3. What is the parent-lightning charge moment change needed to drive sprites during these Argentine storms? How does this compare with the charge moment changes measured over the U.S. High Plains and elsewhere? Are there some sprites that can be driven by relatively low charge moment changes, which are too small to cause breakdown using only the quasi-electrostatic field model?

4. Does the morphology of TLEs differ with meteorological conditions and/or charge moment changes?

Addressing these questions will help lead to a new understanding of the lightning- and TLE-driven coupling between the upper and lower atmosphere in all regions of the world, not just the well-studied U.S. High Plains.

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Author Information

Jeremy N. Thomas, Department of Earth and Space Sciences, University of Washington, Seattle; E-mail: jnt@u.washington.edu; Michael J. Taylor, Dominique Pautet, and Matthew Bailey, Center for Atmospheric and Space Sciences and Physics Department, Utah State University, Logan; Natalia N. Solorzano, Physics Department, Digipen Institute of Technology, Redmond, Wash.; Robert H. Holzworth, Michael P. McCarthy, and Michael Kokorowski, Department of Earth and Space Sciences, University of Washington, Seattle; Fernanda Sao Sabbas and Osmar Pinto Jr., National Institute of Space Research (INPE), Sao Jose dos Campos, Brazil; Steven A. Cummer, Nicolas Jaugey, and Jingbo Li, Department of Electrical and Computer Engineering, Duke University, Durham, N. C.; and Nelson Jorge Schuch, Brazilian Southern Space Observatory, Southern Regional Space Research Center (CRSPE/INPE), Santa Maria, Brazil.

Sea Level Rise in Tampa Bay

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Understanding relative sea level (RSL) rise during periods of rapid climatic change is critical for evaluating modern sea level rise given the vulnerability of Antarctic ice shelves to collapse [*Hodgson et al.,* 2006], the retreat of the world's glaciers [*Oerlemans*, 2005], and mass balance trends of the Greenland ice sheet [*Rignot and Kanagaratnam*, 2006]. The first-order pattern of global sea level rise following the Last Glacial Maximum (LGM, ~21,000 years ago) is well established from coral [*Fairbanks,* 1989], continental shelf [*Hanebuth et al.,* 2000], and other records [*Pirazzoli*, 2000] and has been integrated into a global ICE-5G model of glacio-isostatic adjustment (GIA) [*Peltier*, 2004]. However, uncertainty introduced by paleo water depth of sea level indicators, radiocarbon chronology (i.e., reservoir corrections for marine shell dates), postglacial isostatic adjustment, and other processes affecting vertical position of former shorelines produces scatter in RSL curves, limiting our knowledge of sea level rise during periods of rapid glacial decay.

One example of this limitation is the Gulf of Mexico/Florida region where, despite decades of study, RSL curves produce two conflicting patterns: those showing progressive submergence with a decelerating rate during the past 5000 years [*Scholl et al.,* 1969] and those showing high sea level during the middle of the Holocene [*Blum et al.,* 2001; *Balsillie and Donoghue*, 2004], where the Holocene represents a geologic epoch that extends from about 10,000 years ago to present times. This discrepancy is emblematic of the uncertainty surrounding Holocene sea level and ice volume history in general.

Tampa Bay is a shallow (~4 meter depth) estuary formed by dissolution of the Miocene Arcadia Formation [*Hine et al.,* in press] and deposition of Quaternary sediments in sinkholes and karst depressions during glacio-eustatic sea level cycles. The Tampa Bay Study (http://gulfsci.usgs.gov/tampabay/index.html), a collaborative project—between the U.S. Geological Survey (USGS), and the University of South Florida and Eckerd College, both in St. Petersburg—is investigating the sea level, climatic, and environmental history of Tampa Bay (Figure 1). Here we report on the sedimentary record of early Holocene sea level rise and its relationship to regional and global sea level and polar ice volume.

Quaternary Stratigraphy and Chronology

Tampa Bay stratigraphy features alternating episodes of estuarine-marine and nonmarine sedimentation during periods of relatively high (interglacial) and low (glacial) sea level. An 11.28-meter piston core (MD02-2579) recovered by the R/V *Marion Dufresne* in July 2002 from 9.14 meters of water in a depression in the central part of Tampa Bay (Figure 1) contained three stratigraphic units characterized by distinct lithology and microfaunas. The lowermost unit 1 (11.2–7.2 meter core depth) consists of shelly sands and yielded radiocarbon ages from greater than 43,000 years ago. Amino acid racemization ages on mollusks, interglacial pollen assemblages, and marine ostracodes suggest it represents the last interglacial period, termed marine oxygen isotope stage 5. Unit 2 (7.2–2.9 meters) consists of organic and calcareous muds containing nonmarine ostracodes that were deposited in lakes, ponds, and wetlands between the LGM and the end of the Younger Dryas cooling episode (~11,500 years ago) (D. Willard et al., Deglacial climate variability from central Florida, USA, submitted to *Palaeogeography, Palaeoclimatology, Palaeoecology*, 2006, hereinafter referred to as D. Willard et al., submitted manuscript, 2006). Unit 3 (2.9–0 meters) consists of marine sandy muds, and represents late Holocene sediments deposited during the past approximately 3500 years.

Unit 2 pinches out laterally from the karst basin in central Tampa Bay, resulting in a 7500-year hiatus between units 2 and 3 due to erosion or nondeposition of lake sediment prior to Holocene sea level rise. However, cores from the nearby Hillsborough Bay region (VC-75, VC-77, VC-78) recovered a conformable sequence of lacustrine and estuarine sediments continuously deposited in a separate karst-like basin, which allow us to pinpoint the age and elevation of early Holo-

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By T. Cronin, N. T. Edgar, G. Brooks, D. Hastings, R. Larson, A. Hine, S. Locker, B. Suthard, B. Flower, D. Hollander, J. Wehmiller, D. Willard, and S. Smith

cene RSL (Figure 2). A transition zone from nonmarine to estuarine deposition is evident in all three cores by the change from lacustrine pinkish white to pale brown mud overlain by dark sandy muds. The top of the transition zone has a gradational to sharp contact at 3.6–3.3 meter core depth. Nonmarine ostracodes and mollusks dominate the underlying lacustrine facies; benthic foraminifera and ostracodes tolerant of variable salinity and typical of coastal environments such as tidal mudflats, mangroves, and oyster reefs dominate the transition zone.

Radiocarbon ages on marine and freshwater mollusks, seeds, wood, and organic material from horizons within and bracketing the lacustrine-estuarine transition were calibrated using atmospheric (wood and nonmarine shells) and marine (estuarine and marine shells) corrections (CALIB 5.0.2, http://calib.qub.ac.uk/calib/). Reworking, transport, or reservoir carbon uptake can potentially result in anomalous radiocarbon dates in coastal and estuarine settings, and we excluded dates from bulk organic carbon and one mollusk (parentheses in Figure 2) from age models. Calibrated ages from seeds and wood from the underlying nonmarine facies, deposited before RSL rise flooded the bay, have a mean age of 8250 years B.P. Three brackish-water mollusks from the transition zone have mean calibrated age of 7123 years B.P.; in VC-75 the upper contact lies approximately 20 centimeters above two shell dates of 6722 and 7261 years B.P. (362–387 centimeter core depth). With a water depth of approximately 400 centimeters below modern mean sea level (MSL), these results yield a relative paleo sea level position approximately 7.5–8 meters below MSL at approximately 6700–7200 years B.P.

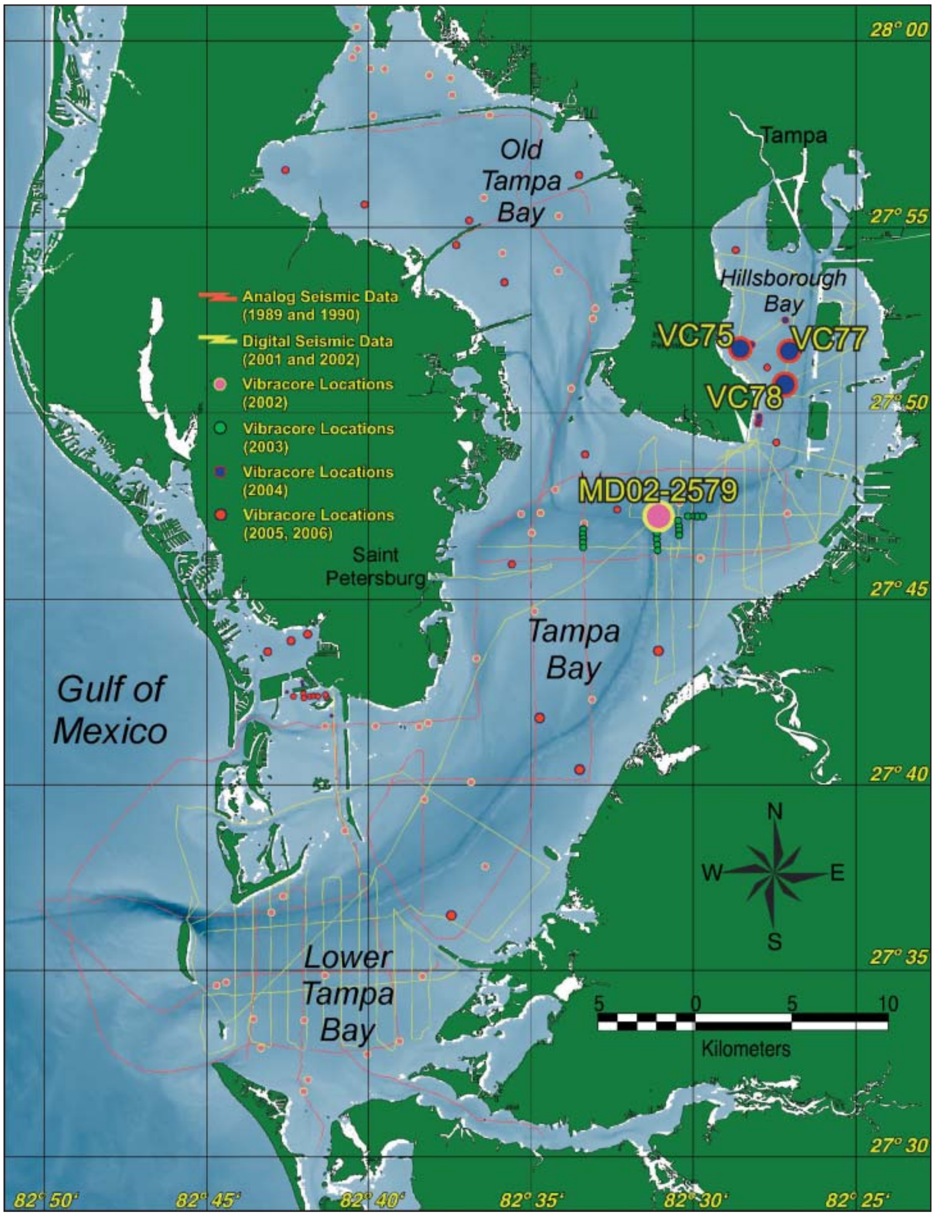

*Fig. 1. Map of Tampa Bay showing the location of sediment cores that recovered alternating fresh and marine Quaternary sediments and seismic lines [*Hine et al., *2007] showing the three-dimensional structure of sedimentary infilling of sinkhole depressions. Calypso core MD02-2579 is the focus of paleoclimatic study of the glacial and deglacial interval (D. Willard et al., submitted manuscript, 2006); cores VC04-75, 77, and 78 (see Figure 2) from Hillsborough Bay were used to study Holocene sea level.*

Relative Sea Level Rise

These results have a bearing on the regional sea level curve for the Gulf of Mexico and Florida and the contribution of ice sheet decay to the final post-LGM phase of global sea level rise. In the tectonically stable Florida peninsula, two factors can account for the relative sea level rise into Tampa Bay: Either global ice volume 7000 years ago was larger than today by up to 7–8 meters of sea level equivalent, and/or the region, located near the edge of the collapsing forebulge, has subsided up to 8 meters due to glacio-isostatic adjustment. All or most post-LGM deglaciation in the Northern Hemisphere was completed by 7000 years ago [*Dyke et al.*, 2003], but melting Antarctic ice may be a source of rising sea level because deglaciation continued in parts of Antarctica during the early Holocene (8000–6000 years ago) prior to late Holocene Neoglacial cooling [*Ingólfsson*, 2004].

According to the ICE-5G model, regional GIA submergence in Florida occurred at a rate of approximately 1 millimeter per year, and, if maintained for 7000 years, the GIA-corrected sea level in Hillsborough Bay at 7000 years ago would be near present MSL, implying little or no glacial meltwater contribution to RSL rise. However, GIA-caused subsidence hinges on partially known factors, such as the thickness and location of the Laurentide Ice Sheet and mantle viscosity. A lower submergence rate of 0.4–0.55 millimeters per year due to GIA is suggested by analysis of the past 1000 years of sea level in the Gulf of Mexico [*Gonzalez and Törnqvist,* 2006]. At this rate, melting Antarctic ice would in fact account for several meters of the observed early Holocene sea level rise approximately 7000 years ago, a hypothesis that can be tested with additional studies of sea level change in the Gulf and southeastern United States and the glaciological history of Antarctica.

Documenting relatively small changes in sea level of only a few meters is particularly challenging but must be considered a priority area for research if we are to understand modern sea level rise and climate change. The Tampa Bay record shows the value of integrated geophysical, stratigraphic, and paleoenvironmental reconstructions in sea level research.

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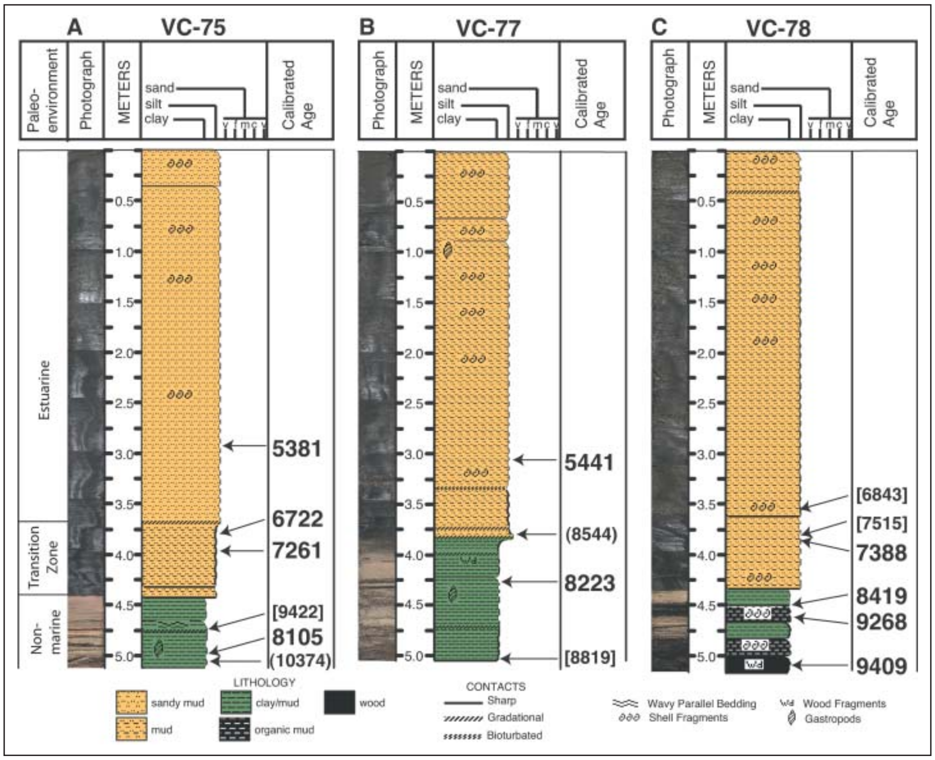

Fig. 2. Holocene stratigraphy and calibrated radiocarbon dates from cores VC04-75, 77, and 78 in the Hillsborough Bay region of Tampa Bay. The nonmarine to marine transition (core depth, 3.4–4.4 meters, VC-75; 3.3–3.6 meters, VC-77; and 3.6–4.3 meters, VC-78) signifies relative sea level rise into Tampa Bay approximately 7000 years ago. Radiocarbon dates in parentheses are from bulk organic carbon, and those in brackets are from mollusk (Melongea, core VC-77, 375 centimeters); they may not be reliable due to reworking, transport, or reservoir carbon. (A table of radiocarbon ages can be obtained from http://gulfsci.usgs.gov/tampabay/index.html.)

Author Information

Thomas Cronin, U.S. Geological Survey (USGS), Reston, Va.; E-mail: tcronin@usgs.gov; N. Terence Edgar, USGS, St. Petersburg, Fla.; Gregg Brooks, David Hastings, and Rebekka Larson, Eckerd College, St. Petersburg, Fla.; Albert Hine, Stanley Locker, Beau Suthard, Benjamin Flower, and David Hollander, University of South Florida, St. Petersburg; John Wehmiller, University of Delaware, Newark; Debra Willard, and Shannon Smith, USGS, Reston, Va.