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A unified conceptual model of coastal response to accelerating sea level rise, Florida, U.S.A.

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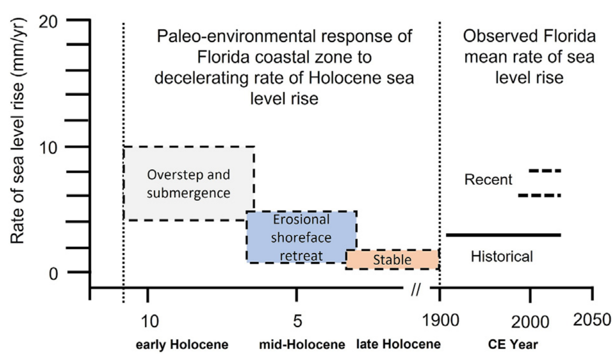
HIGHLIGHTS

- Coastal response to Holocene marine transgression dictated by rate of SLR
- Analysis of NOAA tide gauge station data reveals substantial recent acceleration.
- Recent rates of SLR are the same as those associated with the early Holocene.
- The coastal zone was overstepped and submerged during the early Holocene.
- Widespread coastal instability and submergence are expected by year 2050.

GRAPHICAL ABSTRACT



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ABSTRACT

Aggregation of paleo-environmental data derived from geological investigations conducted on the shoreface and inner shelf of Florida's six coastal geomorphic sectors revealed a common and synchronous response to a decelerating rate of Holocene sea level rise: (1) early Holocene overstep and submergence (~10–5 mm yr^{-1}), (2) mid-Holocene erosional shoreface retreat (~2 mm yr^{-1}), and (3) late Holocene stabilization (<1 mm yr^{-1}). Linear best-fit analysis of sea level data collected at 14 NOAA tide gauge stations distributed along the entire Florida coast indicates the rate of sea level rise has accelerated from a historical average of 3.1 mm yr^{-1} (<1972–2022; range 2.2 to 4.2) to 5.9 mm yr^{-1} (1993–2022; range 4.8 to 6.9) and 8.2 mm yr^{-1} during the 21st century (2003–2022; range 7.6 to 10.0). The 21st century rates vary between stations, however all fall within the range of values documented during the early Holocene; a time when Florida's coastline was rapidly transgressed. Recent studies have demonstrated that the destabilizing effects of this acceleration on Florida's coastal geomorphology and ecology are already evident. Rates of rise are expected to continue increasing and this will accelerate the pace and scale of landward translation and submergence of Florida's coastal environment.

1. Introduction

Both the rate and magnitude of sea level rise (SLR) are increasing in response to global climate change and current projections to year 2100 (c.f., Sweet et al., 2022) are likely to be exceeded in response to additional loss of ice sheet mass, thermal expansion of seawater, and the ever-widening greenhouse gas emissions deficit (Cozannet et al., 2019; Frederikse et al., 2020; Siegert et al., 2020; DeConto et al., 2021; Noel et al., 2021; United Nations Environmental Program, 2021; Box et al., 2022; Greene et al., 2022; Horhold et al., 2023). Understanding how coastal environments will respond to accelerating SLR is important because these systems provide substantial ecosystem services including (a) attenuation of storm surge and saltwater encroachment, (b) habitat to threatened and endangered species, as well as

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recreational and commercial fisheries, and (c) esthetic landscapes that support ecotourism and resident quality of life (Barbier et al., 2011; Arkema et al., 2013; Geselbracht et al., 2015; Hughes et al., 2017). Previous studies reporting the likely effects of SLR on Florida's coastal environment have focused on a *specific location* (Wanless et al., 1994; Wanless and Vlaswinkel, 2005), *habitat type* (Parkinson et al., 1994; Geselbracht et al., 2011) or *geomorphic feature* (e.g., estuaries; Geselbracht et al., 2015) based upon *global projections* (Overpeck et al., 2006; Vermeer and Rahmstorf, 2009; Church et al., 2013). Each conveyed the probability of substantial deleterious impacts on Florida's coastal environment. However, as pointed out by Hamlington et al. (2020), coastal vulnerability assessments should consider a site-specific sea level history whenever possible to account for the diverse set of processes that lead to local variations in SLR relative global observations. While there have been a few recent analyses of local and regional SLR trajectories along the Florida coast (Southeast Florida Climate Compact, 2020; Hamlington et al., 2022; Sweet et al., 2022), none have translated those projections into coastal response scenarios of geomorphic or ecologic change.

In this investigation, a novel application of the principle of uniformitarianism was used to constrain the likely response of Florida coastal zone (Fig. 1) to accelerating SLR by 2050. This timeframe was chosen because it is compatible with the renewal cycle of statuary planning frameworks, limits the magnitude of model assumption uncertainties which increase over time, and is similar to the typical design life and financing of urban buildings and infrastructure (Parkinson, 2009; Lawrence et al., 2018; McAlpine and Porter, 2018).

2. Study area

2.1. Coastal geomorphology

The Florida coastal zone consists of two distinct geological provinces: the peninsula and the panhandle. The Florida peninsula is the emergent portion of a karstified, Tertiary carbonate platform (Hine et al., 2003). Siliciclastic (e.g., terrigenous) sediments are locally abundant and derived from erosion of relict sea level high stand deposits (e.g., Atlantic Coastal and Brooksville Ridge; Hine and Belknap, 1986) emplaced prior to the last glacial maximum (Davis et al., 1992). Carbonate sediments increase in relative abundance from north-to-south as a consequence of both the diminishing availability of siliciclastic sediment and the increase in carbonate production associated with the transition from a temperate to sub-tropical climate (Parkinson and White, 1994). The coastal geomorphology and sediments of the panhandle share some similarities to the peninsula (e.g., barrier islands), but this province is more aptly characterized by the presence of incised fluvial embayments and bays, bayhead deltas and large rivers (e.g., Mobile, Escambia, Choctawhatchee, and Apalachicola) that deliver siliciclastic sediments to the coastal zone (Otvos, 1985; Donoghue and Tanner, 1992). The Florida coastal zone is further divisible into six geomorphic sectors (Davis et al., 1992) (Fig. 1), each consisting of distinct coastal landforms, depositional environments, and patterns of sedimentation (Table 1). All were subject to the same submergence history during the Holocene Epoch (Fig. 2). The unified conceptual model developed during this investigation is based upon an analysis of each sector's paleo-environmental response to the Holocene marine transgression.

2.2. Holocene sea level rise

Since the last glacial maximum, globally averaged eustatic sea level has risen by at least 120 m, with the rate of SLR decelerating during the Holocene Epoch (Lambeck et al., 2014). Records of SLR since the last glacial maximum indicate the initial transgression was accompanied by several intervals (e.g., melt water pulses; Fairbanks, 1989; Fairbanks et al., 1992) of extremely rapid rise (e.g., >40 mm yr^{-1}; Stanford et al., 2006; Bard et al., 2010; Donoghue, 2011) until ~11 Kyr cal BP or the onset of the Holocene Epoch. Thereafter, the long-term (i.e., centuries) average trend of SLR in the study domain is typically illustrated as a relatively smooth curve with rates of rise decelerating to the present (Bard et al., 1990; Brooks et al., 2003; Toscano and Macintyre, 2003; Otvos, 2005; Donoghue, 2011; Khan et al., 2022). While there are numerous processes that contribute to SLR in the coastal zone (e.g., eustatic, glacio-isostatic, sediment compaction), it is their net sum that determines the relative rate of rise to which the geomorphology and ecosystem are responding.

In this investigation, five submergence curves were considered, each illustrating the elevation of sea level relative to present within the study domain during the Holocene Epoch (Fig. 2, Table 2). All indicate an initial (e.g., early Holocene) rapid rate of SLR (~10–5 mm yr^{-1} depending on the duration of record) to ~7 Kyr ago. Thereafter and until ~3.5 Kyr ago (e.g., mid-Holocene), it was ~2 mm yr^{-1}, and since then (e.g., late Holocene) has averaged <1 mm yr^{-1} (Donoghue, 1989; Wanless et al., 1994; Parkinson et al., 2015). The late Holocene deceleration is depicted in some (e.g., Brooks et al., 2003), but not all (e.g., Balsille and Donoghue, 2004) submergence curves constructed from data collected in the Gulf of Mexico.

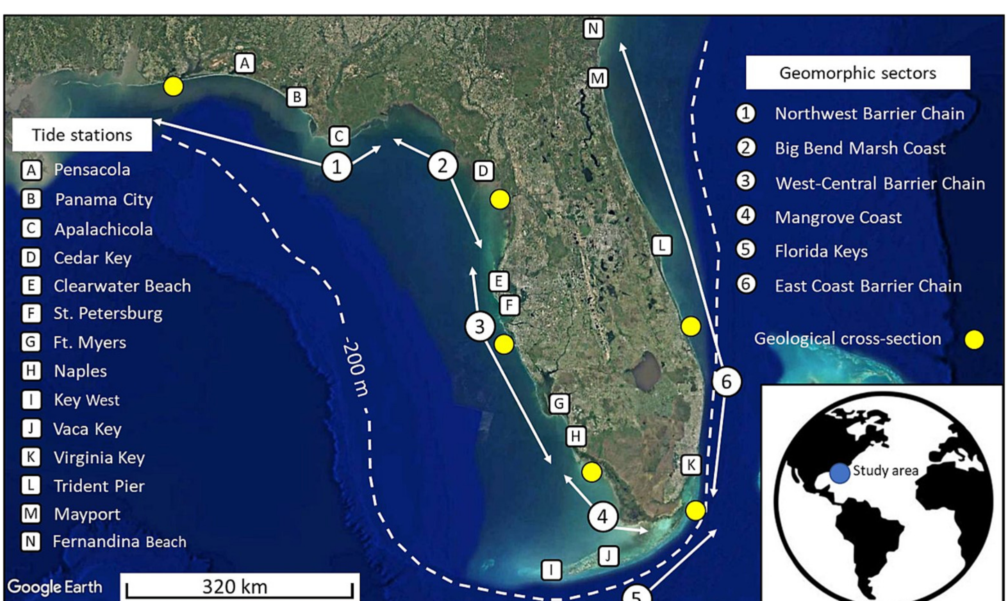

Fig. 1. Satellite image of Florida showing location of six geomorphic sectors described in study, NOAA tide gauge stations from which historical water level data was collected, and geological transects constructed as representative of each sector.

Table 1
Summary of attributes associated with six geomorphic sectors of the Florida coast.
Sources: NWBC - Donoghue and White (1995); Donoghue (1989); Donoghue and Tanner (1992); Locker and Doyle (1992); Otvos (2005), BBM – Hine et al. (1988); Hine and Belknap (1986), WCBC - Davis et al. (1992); Edwards et al. (2003); Finkl et al. (2007); Hine et al. (2003), MC - Davis and Klay (1989); Parkinson (1989); Roberts et al. (1977); Scholl (1964); Shier (1969); Wanless et al. (1994); Wanless and Tagett (1989); Wingard and Lorenz (2014); Yao and Liu (2017), FK – Enos (1977); Hoffmeister et al. (1967); Lidz et al. (2003), ECBC - Field and Duane (1974); Field and Meisburger (1975); Finkl and Andrews (2008); Lighty et al. (1978); Meisburger and Duane (1971); Miller et al. (2014); Parkinson and White (1994); Stathakopoulos and Riegl (2015).

Geomorphic sector	Location	Physical oceanography	Province	Predominant coastal landform	Predominant sediment type
Northwest Barrier Chain	Pensacola to Apalachicola River Delta (300 km)	Low-to-moderate wave climate, microtidal	Alabama-Florida shelf	Narrow linear barrier islands with large back-barrier estuaries and rivers	Siliciclastics derived from fluvial processes, littoral drift, reworking of high stand deposits
			Apalachicola Embayment	Cuspate barrier islands	
Big Bend Marsh	Apalachicola River Delta to Anclote Key (270 km)	Low wave climate, microtidal	NA	Exposed karstified limestone bedrock, salt marsh and oyster reef	Salt marsh peat, oyster
West-Central Barrier Chain	Anclote Key to Cape Romano (300 km)	Low-to-moderate wave climate, microtidal	NA	Narrow linear and drumstick barrier islands with large back-barrier estuaries	Siliciclastics derived from littoral drift and the reworking of high stand deposits
Mangrove Coast	Cape Romano to Florida Bay (120 km)	Low wave climate, microtidal	Ten Thousand Islands	Mangrove forest, oyster reef	Mangrove peat, oyster
			Everglades/Shark River Slough	Mangrove forest	Mangrove peat
			Cape Sable/Whitewater Bay	Cuspate foreland, mangrove forest	Mangrove peat, biogenic carbonate mud
			Florida Bay	Coastal embayment, mudbanks	Biogenic carbonate mud, mangrove peat
Florida Keys	Try Tortugas to Soldier Key (350 km)	Low wave climate, microtidal	NA	Limestone island archipelago	Coral reef debris, biogenic carbonate sand and mud, mangrove peat
East Coast Barrier Chain	Soldier Key to Georgia border (550 km)	Moderate-to-high wave climate, microtidal	NA	Narrow linear barrier islands	Siliciclastics derived from littoral drift and the reworking of high stand deposits

2.3. Susceptibility to sea-level rise

Florida's coastal environments are especially vulnerable to climate change and concomitant RSL rise. Elevations in the coastal zone are low (i.e., meters) and already subject to intermittent flooding during intense rainfall events, exceptional tides, and storm surge (Kiflai et al., 2020; Mahjabin and Abdul-Aziz, 2020; Sweet et al., 2021). The extensive barrier chains and open ocean coastline are susceptible to erosion, overwash, and breaching (Wang and Briggs, 2015). The surficial and near-surface geology consists primarily of unconsolidated sand and porous limestone through which water is easily transmitted, further exacerbating the magnitude and extent of saltwater encroachment, as well as coastal and inland

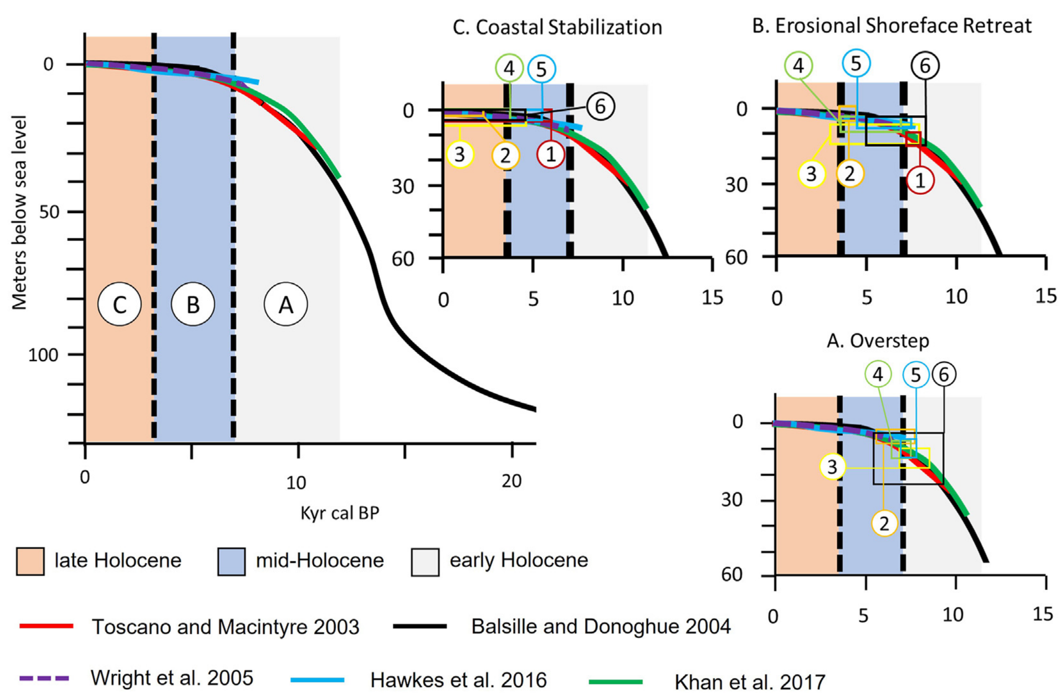

Fig. 2. Left panel. Sea level trends constructed using data from the Gulf of Mexico (Balsille and Donoghue, 2004), Big Bend Marsh Coast (Wright et al., 2005), South Florida (Khan et al., 2022), Florida Keys (Toscano and Macintyre, 2003), and Northeast Florida (Hawkes et al., 2016). Also shown are the age range and average rate of sea level rise associated with the late, mid, and early Holocene. Center and right panels. Age-depth polygons corresponding to the predominant depositional events that occurred in each geomorphic sector during the early, mid, and late Holocene. Polygon input data provided in Supplementary materials. 1 = Northwest Barrier Chain. 2 = Big Bend Marsh Coast. 3 = West-Central Barrier Chain. 4 = Mangrove Coast. 5 = Florida Keys. 6 = East Coast Barrier Chain.

Table 2
Source and type of information used to constrain relative sea level rise during the Holocene Epoch in the study domain.

Reference	Location	Isotope	Material analyzed	Units
Balsille and Donoghue, 2004	Gulf of Mexico	^{14}C	Shells, wood, peat	Cal yrs. BP
Wright et al., 2005	Big Bend Florida	^{14}C	Bulk samples, wood, oyster	Cal yrs. BP
Khan et al., 2022	South Florida	^{14}C, U-Th	Previously published data	Cal yrs. BP, yrs. BP
Toscano and Macintyre, 2003	Florida Keys	^{14}C	Previously published, coral, peat	Cal yrs. BP
Hawkes et al., 2016	Northeast Florida	^{14}C	Plant matter	Cal yrs. BP

flooding. Much of the Florida coastline is urbanized, which compromises the resilience of natural landscapes by limiting their adaptive capacity (e.g., migration; Geselbracht et al., 2011).

3. Methods

3.1. Response of Florida's coastal environment to Holocene sea level rise

The methodological approach of this investigation is grounded in the pioneering work of Curray (1964). Curray recognized the stratigraphic record of marine transgression and regression was dictated by two fundamental factors: (a) sea level change and (b) net sedimentation. For example, shoreline transgression (i.e., landward migration or onlap) occurs when the rate of SLR exceeds the rate of net sedimentation. During the Holocene marine transgression of the Florida platform, the rate of SLR was not constant but slowed over time. This deceleration was accompanied by changing patterns of sedimentation and stratigraphy as the coastal zone responded to new and evolving environmental conditions. It follows, if changes in the rate of Holocene SLR are synchronous with regionally significant shifts in the paleo-environmental evolution of Florida's coastal zone, then these rates or tipping points can be utilized to model the likely response of the modern coastal zone to future conditions of accelerating SLR.

In this study, the quantification of relationships between the evolution of Florida's coastal environment and contemporaneous Holocene SLR was based upon the analysis of geological investigations that (a) were conducted along the modern shoreface and/or inner continental shelf, (b) targeted the Holocene stratigraphic succession, (c) included detailed descriptions of the sedimentology, stratigraphy, and geochronology, and (d) included paleo-environmental descriptions of coastal evolution in the context of contemporaneous sea level change. A companion literature review was also conducted seeking reports and publications describing research specifically designed to reconstruct a detailed record of Holocene sea level change in the eastern Gulf of Mexico, southeast Atlantic, and wider Caribbean.

3.2. Sea level rise in the 20th and 21st centuries

Trends of sea level change along the Florida coast were calculated using 15 Florida tide gauge records included in the supplementary data files to NOAA's 2022 sea level rise technical report (Sweet et al., 2022; https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-data.html). We used the NOAA mean sea level monthly data products (NOAA, 2021), including monthly mean, lowest, and highest values. The two-stage records acquired in Mayport (near Jacksonville, FL) are nearby and complementary to one another (Mayport, operated 1928–2001; Mayport Bar Pilots Port, operated 1995–1996 and 2001–present). Thus, we concatenated the Mayport records by minimizing the offset between the two records that were acquired during a nine-month period between 1995/09/19 and 1996/06/10. Thus, our dataset was reduced to a total of 14 stations (Fig. 1).

We first translated the sea level observations for each station from the mean sea level datum to another local datum, mean sea level at year 2000, by calculating the mean sea level value for the year 2000 and subtracting this value from all observations. We chose the mean sea level at year 2000 local datum to be consistent with other studies that consider future changes in sea level (e.g., Sweet et al., 2022). Trends of sea level change were characterized using a multi-parameter linear least-square estimator, which provides both best-fit parameters and their uncertainties. The best-fit analyses were conducted using Python's scipy.optimize.curve_fit function. The analyses included linear fit (two parameters: intercept and slope) and linear with a periodic (sinusoidal) fit, which required the use of two additional parameters (amplitude and phase) of the 18.61-year lunar tide periodicity that can have a significant impact on mean and highest sea level values (Peng et al., 2019). However, our results using the linear + periodic analyses showed only minor deviations from the analyses without the periodic signal. Thus, the paper focuses on the simpler linear analyses and results.

The variable length of the 14 sea level time series (28–125 years) significantly affects the trend estimation results calculated for each station. To minimize the impact of the variable time series length, we conducted the best-fit analyses using three series subsets, each defined using different start dates but the same end date (end of 2022). The first subset used all the observations; thus, the start date (t_{start}) varies between 1897 (Fernandina Beach) and 1973 (Panama City and Clearwater Beach). The records of two stations that started operation after 1993 (Virginia Key and Trident Pier) were not considered. The second subset, 1993–2022, included 12 stations with 30 years of observation and two stations with 29 years. Finally, the third subset, 2003–2022, consisted of all 14 stations.

The accelerating trends in SLR along the US Atlantic and Gulf coasts began toward the end of the 20th century (e.g., Ezer, 2013; Nerem et al., 2018). Thus, by applying the linear fit to three time series lengths, t_{start}-2022, 1993–2022, and 2003–2022, it was possible to detect changes in the linear rate of SLR along the Florida coastline. Observational trends calculated for the three time series subsets were then extended to 2050 and the elevations compared with NOAA's projected SLR for the same time period (Sweet et al., 2022; https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-data.html).

3.3. Unified conceptual model

The unified conceptual model is based upon the premise that the past is the key to the future. Specifically, the likely geomorphic and ecologic response of the modern coastal environment can be predicted by comparison between (a) rate of Holocene SLR tipping points that induced a change in the paleo-environmental trajectory of the coastal environment being transgressed and (b) projected rates of future SLR derived from the NOAA tide gauge data. The authors have successfully applied this methodology in previous studies designed to identify the Holocene rate of SLR tipping points (Parkinson, 1989; Turner et al., 2018) and construct predictive conceptual models of environmental change (Parkinson and Wdowinski, 2022; Parkinson et al., 1994; Turner et al., 2018).

4. Results

4.1. Response of Florida's coastal environments to Holocene sea level rise

In the following sections, the Holocene paleo-environmental evolution of Florida's six coastal geomorphic sectors is described with respect to sedimentology, stratigraphy, depositional framework, geochronology, and contemporaneous rate of SLR. These descriptions are based on a review of 66 geological and 11 sea level publications conducted within the study domain. All radiocarbon ages used in this investigation are expressed in Kyrs cal BP. Conventional dates were calibrated using the online IntCal20 model by OxCal (https://c14.arch.ox.ac.uk/oxcal/OxCal.html#) (Bronk Ramsey, 2008, 2009; Bronk Ramsey and Lee, 2013; Reimer et al., 2020). The reported dates are relative to 1950 BP. The original data and the calibrated estimates are provided in Supplementary materials Table 1. Generalized geological cross-sections illustrating the regional sedimentologic, stratigraphic, and geomorphic features in each sector are shown in Fig. 3. Transect locations are shown in Fig. 1. Associations between the duration and elevation of the predominant paleo-environmental events observed in each geomorphic segment and RSL are shown in Fig. 2 and Supplementary materials Fig. 1.

4.1.1. Northwest Barrier Chain

Investigations conducted on the inner shelf of the Northwest Barrier Chain have documented the presence of a transgressive sand layer. When present, it consists of reworked, older (e.g., relict) Holocene, Pleistocene, or Miocene deposits (Locker and Doyle, 1992). Based upon the data provided by Locker and Doyle (1992) and Donoghue and White (1995), transgression over the inner shelf occurred ~11 Kyr cal BP. At the inner shelf/lower shoreface boundary, a transgressive facies sequence is present (Houser, 2012) and interpreted to have formed by erosional shoreface retreat of a barrier island complex (see Swift, 1975). Age-depth associations suggest this transition occurred ~8 Kyr cal BP. The modern barrier island system was established ~5.1 Kyr cal BP (Otvos, 1985, 2005).

4.1.2. Big Bend Marsh Coast

Most of the Big Bend Marsh Coast inner shelf and nearshore are reported to consist of exposed karstified limestone and palimpsest beds that were transgressed ~8 Kyr cal BP (Hine and Belknap, 1986). Along the coastline, oyster reefs and inter-reef muddy sands are common. Samples collected from the reef base indicate formation initiated ~4.5 Kyr cal BP (Wright et al., 2005). The mainland is host to extensive coastal wetland plant communities and radiocarbon dates indicate the modern coastal salt marshes and associated shoreline stabilization occurred ~2.4 Kyr cal BP (Wright et al., 2005).

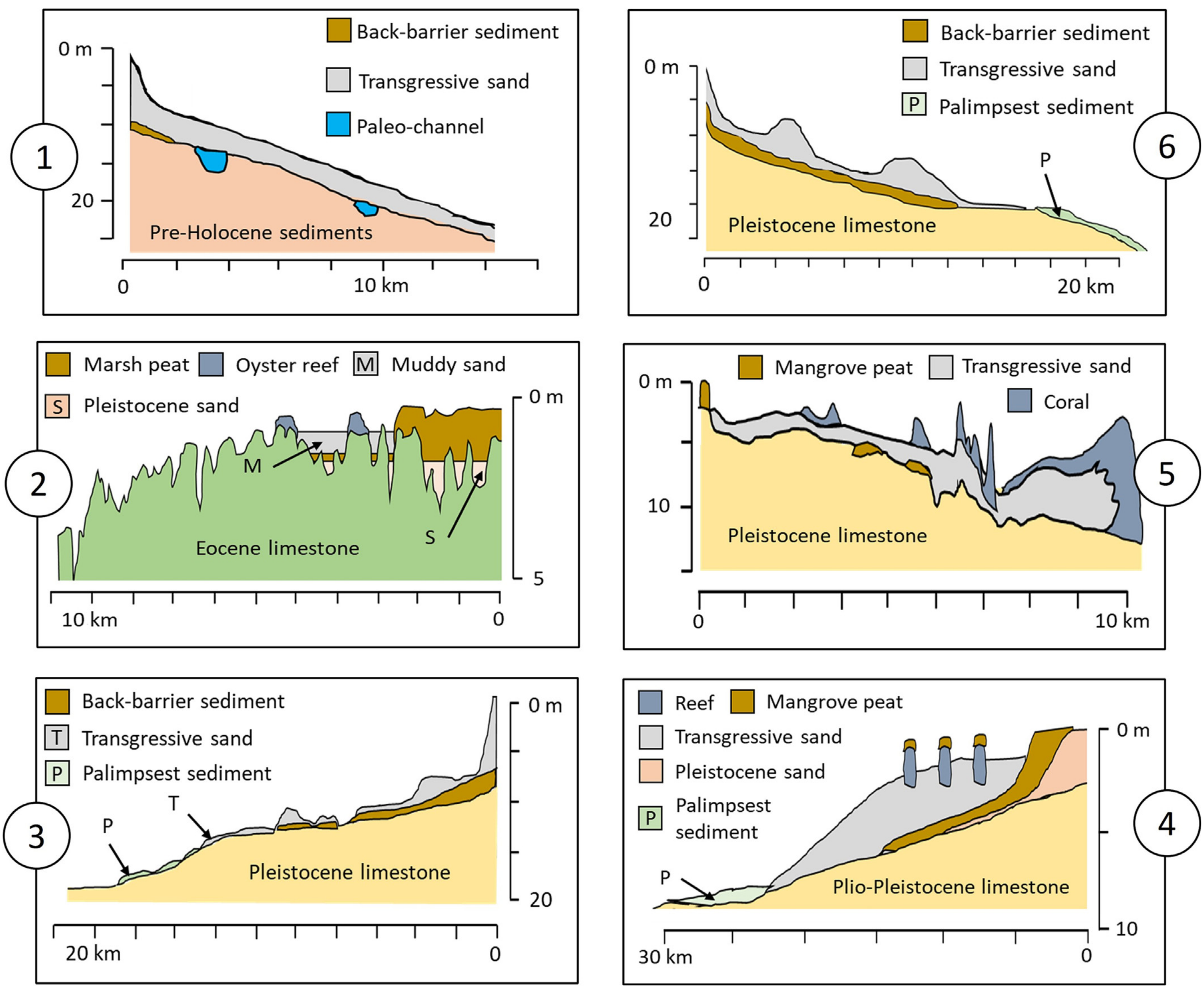

Fig. 3. Simplified geologic cross-sections for each of the six geomorphic sectors showing prominent stratigraphic units and corresponding paleo-environment of deposition: 1) Northwest Barrier Chain (Houser, 2012; Locker and Doyle, 1992; and URS Corporation, 2004), 2) Big Bend Marsh Coast (Hine and Belknap, 1986; Hine et al., 1988), 3) West-Central Barrier Chain (Brooks et al., 2003; Locker et al., 2003), 4) Mangrove Coast (Davis and Klay, 1989; Parkinson, 1987, 1989), 5) Florida Keys (Enos, 1977; Lidz et al., 2003;, Macintyre, 2007; Robbin, 1984; Toth et al., 2022), and 6) East Coast Barrier Chain (Civil, 1990; Fluke, 1994; Mayhew and Parkinson, 2007; Meisburger and Duane, 1971; Parkinson and White, 1994). Note horizontal scale and vertical exaggeration vary between segments. Location of each transect shown in Fig. 1.

4.1.3. West-Central Barrier Chain

The inner shelf of West-Central Barrier Chain consists of exposed Neogene and Pleistocene limestone with a thin and discontinuous layer of palimpsest sediment (Brooks et al., 2003; Hine et al., 2003; Locker et al., 2003; Finkl et al., 2007). Age-depth associations suggest this period of shoreline transgression initiated ~9 Kyr cal BP. The unconsolidated sediment sequence thickens landward into a transgressive facies sequence interpreted to have formed during erosional shoreface retreat of the barrier island complex between ~8 and 3 Kyr cal BP (Brooks et al., 2003). The cessation of island retreat and concomitant shoreline stabilization is generally reported at ~5 Kyr cal BP; (Stapor et al., 1991; Davis et al., 1992; Brooks et al., 2003; Donahue et al., 2003; Locker et al., 2003).

4.1.4. Mangrove Coast

Geological investigations of the inner shelf of the Mangrove Coast appear limited to the work of Davis and Klay (1989), who described the presence of exposed limestone at depths >8 m seaward of the Ten Thousand Islands. In the Ten Thousand Islands, a transgressive facies sequence consisting of mangrove peat overlain by estuarine sediments is present beneath the archipelago of mangrove capped vermetid and oyster reefs (Davis and Klay, 1989; Parkinson, 1989). These investigators report the transgressive sequence formed between ~6.7 to 3.7 Kyr cal BP. Overlying the transgressive interval in the island archipelago and along the mainland shoreline, Parkinson (1989) reports the presence of a relatively thick (~1 to 2 m) regressive mangrove peat sequence, interpreted to reflect a period of coastal stability that began ~3.8 Kyr cal BP. Shoreline sequences in the Everglades/Shark River Slough province consist of a thick (~4 m) interval of mangrove peat over bedrock. Basal mangrove peat radiocarbon dates indicate the modern coastline formed ~3.8 Kyr cal BP (Yao and Liu, 2017). In the Cape Sable/Whitewater Bay and Florida Bay provinces, exposed limestone is present on the inner shelf, grading landward into a transgressive facies sequence consisting of freshwater deposits (e.g., carbonate mud and peat) and/or marine peats (e.g., mangrove) (c.f., Wanless and Tagett, 1989). The transgressive sequence is in turn locally overlain by a ~3 m regressive sequence associated with the modern coastline of Cape Sable (Spackman et al., 1969; Roberts et al., 1977; Vlaswinkel and Wanless, 2009) and emergence of Florida Bay mudbanks and islands (Enos, 1989; Parkinson and Meeder, 1991; Jones et al., 2019). Geochronologies in both provinces suggest this period of regressive sedimentation began about ~5 Kyr cal BP.

4.1.5. Florida Keys

Based upon U—Th dates, the sustained presence of corals as the predominant geomorphic feature in the Florida Keys began ~8.6 Kyr BP, when outlier and now relict reefs flourished on the shelf margin (Toscano and Lundberg, 1998). The modern reef system emerged between ~8.0 and 6.5 Kyr cal BP (Toth et al., 2018), with evidence of backstepping occurring from ~7.5 to 4.5 Kyr cal BP (Lidz et al., 2003). Beneath and around the modern reefs are transgressive carbonate sands (Enos, 1977). Radiocarbon dates collected from peat samples collected at the base of extant mangrove forests indicate a sustained presence along the Florida Keys shoreline began ~5.5 Kyr cal BP (Robbin, 1984).

4.1.6. East Coast Barrier Chain

Surveys conducted on the inner continental shelf of the East Coast Barrier Chain indicate the seabed is a surface of non-deposition and erosion, characterized by the presence exposed Pleistocene bedrock, overlain by a thin and discontinuous layer of palimpsest sediments (Meisburger and Duane, 1971; Field and Meisburger, 1975; Fluke, 1994). Meisburger and Duane (1971) estimated the coastline was transgressed along this portion of the Florida platform ~8 Kyr ago. Sediments thicken landward into a transgressive facies sequence that accumulated in response to the erosional shoreface retreat of a barrier island chain (Field and Duane, 1977; Civil, 1990). In the central portion of this sector, radiocarbon samples obtained from back-barrier lagoon sediments indicate the age of the modern island chain is ~4.9 Kyr cal BP (Mayhew and Parkinson, 2007). At Cape Canaveral, Rodrigues et al. (2022) state the oldest beach ridge formed ~5.8 Kyr cal BP. Near the Georgia boarder, radiocarbon dates collected from extant salt marsh and mangrove plant communities indicate the age of the barrier island is at least ~4.7 Kyr cal BP (Vaughn et al., 2020, 2021).

In the southern region of this sector (e.g., Palm Beach County to Miami-Dade County), the continental shelf is narrow (<10 km wide) and consists of a bathymetry dominated by antecedent topographic features associated with the presence of drowned reef-like ridges (Duane and Meisburger, 1969), more recently referenced as the continental reef tract to distinguish these features from the Florida Key reef track (Stathakopoulos and Riegl, 2015). Coral ages from the continental reef tract indicate they initiated ~10.8 Kyr cal BP and terminated ~8.0 Kyr cal BP (Lighty et al., 1978; Stathakopoulos and Riegl, 2015).

4.2. Sea level rise in the 20th and 21st century

Observed sea level data obtained from the 14 NOAA tide gauge stations (Fig. 4, Table 3) indicate the average rate of rise has accelerated to the present. The mean rate of historical SLR, calculated using data sets with a duration >50 years relative to 2022, ranged from 2.2 ± 0.0 mm yr^{-1} (Fernandina Beach) to 4.2 ± 0.1 mm yr^{-1} (Vaca Key) and averaged 3.1 ± 0.2 mm yr^{-1}. The mean rate of SLR since 1993 ranged from 4.7 ± 0.6 mm yr^{-1} (Mayport) to 6.9 ± 0.4 mm yr^{-1} (Pensacola) and averaged 5.9 ± 0.2 mm yr^{-1}. The mean rate of SLR during the 21st century (2003 − 2022) ranged from 7.6 ± 0.9 mm yr^{-1} (St. Petersburg) to 10.0 ± 1.4 mm yr^{-1} (Pensacola) and averaged 8.2 ± 0.2 mm yr^{-1}. The calculated rates of SLR at each station vary as a function of the duration of the record considered, with shorter data sets yielding faster rates. Between station differences in the rate of SLR are apparent and attributed to variations in local and regional processes that contribute to relative SLR as described previously (e.g., glacio-isostatic).

This study's observation-based extrapolations of sea level elevation in 2050 are shown in Table 4. Extrapolations based upon the 21st century (e.g., 2003–2022) data fall within the range of intermediate, intermediate-high, and high scenario-based estimates calculated by Sweet et al. (2022).

5. Discussion

5.1. Generalized response of the Florida coastal environment to Holocene sea level rise

The aggregated paleo-environmental observations derived from geological investigations conducted on Florida's inner shelf and modern shoreface reveal a common regional and synchronous response to changing rates of Holocene SLR (Fig. 2, Supplementary materials Fig. 1). Between sector distinctions in sedimentology, stratigraphy, and geochronology are evident and attributed to differences in (a) isostacy and sediment compaction, (b) elevation and geology (e.g., limestone, unconsolidated sand) of the antecedent topography transgressed, (c) sediment supply (i.e., autochthonous, allochthonous), (d) climate, (e) physical oceanography, and (f) data density. But these differences did not mask evidence of a synchronous sequence of paleo-environmental events that accompanied the Holocene marine transgression of the Florida coastline.

The outer reaches of Florida's inner shelf typically consist of exposed pre-Holocene formations locally overlain by palimpsest sediments and submerged coral reefs. This period of coastal *overstep* occurred during the early Holocene, when the rate of SLR exceeded 5 mm yr^{-1}. In shallower inner shelf waters of the barrier chain sectors, Holocene sediments thicken into a transgressive facies sequence created during erosional shoreface retreat of a barrier island chain (c.f., Swift, 1975). In the carbonate dominated Florida Keys sector, concurrent coral reef backstepping has been documented. This interval of shoreline *retreat* and reef backstepping occurred during the mid-Holocene, when the rate of SLR averaged ~2 mm yr^{-1}. The modern shoreline (e.g., barrier island shoreface, coastal wetlands) and adjacent reefs (e.g., coral, oyster) *stabilized* during the late Holocene, when sea level was rising at a rate of <1 mm yr^{-1}.

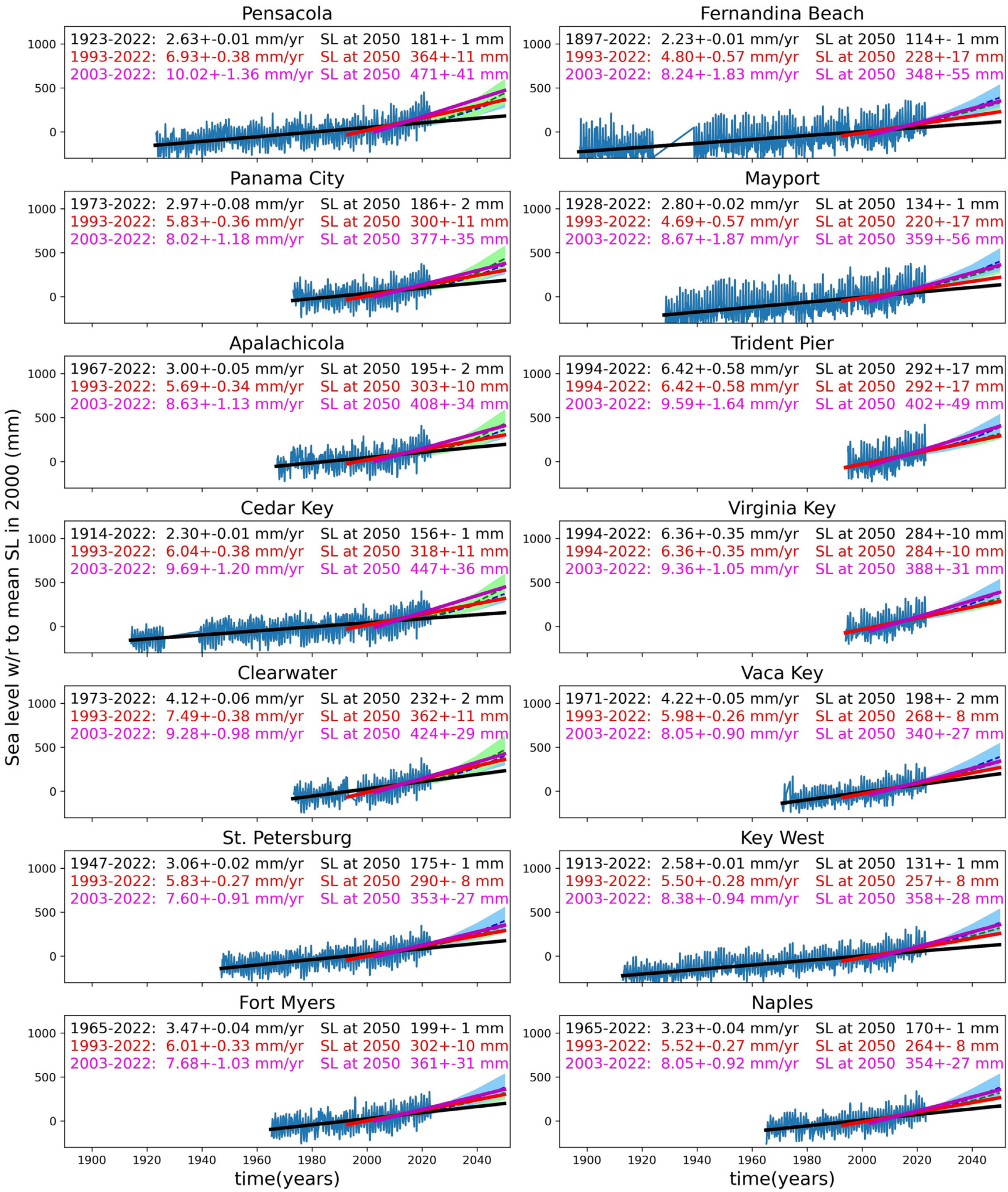

Fig. 4. Observed sea level trends (solid blue line) at each of the 14 NOAA tide gauge stations deployed along the Florida coast. Also shown is the average rate of rise calculated as a function of record length (error = uncertainty). Observational-based (this study) and scenario-based (Sweet et al., 2022) extrapolations of sea level elevation in 2050 are indicated using solid and dashed lines, respectively. Solid black line = historical average of 3.05 mm yr^{-1} (<1972–2022). Solid red line = 5.94 mm yr^{-1} (1993–2022). Solid purple line = 8.24 mm yr^{-1} (2003–2022). Dashed blue line = intermediate-high. Dashed green line = high. The shaded areas delineate the 17th–83rd percentile range of uncertainty for each of the two scenario-based projections.

Table 3
NOAA tide gauge station details and rate of sea level rise (mm yr^{-1}) trends considered in this study. Error expressed as uncertainty level.

Location	NOAA ID	Latitude	Longitude	Observation period	Trend t_{start} - 2022	Trend 1993–2022	Trend 2003–2022
Pensacola	8729840	30.40	−87.21	1923–2002	2.63 ± 0.01	6.93 ± 0.38	10.02 ± 1.36
Panama City	8729108	30.15	−85.67	1973–2002	2.97 ± 0.08	5.83 ± 0.36	8.02 ± 1.18
Apalachicola	8728690	29.73	−84.98	1967–2022	3.00 ± 0.05	5.69 ± 0.34	8.63 ± 1.13
Cedar Key	8727520	29.14	−83.03	1914–2022	2.30 ± 0.01	6.04 ± 0.38	9.69 ± 1.20
Clearwater Beach	8726724	27.98	−82.83	1973–2022	4.12 ± 0.06	7.49 ± 0.38	9.28 ± 0.98
St Petersburg	8726520	27.76	−82.63	1947–2002	3.06 ± 0.02	5.83 ± 0.27	7.60 ± 0.91
Fort Myers	8725520	26.65	−81.87	1965–2002	3.47 ± 0.04	6.01 ± 0.33	7.68 ± 1.03
Naples	8725110	26.13	−81.81	1965–2002	3.23 ± 0.04	5.52 ± 0.27	8.05 ± 0.92
Key West	8724580	24.56	−81.81	1913–2002	2.58 ± 0.01	5.50 ± 0.28	8.38 ± 0.94
Vaca Key	8723970	24.71	−81.11	1971–2002	4.22 ± 0.05	5.98 ± 0.26	8.05 ± 0.90
Virginia Key	8723214	25.73	−80.16	1994–2002	nd	6.36 ± 0.35	9.36 ± 1.05
Trident Pier	8721604	28.42	−80.59	1994–2002	nd	6.42 ± 0.58	9.59 ± 1.64
Mayport	8720218	30.67	−81.47	1928–2002	2.80 ± 0.02	4.69 ± 0.57	8.67 ± 1.87
Fernandina Beach	8720030	30.67	−81.47	1897–2002	2.23 ± 0.01	4.80 ± 0.57	8.24 ± 1.83
				Average	*3.05 ± 0.18*	*5.94 ± 0.20*	*8.24 ± 0.21*

5.2. Unified conceptual model

The observed rates of SLR during the 21st century along the Florida coastline fall within the range of values that accompanied the early Holocene marine transgression (e.g., ~10 to 5 mm yr^{-1}), at which time Florida coastal environments were subject to overstep and submergence. It follows the geomorphic and ecologic response of Florida's modern coastal zone to the recent acceleration in the rate of SLR will be similar, e.g., toward 2050 and beyond it will become increasingly unstable. Manifestations will include increasing rate and extent of (a) shoreline erosion, overwash, and barrier island breaching, (b) saltwater encroachment and formation of wetland inundation ponds, and (c) landward translation of the shoreline and concomitant submergence of the coastal zone.

5.2.1. Evidence of recent change

There is abundant evidence of recent geomorphic and ecologic change along the Florida coastline which investigators have attributed to an acceleration in the rate of SLR or companion stressors (e.g., saltwater

Table 4
Observation-based linear extrapolations (this study, left column) and scenario-based median estimates with likely ranges bracketed (i.e., 17th–83rd percentile, Sweet et al., 2022) of sea level elevation in 2050 relative to a baseline of 2000. The observation-based extrapolations are derived from best-fit analysis of all data (black), three decades: 1993–2022 (red), and 21st century: 2003–2022 (purple). The two scenarios that bound the observation-based extrapolations are provided for each of the 14 Florida tide gauge stations and indicated by vertical dividing lines using the same color scheme. At locations where the observation-based extrapolation is the same as a particular scenario, the scenario is indicated by red font. Scenario-based estimates obtained from supplementary data files to NOAA's 2022 sea level rise technical report (Sweet et al., 2022; https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-data.html).

Observation Extrapolation	Low	Intermediate-Low	Intermediate	Intermediate-High	High
Pensacola 181, 364, 471	230 [180, 290]	280 [210, 340]	320 [250, 400]	380 [280, 520]	440 [320, 590]
Panama City 186, 300, 377	220 [160, 280]	260 [200, 300]	330 [230, 380]	360 [260, 500]	430 [300, 570]
Apalachicola 195, 303, 408	220 [170, 280]	270 [200, 330]	300 [230, 390]	360 [270, 510]	430 [310, 580]
Cedar Key 156, 318, 447	230 [180, 290]	27 [210, 340]	310 [240, 400]	370 [280, 520]	440 [320, 590]
Clearwater Beach 232, 362, 424	260 [200, 310]	300 [240, 360]	340 [270, 420]	400 [300, 550]	470 [350, 620]
St. Petersburg 175, 290, 353	260 [200, 310]	300 [240, 360]	340 [270, 420]	400 [300, 550]	470 [350, 620]
Fort Meyers 199, 302, 361	240 [190, 300]	280 [220, 340]	320 [250, 400]	380 [290, 530]	450 [330, 600]
Naples 170, 264, 354	240 [190, 300]	280 [220, 350]	320 [250, 410]	380 [280, 530]	450 [330, 600]
Key West 131, 257, 358	240 [190, 290]	280 [230, 340]	320 [250, 400]	380 [290, 530]	450 [330, 610]
Vaca Key 198, 268, 340	250 [200, 300]	290 [230, 350]	330 [260, 310]	390 [300, 540]	460 [340, 620]
Virginia Key nd, 284, 388	240 [190, 290]	280 [220, 340]	320 [260, 400]	380 [290, 530]	450 [330, 600]
Trident Pier nd, 292, 402	240 [180, 300]	280 [220, 340]	320 [260, 400]	390 [290, 530]	450 [330, 600]
Mayport 134, 220, 359	250 [200, 310]	300 [230, 360]	340 [270, 420]	400 [300, 540]	460 [360, 610]

encroachment, increasing storminess). For example, in the Northwest Barrier Chain, a historical landward translation of wetland plant communities has occurred (Choi et al., 2001). In the Big Bend Marsh Coast, SLR and saltwater encroachment have resulted in the loss of marsh along the mainland shoreline and replacement of freshwater forests by salt marsh (Williams et al., 1999; Desantis et al., 2007; Raabe and Stumpf, 2016). Along the Mangrove Coast, Krauss et al. (2011) and Andres et al. (2019) document the historical migration of mangrove forests into marsh habitat, transgressive facies sequences, and the expansion of wetland inundation ponds. Further inland, freshwater forest and hammock plant species are being replaced by salt-tolerant plants (Saha et al., 2011). In the Florida Keys, Ross et al. (1994) attributed an historical reduction in the extent of upland pine forests to an acceleration in the recent rate of SLR. In southeast Florida, the coastal vegetation zones are migrating landward in response to saltwater encroachment (Gaiser et al., 2006). Meeder and Parkinson (2018) attribute the formation and expansion of inundation ponds in the mangrove scrub habitat of southeast Florida to an historical acceleration in the rate of SLR.

The authors could find no descriptions of historic or recent geomorphologic changes to Florida's barrier chains that have been attributed to SLR or climate change. However, this is not unexpected because there are numerous other anthropogenic factors that complicate the ability to detect change that can be confidently attributed to natural processes. These include landscape urbanization, construction of shore protection features (e.g., sea walls, bulkheads, and revetments), beach nourishment, and inlet management (e.g., sand back- and by-passing) (c.f., Sankar, 2015). Roughly 50 % (e.g., ~1110 km) of the Florida coastal zone (e.g., shorelines in contact with the Atlantic Ocean or Gulf of Mexico) is now urbanized. These anthropogenic alterations exacerbate the vulnerability of Florida's coastal environments to SLR and other climate change stressors. For example, changes in hydrology (e.g., construction of roads, surface water diversion, levees) induce stress and mortality in wetlands (Krauss et al., 2018; Radabaugh et al., 2021). Water quality impairment from urban areas has caused coral populations to decline and has reduced their capacity to maintain elevation relative to SLR (Toth et al., 2018, 2022).

The intensity and destructiveness of tropical cyclones are expected to increase as the climate warms (Emanuel, 2005; Elsner et al., 2008; Sobel et al., 2016; Xi et al., 2023) and these events will further exacerbate the demise of Florida's coastal environment because landfall generates extensive shoreline erosion, elevates surface- and groundwater salinity, causes substrate elevation deflation, and landscape-level plant community diebacks (Swiadek, 1997; Radabaugh et al., 2019; Kiflai et al., 2020; Osland et al., 2020; Lagomasino et al., 2021). The combination of faster rates SLR, increasing storminess, and ongoing coastal urbanization is expected to elevate the tempo and scale of geomorphic and ecologic change as has been reported over the past two decades.

5.2.2. Likelihood of faster and more widespread changes to the coastal environment

It is now highly probable atmospheric temperatures will exceed +2 °C by the end of this century even if current national climate commitments are fully implemented (Boehm et al., 2022; United Nations, 2022). Others have indicated that threshold will be reached between 2040 and 2050 (Jevrejeva et al., 2016). Even under ambitious emission reduction scenarios, ice losses and thermal expansion are foreseen to lead to the continued acceleration in the rate of SLR throughout the century and especially during the second half (Overland et al., 2019; Sweet et al., 2022; Ciracì et al., 2023). These observations lead Bamber et al. (2019) to suggest a SLR of 2 m by 2100, relative to 2005, should be used when preparing coastal adaptation plans: that's an average rate of rise of ~20 mm yr^{-1}. Hence, the projections derived from the observations reported in this study are likely a 'best case' scenario. Faster rates of SLR to higher elevations are now considered probable and will accelerate the pace and magnitude of geomorphic and ecological change as described herein.

5.3. Application of findings to other regions

To gauge the application of this study's findings to other regions, a preliminary review of published paleo-environmental investigations undertaken on the modern shoreface and shelf in other areas of the United States and on other continents was conducted. The results indicate the sequence of synchronous paleo-environmental events observed along the Florida coast was occurring on a global scale in regions where relative SLR rise during the Holocene Epoch was predominantly a consequence of global eustatic processes. For example, in North America, studies have described the presence of overstepped antecedent topography and palimpsest or relict sediments on the continental shelves of the Western North Atlantic (Swift et al., 1971; Belknap and Kraft, 1981) and northern Gulf of Mexico (Parker et al., 1992). Transgressive facies sequences attributed to erosional shoreface retreat have been reported on the inner shelf and lower shoreface of the Western Atlantic (Swift, 1975; Kraft et al., 1987; Thieler et al., 2014), Georgia Bight (Thieler et al., 2014; Long et al., 2021) and northern Gulf of Mexico (Anderson et al., 2022). Stratigraphic sequences, paleo-environmental interpretations, and geochronologies similar to those described in this study have also been reported from the Gulf of California (Curray et al., 1978), the Yucatan (Platt and Wright, 2022), Brazil (Rangel and Dominguez, 2020), northern Qatar (Rivers et al., 2020), the Great Barrier Reef (Sanborn et al., 2020), Japan (Saito, 1994), and the Yellow (Lee and Yoon, 1997) and Adriatic (Correggiari et al., 1996) Seas. In summary, there appears to have been a globally similar and synchronous coastal response to changing rates of eustatic Holocene SLR in both siliciclastic and carbonate depositional settings. Efforts to model the response of these coastal systems to accelerating rates of SLR forecast accompanying climate change may therefore benefit from consideration of locally derived paleo-environmental reconstructions and associated SLR tipping points.

6. Conclusions

Sedimentologic, stratigraphic, and geochronologic data generated during the Holocene marine transgression along the Florida coast indicate a uniform and synchronous response to rate of RSL rise tipping points. During the early Holocene, when the rate of SLR averaged at least 5 mm yr^{-1}, the coastal zone experienced overstep and submergence as evidenced by the presence relict or palimpsest sediments discontinuously overlying pre-Holocene strata on the modern continental shelf. The rate of SLR slowed to an average of ~2 mm yr^{-1} during the mid-Holocene and this was accompanied by erosional shoreface retreat of coastal environments and formation of a transgressive facies sequence. During the late Holocene, the rate of SLR averaged <1 mm yr^{-1}. All of Florida's modern coastal environments originated and/or stabilized during this period.

Based upon observations obtained from 14 NOAA tide gauge stations located along the Florida coastline, the rate of SLR has accelerated from an historical average of 3.1 mm yr^{-1} (<1972–2022; range 2.2 to 4.2) to 5.9 mm yr^{-1} over the past 30 years (1993–2022; range 4.8 to 6.9) and 8.2 mm yr^{-1} during the 21st century (2003–2022; range 7.6 to 10.0). The 21st century rates of SLR vary between stations, however all fall within the range of values documented during the early Holocene; a time when the Florida coastal zone was rapidly transgressed and submerged. Observational extrapolations of these data to 2050 align with the intermediate, intermediate-high, and high scenario-based estimates of Sweet et al. (2022).

Recent studies have demonstrated that the destabilizing effects of this acceleration on Florida's coastal geomorphology and ecology are already evident. Rates of rise are expected to continue accelerating. Therefore, the tempo and scale of landward translation and concomitant submergence of Florida's coastal environment will likely increase over the duration of this century.

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CRediT authorship contribution statement

Randall W. Parkinson: Conceptualization, Methodology, Validation, Investigation, Writing – review & editing, Visualization. **Shimon Wdowinski:** Methodology, Validation, Investigation, Writing – review & editing, Visualization, Funding acquisition.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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