest correlation ($r = 0.46$) occurs at zero lag (Fig. S8). On decadal time scales, shifts in the position and intensity of Atlantic atmospheric high and low pressure regions which define the NAO account for 63% of annual mean sea level variability [*Kolker and Hameed*, 2007].

[15] Since the mixing zone moves in response to sea level changes, processes capable of influencing sea level over time scales of weeks or greater (e.g. the annual tidal component or sustained winter storms [*Wilson et al*., 2011]) have the potential to directly impact chemical cycling within the mixing zone of unconfined coastal aquifers and subsequent chemical loading to the coastal ocean. Mixing between terrestrial and marine groundwater within coastal aquifers results in large geochemical gradients in oxygen, nutrients and trace metals. Oscillation of the saltwater interface will result in movement of redox and ion exchange boundaries within the coastal aquifer [*Santos et al*., 2011]. Redox sensitive elements such as iron and manganese [*Charette and Sholkovitz*, 2006], and contaminant metals such as mercury [*Bone et al*., 2007] and copper [*Beck et al*., 2010], will tend to migrate with the movement of the interface, which can result in either net storage or release of these elements from aquifer sediments and therefore can influence their impact on receiving water bodies.

[16] To this end, the seasonally variable magnitude and salinity of SGD predicted by the hydrologic model will affect both the magnitude and timing of chemical loading associated with SGD. Our results now provide a driving mechanism for previous studies that reported maximum SGD and associated nutrient flux rates in the summer [*Kelly and Moran*, 2002; *Moore and Shaw*, 2008], a paradoxical observation since at that time groundwater elevation is typically at a minimum. These sites (Rhode Island and the South Atlantic Bight) experience a similar annual sea level cycle, with high sea level during the summer. Furthermore, our findings have implications for biogeochemical processes within the coastal aquifer, which have been shown to modulate input of terrestrial nitrogen to the coastal ocean [*Kroeger and Charette*, 2008]. For example, the model predicts enhanced mixing between terrestrial and marine groundwater during summer months (Fig. 3), which may lead to greater removal of fixed nitrogen prior to discharge via increased denitrification. Thus, sea level driven biogeochemical processes within coastal aquifers may alleviate some nitrogen loading during summer months when the eutrophication-related ecosystem impacts are at their peak. Conversely, enhanced flux of terrestrial groundwater during the winter may result in greater export of nitrogen to the open ocean, allowing fixed nitrogen to transit coastal aquifers and estuaries at a time when near shore surface water removal processes are minimal [*Salisbury et al*., 2008]. This flux of nutrients may help to fuel spring blooms over the continental shelf [*Townsend*, 1998].

5. Conclusions

[17] Our results provide a conclusive link between large-scale climate mode forcing (ENSO/NAO) of sea level and both submarine groundwater discharge and biogeochemical cycling within unconfined coastal aquifers such as at Waquoit Bay. Changes in sea level lead to movement of the saltwater interface and directly affect model-predicted mixing between terrestrial and marine groundwater within the coastal aquifer. Furthermore, sustained positive sea level anomalies [*Sallenger et al*., 2012; *Yin et al*., 2009] will lead to significant saltwater intrusion into fresh aquifers, with the potential for dramatic impacts on the fresh water reserves of coastal communities. With predicted future increases in regional climate variability, these findings have important implications for the role of submarine groundwater discharge and coastal aquifer biogeochemical cycling in water resource management and coastal marine ecology.

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