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Shannon Ferguson
Louisiana State University

Sophie Warny
Louisiana State University

John B. Anderson
Rice University

Alexander R. Simms
University of California, Santa Barbara

Gilles Escarguel
Université Claude Bernard Lyon 1

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Authors

Ferguson, S
Warny, S
Anderson, JB
et al.

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Holocene vegetation and climate evolution of Corpus Christi and Trinity bays: implications on coastal Texas source-to-sink deposition

Shannon Ferguson^{a,b*}, Sophie Warny^{a,b}, John B. Anderson^c, Alexander R. Simms^d, Gilles Escarguel^e

^aDepartment of Geology and Geophysics

^bMuseum of Natural Science, Louisiana State University, Baton Rouge, Louisiana, 70803 USA

^cDepartment of Earth Science, Rice University, Houston, Texas 77005, USA

^dDepartment of Earth Science, University of California, Santa Barbara, California 93106, USA

^eLaboratoire d'Ecologie des Hydrosystèmes Naturels et Anthropisés, UMR CNRS 5023 LEHNA - Université Claude Bernard Lyon 1, Villeurbanne Cedex, France

* Corresponding author: Shannon Ferguson (ferg.shannon@gmail.com)

ABSTRACT

The Texas coastline stretches 595 km across almost 4° of latitude and is home to diverse coastal vegetation assemblages, yet only a handful of studies have documented the climate and vegetative change of this region through the Holocene. We provide a detailed palynological record of Holocene climate for coastal Texas, based upon three subaqueous sediment cores from Corpus Christi Bay, TX and Trinity Bay, TX. Cluster analysis and correspondence analysis were used to investigate changes in palynological assemblages through time within each core. Common to both bays are nonarboreal taxa including Asteraceae (mainly *Ambrosia*, and *Helianthus*), *Chenopodium*, Poaceae, and arboreal taxa such as *Carya*, *Pinus*, and *Quercus*. Our record shows that the coastal environments of central Texas began a transition from herbaceous (nonarboreal) dominated vegetation to arboreal vegetation as early as 8.4 ka within Corpus Christi Bay, and 3.8 ka within Trinity Bay. We note flooding events at 8.2 ka, 5.4 ka, and 3.6 ka in Corpus Christi Bay, and at 1.7 ka, 1.2 ka, and 0.8 ka in Trinity Bay. These events are caused by storms, changes to sea level including flooding of relict river terraces, and changes in sediment delivery to the bays. The pollen record also shows evidence for changes in fluvial discharge to Corpus Christi Bay at 4.1 ka and 2.2 ka, and at 1.8 ka in Trinity Bay. We also see *Zea mays* in Trinity Bay, indicating local Native American agriculture. We observe no significant changes during the middle Holocene Climatic Optimum, and subtle, but not statistically significant, evidence of more variable climate oscillations than other records from more interior sites in Texas show for the late Holocene. This indicates that coastal Texas' climate has operated semi-independently from central Texas regions, and is primarily driven by a coast-wise gradient of precipitation and evapotranspiration.

Keywords: Holocene; coastal Texas; pollen; vegetation; arboreal; Gulf of Mexico

1. Introduction

A major challenge in interpreting earth's history is understanding how climate has changed in the past. Understanding these changes is important for placing present and future climate change into context. Coastal regions are both densely populated and susceptible to the negative effects of

these changes, particularly as they relate to sea-level rise and increasing strength of tropical cyclones (Emanuel, 2005; Knutson et al., 2010; Törnqvist and Hijma, 2012).

The extensive Texas coastline is characterized by a large precipitation across the region, making it vulnerable to climate variability. Yet, relatively few studies have documented the climate and vegetative change of the region through the Holocene. This study aims to fill this gap; we examine the record of coastal marine and terrestrial palynoflora, create a record of coastal vegetative change through the Holocene, and finally examine whether the climate histories available for central and western Texas are also reflective of coastal Texas climate.

The modern mean annual precipitation gradient along the coast ranges from 50 to 150 cm/yr from north to south (Fig. 1), while temperatures vary little across the region. Given this strong precipitation gradient, the region is sensitive to climate change and associated changes in coastal ecosystems (Osland et al., 2014; Gabler et al., 2017). Holocene paleoclimate records for the region are sparse, but reveal shifts between cold-wet and warm-dry conditions over millennial time scales (Toomey et al., 1993; Humphrey and Ferring, 1994; Wilkins and Currey, 1999; Nordt et al., 2002) that are believed to be driven by large scale climate forcing mechanisms (e.g. North American Monsoon; Atlantic Multidecadal Oscillation, and El Nino-Southern Oscillation) (Buzas-Stephens et al., 2014; Livsey et al., 2016). Records from central and south Texas suggest that the early Holocene was dominated by cool/wet conditions, followed by warm dry conditions of the mid-Holocene Climate Optimum, and a shift to higher frequency changes during the late Holocene (Humphrey and Ferring, 1994; Nordt et al., 1994; Russ et al., 2000; Nordt et al., 2002; Buzas-Stephens et al., 2014). However, the actual duration and magnitude of these climate changes remains uncertain, especially for east Texas, so the potential climate forcing mechanisms remains

uncertain. Thus, the value of the paleoclimate record for testing and refining climate models is limited.

This study uses subaqueous cores, which both eliminate the palynomorph preservation problems of coastal Texas and have the added benefit of containing both terrestrial (pollen) and marine (dinoflagellate) palynomorphs. Samples come from sedimentary records obtained from 3 cores collected from subaqueous bayhead deltas and associated upper bay deposits in Corpus Christi Bay (central coast) and Trinity Bay (eastern coast). Both bays exhibit significant changes in paleo-environments throughout the Holocene, but the cause of these changes (sea-level, climate change or changes in valley geomorphology which influenced bay flooding history) have remained uncertain. We rely on results from detailed seismic and sedimentological analyses of these and other bays of the western Gulf Coast region (Galveston estuary complex, Matagorda Bay, Sabine Lake, Calcasieu Lake, Corpus Christi Bay, and Copano Bay; Anderson et al., 2008; Maddox et al., 2008; Milliken, 2008a; Simms et al., 2008; Troiani et al., 2011) to address the potential causes of environmental changes observed in these bays during the Holocene, and to investigate likely forcing mechanisms for climate change in the region.

2. Study Areas

2.1 Physical attributes

Corpus Christi Bay is a moderate-sized bay located within Texas' central coast with a surface area of roughly 434 km² (Fig. 2A). The bay is a shallow estuary, with an average a depth of 3 to 4 m (Simms et al., 2008). Average subsidence rates for this region are less than 0.05 mm/yr (Paine, 1993; Simms et al., 2013). The bay is fed water and sediment by the Nueces River. It provided 6.3 x 10⁸ m³ yr⁻¹ of freshwater (Henley and Rauschuber, 1981; Mannino and Montagna, 1996;

Wermund, 1996) and 750,000 tons yr^{-1} of sediment before installation of Nueces basin dams (constructed in 1958 and 1982) (Shepard, 1953; Shepard, 1955; Montagna et al., 2002). The river is 500 km in length and has a drainage area of 43,502 km^2 (Hudson and Heitmuller, 2008). Mustang Island separates Corpus Christi Bay from Gulf of Mexico waters, and has been stable since ~7.5 ka (Morton and McGowen, 1980; Simms et al., 2006; Simms et al., 2008; Ferguson et al., in press). Corpus Christi Bay's proximity to both semiarid and subhumid climatic zones makes it an ideal location for a palynological study (Fig. 1). Since this area serves as the boundary between these climate zones, even a small climatic change would cause a shift in vegetation, and in turn be preserved in the palynological record.

Trinity Bay is located along Texas' northern coastal plain and is one of the five bays that comprise the Galveston estuary complex (Fig. 2C). This complex averages 2–3 m in depth (Anderson et al., 2008), and has more than twice the amount of subsidence seen in Corpus Christi Bay (0.13 mm/yr) (Paine, 1993; Simms et al., 2013). Trinity Bay is fed freshwater by the Trinity River with a mean daily discharge rate of 395 $\text{m}^3 \text{s}^{-1}$ and a combined upper and lower watershed area of 84,500 km^2 (Lester et al., 2002; Wen et al., 2008). The Trinity River has been impounded upstream by the U.S. Army Corps of Engineers at Lake Livingston Dam since 1968 serving as major water source for Houston, TX (Traverse, 1990). Galveston Island and Bolivar Peninsula have separated the Galveston estuary complex from the Gulf of Mexico since 5.5 ka and 2.5 ka, respectively (Anderson et al., 2008; Rodriguez et al., 2004). Marine waters currently flow partially through the 3 km wide Bolivar Roads inlet, located between the barrier island and spit (Anderson et al., 2008; Rodriguez et al., 2004). Trinity Bay is on the border between subtropical Prairie Parkland Province and Southern Mixed Forest Province, making it also potentially sensitive to shifts in vegetation.

2.2 Holocene flooding events

Both bays occupy incised valleys formed during the fall in sea-level between 120 and 20 thousand years before present (ka) (Rodriguez et al., 2004; Simms et al., 2006; Anderson et al., 2008; Simkins et al., 2012). The evolution of the modern bays spans much of the Holocene, from ~ 9.5 ka to present (Anderson et al., 2008; Simms et al., 2008). Throughout the Holocene, the average rate of sea-level rise in the western Gulf of Mexico declined, from 4.2 mm/yr in the early Holocene to 1.4 mm/yr in the mid-Holocene and 0.4 mm/yr in the late Holocene (Milliken et al., 2008b). The evolution of the bays of the western Gulf was characterized by punctuated episodes of change when environments stepped landward (Rodriguez et al., 2005; Anderson et al., 2008; Simms et al., 2008). Some of these flooding events appear to have occurred contemporaneously across the region and were interpreted as having been caused by episodes of accelerated sea-level rise (Milliken, 2008b; Rodriguez et al., 2010; Anderson et al., 2014). Other flooding events were more localized, effecting only one or two bays, and were associated with changes in the antecedent topography of the incised valleys occupied by the different bays that resulted in variable flooding histories (Rodriguez et al., 2005). More specifically, these flooding events were caused by accelerated flooding of broad fluvial terraces along valley margins (Rodriguez et al., 2005). The remaining flooding surfaces were attributed to reductions in sediment supply to the bays in response to climate change, in particular reduced precipitation and fluvial discharge (Anderson et al., 2008; Simms et al., 2008). However, direct evidence for these climate changes remains limited.

The earliest known flooding event and occupation of the modern bays occurred around 9.6 ka, and was followed by the larger 8.2 ka sea-level rise event caused by the drainage of glacial Lake Agassiz-Ojibway (Rodriguez et al., 2010; Simms et al., 2010; Ferguson et al., in press). Several

other flooding events have occurred in these bays during the mid- to late Holocene. This includes a 7.7– 7.4 ka flooding event in Trinity Bay, which is tentatively interpreted as resulting from a decrease in sediment supply to the bay (Anderson et al., 2008). Corpus Christi Bay experienced more recent flooding events at 5.4 ka, and at 3.6 ka that are also believed to have been caused by a decrease in sediment supply (Simms et al., 2008; Troiani et al., 2011).

2.3 Modern coastal vegetation and habitat

Southern to central Texas upland extant vegetation is dominated by a variety of grasses (Poaceae) as well as a variety of coastal scrub species indicative of arid coastal environments. Due to southern Texas' aridity, bottomland hardwood forests (*Carya aquatica*, *Carya texana*, *Ulmus crassifolia*, *Quercus laurifolia*, *Liquidambar styraciflua*, *Nyssa sylvatica*), and swamp forests (*Quercus nigra*, *Nyssa biflora*, *Taxodium distichum*, *Salix nigra*) are not common in this area and are restricted to river floodplains (Hupp and Osterkamp, 1996).

The Strand Plain/Chenier Plain of Texas' eastern shoreline is home to the coastal live oak population (*Quercus virginiana*) (Williams et al., 1999). This species is the most common on Texas' forested barrier islands (or strand environments), on topographic highs, as well as the eastern shoreline (Shaw et al., 1980; Williams et al., 1999). *Carya cordiformis*, *Juglans nigra*, and *Ulmus americana* are restricted to fluvial floodplains and terraces (Hupp and Osterkamp, 1996). Eastern Texas' upland vegetation consists of a variety of grasses (Poaceae) and coastal scrub species like the southern cattail (*Typha domingensis*), which are indicative of moist coastal environments (Williams et al., 1999).

2.4 Previous palynological studies

Although the Gulf of Mexico is one of the most well-studied basins in the world, most of the focus has been on oil exploration or on seismic and sedimentological facies models. Rarely has the intent of these studies been to characterize the Holocene climatic record of coastal Texas. Of those studies that discuss Holocene vegetation change, the majority focus on either the Mississippi River Delta (Törnqvist and Hijma, 2012), the Edwards Plateau (Cooke et al., 2003), or central Florida (Grimm et al., 2006; Huang et al., 2006; Donders, 2014), leaving an absence of insight to western Gulf of Mexico climate in the Texas region. The strong precipitation gradient along the northwestern Gulf Coast results in a diverse coastal vegetation assemblage (Longley, 1995; Williams et al., 1999). Differences in precipitation and evapotranspiration have traditionally defined four different climatic regions, ranging from humid near the Louisiana border to semiarid along the coast and to the Mexican border (Thorntwaite, 1948; Williams et al., 1999) (Fig. 1).

Less than forty palynological studies of Quaternary Texas deposits have been published since the emergence of the discipline in the 1940s. Many of these studies are old in the context of modern analytical techniques (Potzger and Tharp, 1947; Potzger and Tharp, 1954), frequently omitting or broadly estimating age control and pre-dating the standardization of palynological processing. The first Texas palynological studies between the '40s and '50s pre-dated widespread conventional radiocarbon dating and focused on peat bog sediments within the interior of the state (Potzger and Tharp, 1943; Potzger and Tharp, 1947; Potzger and Tharp, 1954). The presence of boreal conifers (*Picea glauca* and *Abies balsamea*) in Patschze Bog provided early evidence for the southern limit of what are now Canadian conifers, and thus dramatically cooler climate (Potzger and Tharp, 1943). In a subsequent study, Potzger and Tharp (1947) proposed a four-stage climate sequence for central Texas following the last glacial maximum. According to the authors, the sequence begins with the presence of spruce and fir (cool-moist climate), giving way to a variety of grasses

and oaks (warm-dry period), then an emergence of alder and chestnut (warm-moist climate), and lastly a hickory and oak vegetation (warm-dry climate) (Potzger and Tharp, 1954). However, the lack of a robust geochronology in this early work limits its usefulness, especially in a modern context.

Graham and Heimsch (1960) included a single radiocarbon date of $7,280 \pm 350$ yr for their central Texas study, and did not agree with the Potzger and Tharp (1954) climate sequence. Rather than four distinct stages, they interpreted a more simplistic climatic history of cooler and wetter conditions at around 12.5 ka, transitioning slowly to today's warm-dry climate in central Texas (Graham and Heimsch, 1960). A subsequent pollen analysis of nearby Hershov Bog with better age control shows the same gradual warming and drying since the early Holocene with decreasing arboreal vegetation (excluding *Quercus*) and an increasing amount of Poaceae and later Asteraceae (Graham and Heimsch, 1960).

Hafsten (1961) examined a playa lake in western Texas and placed several radiocarbon-based age constraints to Potzger and Tharp's (1947; 1954) proposed 4-stage climate sequence. According to Hafsten (1961), at about 30 ka grasslands were present in west Texas and were replaced between 22.5–14 ka by conifer forests as climate cooled. Between 14 and 10 ka, a transitional period occurred with conifer forests being replaced by grasslands and some small shrubs. During the final stage from 10 ka to today, grasslands once again dominate the landscape in the lower elevations of the western region.

Several other palynological studies were completed following these first works (Bryant and Shafer, 1977; Hall, 1985; Holloway et al., 1987; Bousman, 1998), all of which studied the various peat bogs, lakes, and archaeological sites in central and western Texas. Eastern Texas and its associated coastal plains have largely been ignored due to the scarcity of sites promoting

palynological preservation. Palynomorph preservation is generally poor due to a combination of factors including high microbial activity in leaf litter on forest floors, sporopollenin damage caused by the constant drying and wetting of soil, and soil oxidation (Bryant and Holloway, 1985). However, several of these later studies (McAndrews and Larson, 1966; Bryant, 1977) commonly provide brief climatic records, as they primarily focus on specific anthropological questions, and are based on cave samples or other samples that produce a skewed vegetation record, such as human coprolites (Williams-Dean and Bryant, 1975) or rat middens (Van Devender and Riskind, 1979). Indeed, there are only a handful of studies with reasonable age constraints, and therefore relevant to Texas' Holocene climate history (Graham and Heimsch, 1960; Albert, 1981; Holloway and Bryant, 1984; Bousman, 1998), without a clear consensus shared among them.

Here we provide a new record of Holocene climate for eastern Texas, based upon three subaqueous bay floor cores containing well-preserved palynomorphs and supported by an extensive modern radiocarbon geochronology and tied to in-depth seismic and sedimentological analyses of the Texas coast (Anderson et al., 2008; Simms et al., 2008).

3. Materials and methods

3.1 Sampling and radiocarbon age model

Drill core CCB02-01 from Corpus Christi Bay was selected for palynological analysis because it contains fine-grained (silt) central-upper bay sediments where sedimentary facies have remained relatively unchanged since approximately 7,500 years (Fig. 2; Simms et al., 2008). The site was cored to a depth of 21 meters. Nine radiocarbon dates from Simms et al. (2008) provide our basis for age control. Sixty-eight samples were collected for palynological analysis with samples occurring at 10 to 20 cm intervals depending on sediment availability within the archived core.

Two drill cores from Trinity Bay were selected for palynological analysis (TBHD-5-1 and TV99-3 (Fig. 2). Six radiocarbon dates for core TBHD-5-1 and four radiocarbon dates for core TV99-3 provide age control (Fig. 3; Table 1). Two additional radiocarbon samples from core TBHD-5-1 and three from TV99-3 were sent to UC Irvine Keck Carbon Cycle AMS Facility to help further constrain the late Holocene ages (Table 1).

All radiocarbon ages were calibrated using Marine13 (Reimer et al., 2013) and a basin-wide reservoir correction of 300 years was applied as suggested in Törnqvist et al. (2015). An age model was produced for each core using the Bchron package for R (Haslett and Parnell, 2008; Parnell et al., 2008). Dates within the text and figures are reported at the Bchron 50% quantile. Output of the Bchron model quantiles 2.5%, 50%, and 97.5% are provided in Table S1.

3.2 Palynological analysis

Sediment samples were chemically processed by Global GeoLab Limited following standard palynological laboratory methods (Brown, 2008). Dry sample weights were recorded before processing, with an average of 10 grams used per sample. Lastly, a *Lycopodium* spores tablet with a known amount was added in order to determine palynomorph concentration values (palynomorph/gram). A minimum of 300 known in-situ palynomorphs (pollen, spores, and dinoflagellate cysts) were counted when available for each sample to ensure accurate paleo-environmental representation.

3.3 Statistical analyses

Statistical analyses were used in combination with individual core age-models to determine the potential timing of shifts in paleo-environment or climate. Constrained cluster analysis using Bray-

Curtis similarity and correspondence analysis (CA), both based on raw abundance data, were used to examine changes in pollen and spore assemblages through time within each core. Similarity Percentage analysis (SIMPER) based on the Bray-Curtis similarity was achieved to determine which taxa were controlling the clustering (Supplementary Table S2). All statistical analyses were conducted using PAST v. 2.17c freeware (Hammer et al., 2001).

4. Results

4.1 Age models

Corpus Christi Bay core CCB02-01 uses the same age model produced by an earlier study (Ferguson et al., in press). The age models for Trinity Bay's TBHD5-1 and TV-99-3 have been updated and revised from their previously published versions (Anderson et al., 2008), so that the three cores have similarly-derived age models and can be shown on the same age axis (Fig. 3). Ages in the text and figures always refer to the Bchron 50% quantile, and reported in thousands of years before present (ka). Core CCB02-01 covers the most time, from 11.5 ka to 1.6 ka. Our sampling of TBHD5-1 spans from 4.5–1.0 ka, and core TV99-3 includes a short yet detailed look into the most recent past from 1.8 ka to 0.2 ka.

4.2 Palynological results

Twenty-three unique taxa were observed within these cores (Supplementary Table S1). Common to all samples were nonarboreal taxa including low and high spine Asteraceae (mainly *Ambrosia* and *Helianthus*), *Chenopodium*, Poaceae, and arboreal taxa such as *Carya*, *Pinus*, and *Quercus*. The abundance of these taxa varies between cores; however, the majority of taxa are shared by both bays. Absolute abundance of palynomorphs generally decreases down-core, likely

due to oxidation after deposition. No clear first or last occurrence for any given taxa was found, but rather a transition through time of dominance of one group versus another. Lack of reworked taxa and the high quality of observed palynomorphs imply that the studied cores are representative mostly of their immediately surrounding environment, and thus mostly represent their respective drainage basins only to a limited extent.

In general, these assemblage results from Trinity Bay and Corpus Christi Bay show a trend of herbaceous nonarboreal dominated assemblages in the early to mid-Holocene transitioning into arboreal dominated assemblages in the late Holocene (Fig. 4). The transition within Trinity Bay occurs much more rapidly. Two noteworthy peaks in *Carya* (hickory tree, pecan tree) are noted at 4.1 ka and 2.2 ka in Corpus Christi Bay. Overall, Corpus Christi Bay has much more nonarboreal than arboreal pollen throughout the studied interval (average relative abundance of nonarboreal is 72%) while Trinity Bay has been clearly more humid throughout the time interval studied with arboreal pollen dominating with average values of 70% (i.e., average relative abundance of nonarboreal of only 30%) (Fig. 5). Statistical results further explore this palynological trend and provide better constraint on the timing of observed changes.

4.3 Statistical results

Cluster analysis (Supplementary Figure 1) followed by correspondence analysis were performed on complete pollen assemblages within each core (Fig. 6A–C), as well on just the 11 taxa common to each core. The all-taxon and 11-taxon analyses for each separate core produced essentially similar results, as the 11 common taxa together control more than 80% of among-cluster differences. These 11 major taxa are Asteraceae, *Chenopodium*, Poaceae, *Ilex*, Onagraceae, *Acer*, *Alnus*, *Carya*, *Juglans*, *Pinus*, and *Quercus*.

Four distinct sample clusters (Fig. 6A, colored polygons) are present in both CCB02-01 and TBHD5-1; TV99-3 has the fewest samples, and only produced three clusters. The clusters correspond to different age ranges within each core, with no inversions or mixing. The same observational trend seen within the palynological results (Fig. 4) is also seen within these clusters: deeper samples are dominated by herbaceous and nonarboreal taxa, which transition to mostly arboreal taxa towards the top of the cores. In addition, the clusters provide important age control for each transitional event. At Corpus Christi, the first cluster occurs from 11.2 to 10.1 ka, and is characterized by the strongest representation of herbaceous plants with mostly *Chenopodium*. A second cluster occurs from 10 to 8.4 ka; the samples included in this cluster are mainly composed of herbaceous plants (Poaceae, Asteraceae) but also a variety of angiosperms (*Juglans*, Onagraceae, and Apiaceae) and *Ephedra*. A unique 200 year-long cluster occurs from 8.4 until 8.2 ka. The vegetation is not extremely different in this horizon, however pollen abundance decreases tremendously, while dinoflagellate cyst peaks in abundance (Fig. 5). Finally, the fourth cluster represents a tree-dominated environment (*Alnus*, *Carex*, *Quercus*, *Ulmus*, *Pinus* and *Carya*) from 8.2 ka onwards.

Although the interval at Trinity Bay is shorter (the last 4.9 ka), a similar trend towards an increasingly tree-dominated environment is noted. Some minor changes allow the subdivisions of the period of tree dominance into four time intervals for core TBHD5-1 (Fig. 6B). These sub-intervals occur at the age intervals 4.9 to 4.1 ka, 3.8 to 2.0 ka, 1.9 to 1.5 ka, and 1.5 to 1.0 ka. It is interesting to note that one of the markers allowing for the separation of the fourth interval is the presence of *Zea mays*, or maize. Despite being wind-pollinated, *Zea mays* pollen grains are large in size and density causing the grains to sink from the air quickly near the crop itself allowing for

a local signal (Traverse, 2007). The presence of maize occurs in core TBHD5-1 at 1.5 ka, 1.3 ka, and 1.2 ka (one grain per interval; Table S2).

Core TV99-3 has three distinct palynological clusters (Fig. 6C). Between 2.8 and 2.6 ka a majority of herbaceous genera (*Chenopodium*, Poaceae, *Utrica*, and *Ilex*) and two arboreal taxa (*Quercus*, and *Carya*). From 2.5 to 1.8 ka arboreal *Juglans*, *Galium*, and *Hippuris* control this transitional cluster. Lastly, between 1.6 ka and 0.2 ka *Pinus* (pine), *Salix* (willow), and *Alnus* (alder) characterize the most recent time period. This core has more taxa as outliers than the other cores because of the relatively low abundance of many of the taxa (Fig 6C).

The same analyses performed on a dataset including all three cores shows that samples from the three cores plot amongst one another, and not within separate, core-dependent groups (Fig. 7). Comparison of the first correspondence axis (CA1) resulting from the combined core analysis against the CA1 resulting from the separate correspondence analysis of core CCB02-01 yields an almost perfect linear relation ($R^2 = 0.96$) (Fig. 8A); comparison with both Trinity Bay cores yields an even higher R^2 of 0.99 (Fig. 8B). Such congruence of the first correspondence (CA1) axis between the three separate cores and the combined core analyses indicates that this axis within each separate core points toward the same environmental gradient controlled by the same taxa. This makes it possible for direct comparisons of the environmental changes seen within the three cores, and strongly suggests that these changes were driven by allogenic factors influencing both bays, rather than separate autogenic forcings.

Based on the sample groups resulting from the cluster analyses of each separate core, SIMPER analyses enable the identification of the taxa that most contribute to cluster's differentiation – i.e., the taxa that most strongly vary in abundance from one cluster to another (Supplementary Table S2). At Corpus Christi Bay, contrasting the two oldest samples groups D and C (Fig. 6A: red and

purple clusters) shows that 78% of the overall average difference (OAD) between these two clusters is controlled by changes in abundances of *Chenopodium*, Asteraceae, *Quercus*, and Poaceae (in order of percent contribution; Table S3). Contrasting the second (C) and third (B) samples groups shows that 72% of their OAD is driven by Asteraceae, *Chenopodium*, *Quercus*, and Poaceae. Last, contrasting the most recent sample groups B and A shows 82% of their OAD is controlled by changes in abundances of *Pinus*, *Quercus*, *Chenopodium*, and Asteraceae. In Trinity Bay these same taxa are involved at similar percentages of contribution to between-group OAD, indicating similar changes in vegetational habitats from one cluster to another. Thus, the main difference between the bays is based not upon the individual clusters of vegetation, but rather the timing and appearance of these clusters (Fig. 6).

5. Discussion

5.1 Vegetational Holocene evolution

Factors such as soil type, water or soil pH, flooding frequency, light intensity, nutrients, and anthropogenic disturbances can produce different community structures composed of different plants or mixtures of plants with or without a climatic forcing (Wharton et al., 1982). This said, clear trends are observed and statistically validated in the studied cores. Cores from both bays show a vegetational trend from nonarboreal-dominated to arboreal-dominated vegetation through the Holocene, the change being more pronounced in Trinity Bay (Fig. 5). Assemblages determined from cluster, correspondence, and SIMPER analyses show little variation between the two bays despite their geographic separation. Overall, the higher relative abundance of trees at Trinity Bay confirms that this area was more humid than Corpus Christi Bay throughout the time interval covered by all three cores. An exception occurs at the base of the observed Trinity Bay record,

where arboreal pollen is close to 15%; it's unclear if this suggests that mid-Holocene Trinity Bay was much drier than it is now, or if this is simply because the Trinity bayhead delta was further away from the cored locations at this point in time, which reduced input of arboreal pollen.

Out of the dominant taxa observed in this study, many are tolerant of infrequent flooding of varying duration. The most tolerant taxon is *Taxodium distichum* (common in shallow waters that experience frequent drying periods between floods), while *Carya* and *Juglans* are unable to survive more than a few days of flooding at a time. Thus, all most likely represent low-lying forest cover types with *Taxodium* in lower sections, and exclude full marsh or backswamp locales. Most *Quercus* species currently living along Texas' coast can only tolerate minimal to occasional flooding (*Quercus alba*, *Q. fusiformis*, *Q. macrocarpa*) (Moulton et al., 1997). Other species (*Q. nigra*, *Q. phellos*, *Q. lyrata*) are slightly more tolerant of flooding and typically occur along river floodplains at higher elevations than *Taxodium distichum* (Moulton et al., 1997). However, *Quercus* pollen is difficult to reliably isolate to the species level with a light microscope and therefore it is important to use other genera to help understand a habitat's tolerance to flooding and typical amount of water saturation. *Carya* is commonly associated with *Juglans*, *Fraxinus*, *Celtis*, and *Ulmus* along shallow marginal swamps and floodplains of the Gulf Coast. *Carya* is particularly common inland and is part of the riparian vegetation of the Nueces River (Vaughn Bryant, pers. comm.). Thus, the peaks observed at 4.1 ka and 2.2 ka in Corpus Christi Bay could indicate an increase in river flux; *Myrica* is normally an understory shrub within this community (Moulton et al., 1997). The prevalence of *Pinus* pollen found in samples is likely a product of regional pollen rain from the drainage basins' interfluvial wet pine flatlands (Moulton et al., 1997). While some *Pinus* pollen is considered to be autochthonous, the abundance of pollen *Pinus*

386 produces, along with its morphological ability to travel large distances, should be kept in mind
387 when determining its presence around the bays and basins they drain.

388 Herbaceous taxa are abundant, particularly in the lower sections of all the cores. Many of these
389 species are confined to open coastal habitats due to their need for full sunlight. Herbaceous plants
390 can also dominate drier environments and tundra plains, but some species of Chenopodiaceae,
391 low-lying Asteraceae, Cyperaceae, and Poaceae (for instance *Spartina* marsh grasses) are also
392 adapted to growing in continually wet fresh to brackish conditions, with many species able to
393 tolerate the salinity of coastal soils in return for the freedom of little to no canopy cover. The
394 occurrence, and at times dominance, of these species within some intervals indicates dominance
395 of a marsh environment.

396 In summary, the environment at both study areas evolved from a marsh-dominated environment
397 to an increasingly dense riparian canopy of trees along the rivers and bays. The trend occurs over
398 a much shorter period in Trinity Bay, as Corpus Christi Bay was transitioning away from
399 nonarboreal vegetation as much as 4 ka earlier. The shorter record from Trinity Bay makes direct
400 comparison of these bay's coeval vegetation regimes impossible for much of the early Holocene,
401 but correspondence analysis results confirm that the clusters occurring at both bays are identical.
402 Thus, a longer record in Trinity Bay would likely only extend the base of the oldest nonarboreal-
403 dominated cluster, and not affect the age of the transition between clusters.

405 5.2 Relationship between the Holocene climate evolution and the sedimentation of coastal Texas

406 In Trinity Bay, *Chenopodium* and Asteraceae are the main vegetational component of the oldest
407 samples from 4.91–4.05 ka (TBHD5-1; Fig. 6B). The vegetational landscape began experiencing
408 more diversity around 3.83 ka, at which time a number of other nonarboreal elements such as

Apiaceae, Onagraceae, Poaceae, and *Ilex* appear in core TBHD5-1. TV99-3's shorter record begins at 2.84 ka, and mirrors the assemblages found within TBHD5-1. *Alnus* and *Carya* are important arboreal components beginning at 2.04 ka, while *Pinus* and *Juglans* have the greatest influence from 1.89–1.53 ka (TBHD5-1 and TV99-3). Increased fluvial discharge, frequency of flooding, and associated increase in sediment delivery to Trinity Bay are thus indicated for the late Holocene. This corresponds to significant growth of the Trinity bayhead delta, as documented by Anderson et al. (2008), and is corroborated by the low dinoflagellate cyst concentrations seen within proximal TBHD5-1 during this time, interpreted as indicating increased freshwater discharge to the bay (Fig. 2; Fig. 5).

Dinoflagellate cyst concentrations at more distal TV99-3 were unaffected in the same way, with a peak in concentrations at that location at ~1.7 ka. This peak is smaller in magnitude than a peak occurring at 0.8 ka that we hypothesize is related to an established major storm (Rodriguez et al., 2004; Anderson et al., 2008). Rodriguez et al. (2004) suggest that the storm cut deeply into the Bolivar Peninsula and resulted in a reduction of the Galveston-Bolivar barrier complex as an effective salinity barrier. Thus, perhaps the 1.7 ka event is similarly storm-related.

Finally, a major shift to oak-pine woodland vegetation occurred around 1.49 ka based on our correspondence analysis. *Pinus* and *Quercus* are the major overall contributors to the pollen assemblage in this recent section. This assemblage also includes *Zea mays*, which is an indication of early agriculture. Thus, this assemblage is likely either indicative of, or coincides with, anthropological influence rather than a climatic change. Native American activity in coastal Texas is known for that time period from other records (Ricklis, 2004), and is thought to have occurred as far back as 9.5 ka (Warny et al., 2012).

431 The Corpus Christi Bay palynological record generally shows a similar overall vegetational
432 evolution as observed in Trinity Bay, but this evolution occurred much earlier. In general, Corpus
433 Christi Bay has an overall lower arboreal component than Trinity Bay, but its transition to
434 dominance of that component occurred up to 4 ka sooner. Similar to Trinity Bay core TBHD5-1,
435 Corpus Christi Bay core CCB02-01 had enough within-core differences allowing for the
436 subdivision of four vegetation assemblages through time. As stated previously, these assemblages
437 are statistically identical to the assemblages seen later in Trinity Bay (TBHD5-1 and TV99-3).
438 *Chenopodium* primarily controls variability in the earliest part of the Corpus Christi Bay record
439 from 11.2–10.1 ka. More herbaceous elements (Asteraceae, Apiaceae, Onagraceae, and Poaceae)
440 are added to the assemblage starting from 10–8.4 ka (Fig. 4a). From 8.4–8.2 ka (Fig. 4a, blue
441 cluster), a brief period of time is isolated by cluster analysis (Supplementary Figure 1), likely due
442 to the low pollen yield recovered during this time. This interval is also marked by a flooding
443 surface (FS2) expressed in seismic records and cores from the bay (Simms et al., 2008; Rodriguez
444 et al., 2010). Ferguson et al. (in press) observed a marked increase in dinoflagellate cysts during
445 that same interval of time with an assemblage dominated by *Polysphaeridium zoharyi*, a
446 dinoflagellate species requiring marine salinity. They postulated that this prominent and sudden
447 increase corresponds to the overtopping of Mustang Island during the ~8.2 ka northern hemisphere
448 ice sheet mass wasting event and associated abrupt sea-level rise (the only major perturbation in
449 the $\delta^{18}\text{O}$ curve for the Holocene, Fig. 5). That interval is not marked by notably different
450 vegetation, so it is indeed likely that the sedimentation at that time was controlled by a punctuated
451 sea-level rise event, rather than a regional climatic event. After this time, from 8.2–1.6 ka, the
452 increasing abundance of trees is the main element controlling the clustering. This is coincident

with the progradation of the delta after the major flooding of the delta during the 8.2 ka event. *Pinus*, *Quercus*, *Acer*, *Alnus*, *Carya*, *Ulmus*, and *Celtis* all contribute to the clustering at this time.

Simms et al. (2008) noted two other potential flooding events at 5.4 ka and 3.6 ka (revised ages of FS3 and FS4 from Ferguson et al., in press age model). At 5.4 ka, our palynological record indicates that this time interval marks the beginning of an increase in arboreal pollen, along with a marine event marked by an increase of dinoflagellate cysts (Fig. 5) (Ferguson et al., in press). Simms et al. (2008) believed that this horizon was either due to a climatic change towards warmer and drier conditions or the flooding of a relict Nueces fluvial terrace. We suggest that the coupled increase of dinoflagellates and arboreal pollen indicates that this event was a result of flooding of relict terraces.

At 3.6 ka, our records from Corpus Christi Bay show arboreal pollen accounts for 50% of the palynological assemblage, well above the core average (Fig. 5). Simms et al. (2008) hypothesized that this horizon might have been associated with a decrease in sediment delivery due to a climatic drying event. Based on the palynological data, the 3.6 ka event was marked by a climate shift but was likely a return to more mesic climatic conditions, which would have increased tree cover, stabilized the landscape, and a decreased fluvial output/sediment supply. This shift to more mesic condition around 3 ka is also shown as a decrease in more salt tolerant foraminifera within Baffin Bay (Buzas-Stephens et al., 2014).

6. Conclusions

Our results show that the Holocene coastal environments of central Texas began transitioning from herbaceous (nonarboreal) dominated vegetation to arboreal dominated vegetation as early as ~8.4 ka. This is indicative of a transition to less aridity as coastal rivers and bays evolved from a

marsh-dominated environment to an increasingly dense riparian canopy of trees. Lack of reworked palynomorphs indicate that our samples are indicative of local vegetation, rather than regional or basin-scale vegetation changes.

In Corpus Christi Bay, pollen indicates potentially increased discharge from Nueces river at 4.1 ka and 2.2 ka. Marine flooding events are seen at 8.2 ka, 5.4 ka, and 3.6 ka. As suggested by Ferguson et al. (in press), the 8.2 ka event is associated with the rapid draining of Lake Agassiz-Ojibway. Simms et al. (2008, FS2) suggested that the 5.4 ka event was the flooding of relict fluvial terraces, which we support with an associated increase in dinoflagellate concentrations likely related to the areal increase in warm brackish surface waters. At about 3.6 ka there was an increase in mesic conditions, indicated by a large abundance of arboreal pollen. This was coincident with a slight increase in dinoflagellate cysts indicating low freshwater input into the bay. This event corresponds to a flooding surface observed by Simms et al. (2008, FS4) which they interpret as the product of low sediment delivery to the bay.

Flooding events in Trinity Bay were observed at 1.7, 1.2, and 0.8 ka; the 0.8 ka event is likely related evidence of a major storm that Rodriguez et al. (2004) suggest cut through the Bolivar Peninsula at that time. The 1.7 and 1.2 ka events are smaller in magnitude, and may also be storm-related. Finally, the most recent vegetation assemblage includes *Zea mays*, indicative of native American activity around Trinity Bay starting at least 1.49 ka.

Our record from Corpus Christi Bay shows a gradual change during the middle Holocene Climate Optimum, which appears to have been a significant climate event based on other paleoclimate records (Toomey, 1993; Humphrey and Ferring, 1994; Nordt et al., 1994; Nordt et al., 2002). We see no evidence that the vegetation assemblage of coastal Texas changed in direct response to the Climate Optimum. There is subtle, but not statistically significant, evidence of the

more variable climate oscillations for the late Holocene. But, our data indicates that Coastal Texas' climate operated independently from the central Texas regions previously studied. Both bays underwent a nonarboreal to arboreal environmental change, starting around 8.4 ka in Corpus Christi Bay, but not until ~5 ka in Trinity Bay. The late Holocene record for Trinity Bay shows a greater dominance of arboreal pollen than in Corpus Christi Bay for the same time interval, likely due to its greater precipitation and lower evapotranspiration rates.

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Table and Figure captions

Table 1. Radiocarbon dates used in this study.

Fig. 1. Location of Corpus Christi Bay and Trinity Bay, Texas. Corpus Christi Bay core CCB02-01 and Trinity Bay cores TBHD5-1 and TV99-3 were used for this investigation. Precipitation gradients were mapped in ArcGis (metadata source from <https://www.sciencebase.gov/catalog/item/513e317ce4b07b9dc9e7e9fb>).

Fig. 2. A. Trinity Bay, TX core locations TBHD5-1 and TV99-3. **B.** Generalized cross section of Trinity Bay, TX (from Anderson et al., 2008). Blue line shows section location. **C.** Location of Corpus Christi Bay, TX core CCB02-01 **D)** Generalized cross section of Corpus Christi Bay (from Simms et al., 2008). Red Line shows section location.

Fig. 3. Complete Bchron Age Model and radiocarbon data for cores CCB02-01, TBHD5-1, TV99-3. See Table 1 for complete radiocarbon data.

Fig. 4. Summary pollen chart for Corpus Christi Bay and Trinity Bay with a common age axis. Inset plates show common species *Chenopodium*, *Quercus*, *Poaceae*, *Pinus*, *Asteraceae*, *Carya*.

Fig. 5. Summary plot of the arboreal pollen concentrations, alongside a gradually sloping $\delta^{18}\text{O}$ record (Rasmussen et al., 2006; Vinther et al., 2006) Overlaps of core records show that each is a part of the same overall linear record of arboreal pollen increasing during the Holocene. Dinoflagellate cyst concentrations from this study are also shown, along with Corpus Christi Bay marine events (ME) from Ferguson et al. (in press), flooding surfaces (FS) from Simms et al. (2008) with revised ages reported from Ferguson et al. (in press). Trinity Bay flooding surfaces and geologic events from Anderson et al. (2008) shown with 1.6 ka (FS8) event matching with our TV99-3 dinoflagellate record. The Trinity Bay (TV99-3) 0.8 ka event corresponds to a major storm event recorded by erosion of beach ridges on Bolivar Peninsula (Rodriguez et al., 2004). The vertical dashed green line represents the average arboreal value for Corpus Christi (28%) while the dashed grey line represents the average arboreal value for Trinity Bay (70%).

Fig. 6. All-taxon correspondence analysis results for each studied core. Polygon grouping was derived from cluster analysis (Supplementary Figure 1–3). **A.** Corpus Christi Bay, core CCB02-01. **B.** Trinity Bay, core TBHD5-1. **C.** Trinity Bay, core TV99-3.

Fig. 7. Correspondence analysis result based on the combined three-core 11-taxon dataset. Samples from different cores plot amongst one another instead of within separate, core-dependent groups.

Fig. 8. Comparison of the first correspondence axis (CA1) of the combined three-core dataset with the CA1 of datasets from the individual bays. **A.** Comparison with CCB02-01 yields an R^2 of 0.96. **B.** Comparison with both Trinity Bay cores yields an R^2 of 0.99.

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

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