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Beach nourishment versus sea level rise on Florida's coasts

By

James R. Houston

U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road, Vicksburg, MS 39180; james.r.houston@usace.army.mil

ABSTRACT

Beach nourishment and sea level rise will dominate future shoreline changes on Florida's 665 miles of sandy coast. Shoreline changes from 2020-2100 are projected along this entire coast using equilibrium profile theory that accurately predicted shoreline changes on Florida's east coast from 1970-2017 (Houston 2019). Projections for 2020-2100 are made assuming past rates of beach nourishment for the 30-yr period from 1988-2017 will continue and sea level will rise according to recent projections of the Intergovernmental Panel on Climate Change (IPCC) that include the latest knowledge on ice melting in Antarctica (IPCC 2019). Using the beach nourishment and sea level rise data, equilibrium profile theory is then used to predict shoreline change from 2020-2100 for each IPCC sea level rise projection. Beach nourishment is shown to produce shoreline advance seaward on average for all IPCC scenarios for both the entire Florida coast and east coast and for all scenarios except the upper confidence level of the worst scenario for the southwest and Panhandle coasts. Some of the 30 counties on these coasts will require a greater rate of nourishment than in the past to offset sea level rise for some or all of the scenarios, whereas some will offset sea level rise for all scenarios with lower nourishment rates than in the past. The annual beach nourishment volume for which a county has a shortfall or surplus in offsetting sea level rise for each IPCC scenario can be calculated with the information provided and examples are presented. The approach can be used on coasts outside Florida if beach nourishment and sea level rise are expected to dominate future shoreline change.

Before about 1970, inlets cut, structured, and/or dredged for navigation on Florida coasts dominated shoreline change, causing extensive recession. These inlet cuts and modifications resulted in both the growth of ebb and flood shoals that removed over 250 million yd³ of sand out of the littoral zone and loss of tens of millions of cubic yards through offshore disposal of dredged sand (Houston and Dean 2014; Houston 2015; Houston 2017). However, inlet impacts to shorelines have moderated considerably since 1970 because new inlets have not been cut, there have been few new navigation structures, and dredged sand is typically placed on beaches rather than being routinely disposed offshore. If there are no inlet changes, ebb and flood shoals stabilize after about 30 years for all but the largest inlets and they no longer take sand out of the littoral zone (Dombrowski and Mehta 1996). In addition, most inlets now have inlet management plans that call for sand bypassing, reducing inlet impacts on shorelines (Florida Department of Environmental Protection, FDEP 2018a, b, c, d, e, f). It is assumed in this paper that inlet management plans will be completely implemented in the near

future. With inlet shoals stabilized and sand bypassing through inlet management plans, inlets will have a relatively small impact on future shoreline change.

Beach nourishment has dominated shoreline change on average along the 665-mile length of Florida's sandy coasts since it began as early as 1970 on the east coast and 1985-1986 on the southwest and Panhandle coasts. Measurements on the east coast show that from 1970 to 2017 nourished beaches widened 118 ft and unnourished beaches widened 46 ft due to sand moving along shore from nourished to unnourished beaches (Houston 2019). Beach nourishment also dominated shoreline change on the southwest coast with the shoreline moving seaward an average of 106 ft from 1972 to 2006 (Absalonsen and Dean 2010). Beach nourishment started late on the Panhandle coast with about 90% of the nourishment that was placed on this coast occurring since 1999 and only a minority of the shoreline having been nourished (FDEP 2018e). However, beach nourishment has dominated where it was placed. For example, from 1856-1970, Pensacola Beach eroded 175 ft on

KEYWORDS: Shoreline change, equilibrium profile theory, climate change, inlets, longshore transport.

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average along 8.5 miles of beach from shoreline marker R107 to R151, whereas the same beach was 160 ft wider from the start of beach nourishment in 2003 to 2018 (Absalonsen and Dean 2010; FDEP 2018e; Houston 2019).

Perceptions and realities of shoreline change sometimes do not agree, leading to the belief among some that beach nourishment is not effective. For example, it is widely perceived that Florida has eroding shorelines despite beach nourishment when, in fact, shorelines have been widening since beach nourishment started about 1970. This perception is seemingly supported by FDEP's designation that 60% of the Florida East coast is "critically eroding" (FDEP 2018g). However, 75% of this "critically eroding" coast has accreted since 1970 (Absalonsen and Dean 2010; Houston 2019). This paradox is resolved by FDEP's definition that all beaches that have been nourished are "critically eroding" regardless of whether they are accreting, stable, or eroding. For example, the beaches of Miami Beach are designated as critically eroding even though they widened 185 ft on average from 1867 to 1973 (structures were built on the accreted beaches in the 1920s-1960s) and widened over 300 ft on average since beach nourishment started in 1978 (Houston 2016a, 2019). In addition, if structures are built too close to the ocean such that they could be damaged by 25-year storms, the shorelines are defined as "critically eroding." Houston (2019) gives an example in Indian River County where the shoreline accreted 320 ft from 1882 to 1980. Houses were built in 1980 too close to the ocean on the accreted land. The shoreline has continued to accrete somewhat since the houses were built, but FDEP designates this long-time

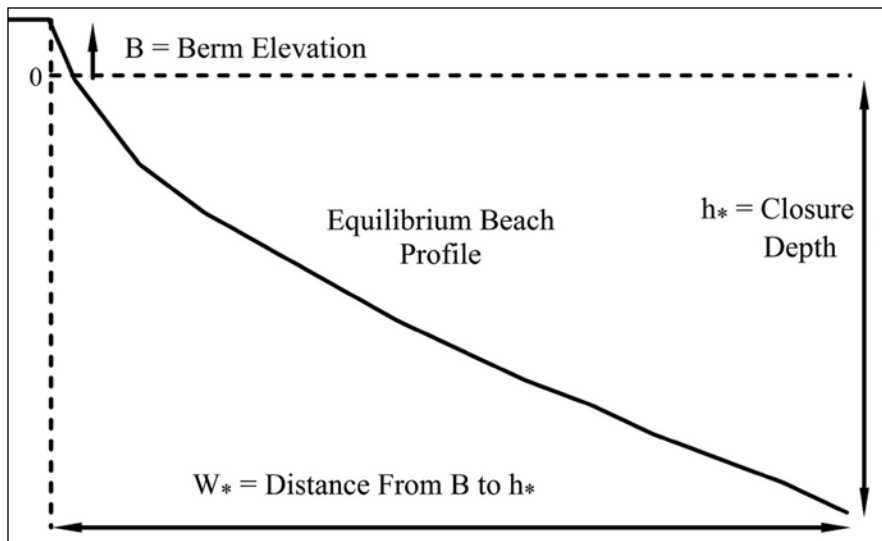
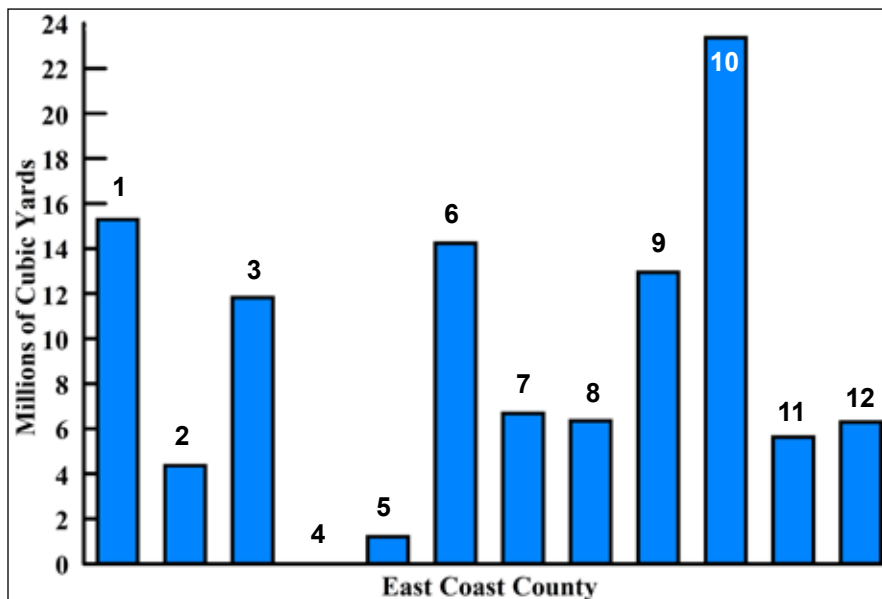


Figure 1. Equilibrium beach profile with the notation used by Dean and Absalonsen (2011) and others.

Figure 2. Beach nourishment sand volumes on the Florida east coast 1988-2017. 1 is Nassau County, 2 Duval, 3 St Johns, 4 Flagler, 5 Volusia, 6 Brevard, 7 Indian River, 8 St Lucie, 9 Martin, 10 Palm Beach, 11 Broward, and 12 Dade. Flagler County has never been nourished as of the end of 2019.



accreting shoreline as “critically eroding” because the houses could be damaged by a 25-year storm.

Sea level rise had the second greatest effect on shoreline change on the Florida East coast from 1970 to 2017, although its effect was about one eighth of that of beach nourishment (Houston 2019). Sea level rise had similar effects on the Southwest and Panhandle shorelines. However, in the future, sea level rise will increase significantly and compete with beach nourishment in determining shoreline change on all three Florida sandy coasts. It would be useful for the State of Florida and individual counties to

have estimates of how their shorelines will fare for different sea level rise scenarios of the Intergovernmental Panel on Climate Change (IPCC) and how their rates of beach nourishment could be changed to offset sea level rises if possible.

APPROACH Equilibrium profiles

Standard beach nourishment design assumes that sand initially placed on the subaerial beach and the nearshore will spread over 2-3 years down to closure depth along an equilibrium profile perpendicular to the shoreline, thereby raising the entire profile (Figure 1; Dean 1991; Corps of Engineers 1995; Dean

and Campbell 1999). Dean and Charles (1994) discuss the equilibrium profile concept and its application.

Houston (2019) showed that equilibrium profile theory predictions of shoreline change on the East coast from 1970-2017 that included effects of beach nourishment, sea level rise, longshore transport, and inlets were within 5% of measured shoreline change and well within standard deviation uncertainties.

Equilibrium profile theory is used to determine future shoreline change from 2020-2100 when beach nourishment and sea level rise will dominate. Using the theory, shoreline advance, , due to adding a beach nourishment volume, V , to the active littoral zone can be estimated by the following equation (Dean and Dalrymple 2002):

$$X_a = v / [(h_* + B) * L] \quad \text{Equation (1)}$$

Figure 1 shows parameter definitions with the notation used by Dean and Absalonsen (2011) and others; h_* being closure depth, B beach berm elevation, W , distance from the landward end of the beach berm to closure depth, and L shoreline length.

Equilibrium profile theory also relates shoreline recession, X_r , caused by relative sea level rise, S , (Bruun 1954, 1962, 1988; Atkinson *et al.*, 2018) as:

$$X_r = (S * W) / (h_* + B) \quad \text{Equation (2)}$$

S is relative sea level rise.

Beach nourishment

Beach nourishment volumes on the east, southwest, and Panhandle coasts are obtained from five recent reports with complete detailed data through 2017 (FDEP 2018a, b, c, d, e). Houston (2019) did not consider sand bypassed around inlets as beach nourishment because he was performing a sediment budget, but in this paper all beach nourishment identified by FDEP (2018a, b, c, d, e) is included regardless of the sand’s origin. Nourishment on Florida’s east coast started as early as 1970 in Broward County and the 1970s in five other counties. However, it started in Nassau, Brevard, and Indian River counties in 1994, 1995, and 2003 respectively (FDEP 2018a, b, c). Beach nourishment on the Southwest and Panhandle coasts started at significant levels in 1988 with less than 3% of nourishment placed in earlier years (FDEP 2018d,e). Therefore, a 30-yr period from 1988 to

Table 1.
Parameter values in feet needed in
Equations (1) and (2)

County	h_{B}	W_{B}	L
Nassau	29.4	1440	79,000
Duval	27.1	1570	79,000
St. Johns	27.6	1270	216,000
Flagler	27.3	1010	95,000
Volusia	27.0	1510	220,000
Brevard	27.0	1050	211,000
Indian River	26.6	910	116,000
St. Lucie	25.0	1090	111,000
Martin	25.5	1060	116,000
Palm Beach	24.7	970	238,000
Broward	24.4	720	127,000
Dade	23.2	1200	121,000
Pinellas	19.8	1080	195,000
Manatee	20.2	910	63,000
Sarasota	21.9	930	174,000
Charlotte	20.7	1320	69,000
Lee	21.7	1360	243,000
Collier	20.4	1240	158,000
Escambia/ Santa Rosa	24.3	1140	216,000
Okaloosa	22.6	1080	50,000
Walton	21.9	1060	132,000
Bay	21.6	960	143,000
Gulf	19.4	1430	164,000
Franklin	19.7	980	195,000

2017 was taken as representative of the past nourishment rate. Escambia and Santa Rosa counties are considered together in Florida data bases of shoreline change and profile elevations (FDEP 2018h), and this convention is continued.

A major beach nourishment project is included that was missed in FDEP (2018e). It involved about 5.4 million yd^3 of sand placed from 1990 to 1991 on Perdido Key in Escambia County and discussed in detail by Dean *et al.* (1995). In addition, over 5 million yd^3 of sand dredged from the Kings Bay Entrance Channel between Georgia and Florida was placed on Nassau beaches (Hodgens *et al.* 2016), but not included in FDEP (2018a), perhaps because the federal government paid 100% of costs.

Figures 2-4 show volumes of beach nourishment sand placed in each of the 30 counties with sandy beaches on the east, southwest, and Panhandle coasts from 1988-2017.

Values of h_{B} used in Equations (1) and (2) are taken from Dean and Absalonsen (2011). It is assumed that beach nourishment will ultimately be required

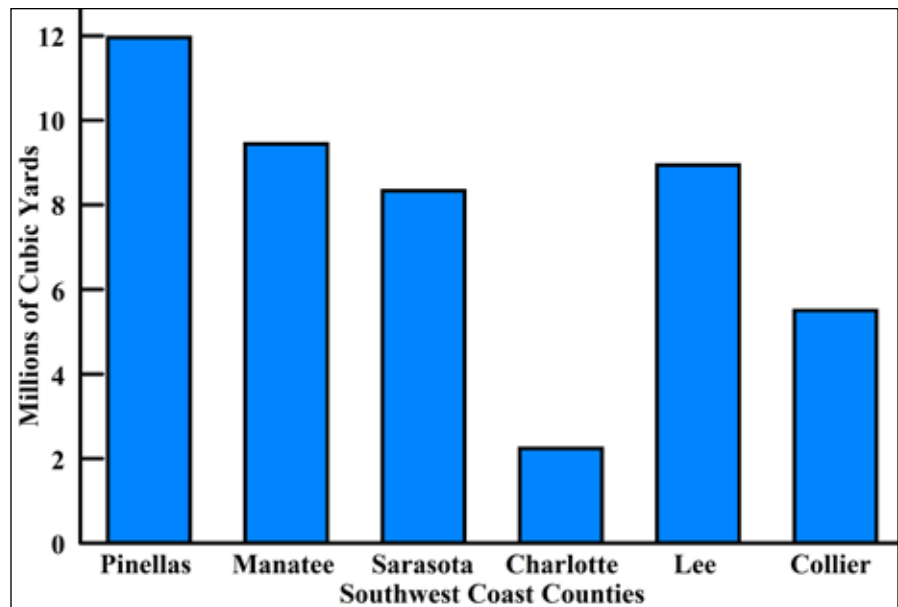
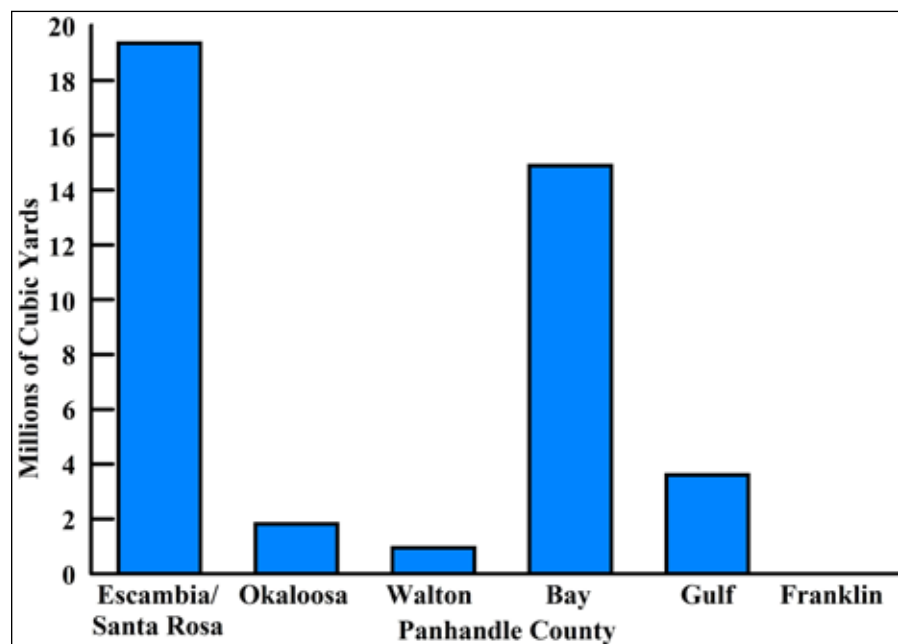


Figure 3. Beach nourishment sand volumes on the Florida southwest coast 1988-2017.

Figure 4. Beach nourishment sand volumes on the Panhandle coast 1988-2017. Franklin County has never been nourished as of the end of 2019.



for all sandy beaches for which the State of Florida is responsible. Therefore, B values are average berm elevations at past nourishment projects in each county or adjacent counties for Flagler and Franklin counties that have not had beach nourishment (FDEP 2018a, b, c, d, e). FDEP (2018h) has measured elevations and water depths on profiles located along about every 1,000 ft of shoreline. The profiles extend from the dunes to typically beyond closure depth. W_{B} values were determined for each of the approximately 3,500 profiles along the 665 miles of shoreline to provide average values for each county.

Shoreline lengths, L , for each county are from Absalonsen and Dean (2010), except that federal government-owned shoreline lengths are subtracted that extend from the Canaveral National Seashore to past the Kennedy Space Center in Volusia and Brevard counties, Eglin Airforce Base in Escambia/Santa Rosa and Okaloosa counties, and Tyndall Airforce Base in Gulf County. There are limited shoreline and profile data for much of these shorelines. In addition, local governments and the State of Florida are not responsible for nourishment of these shorelines, and some such

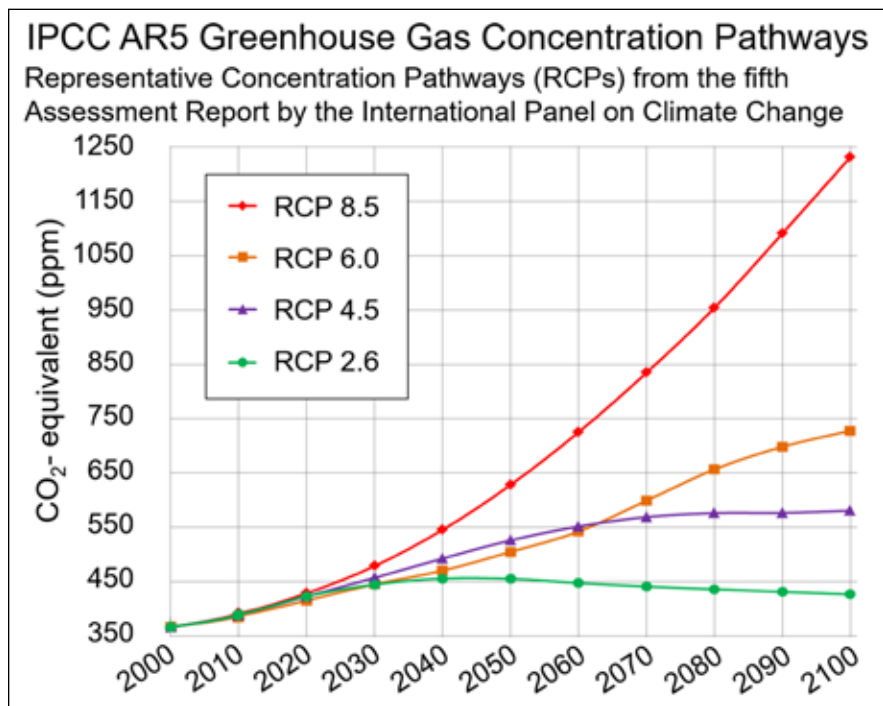
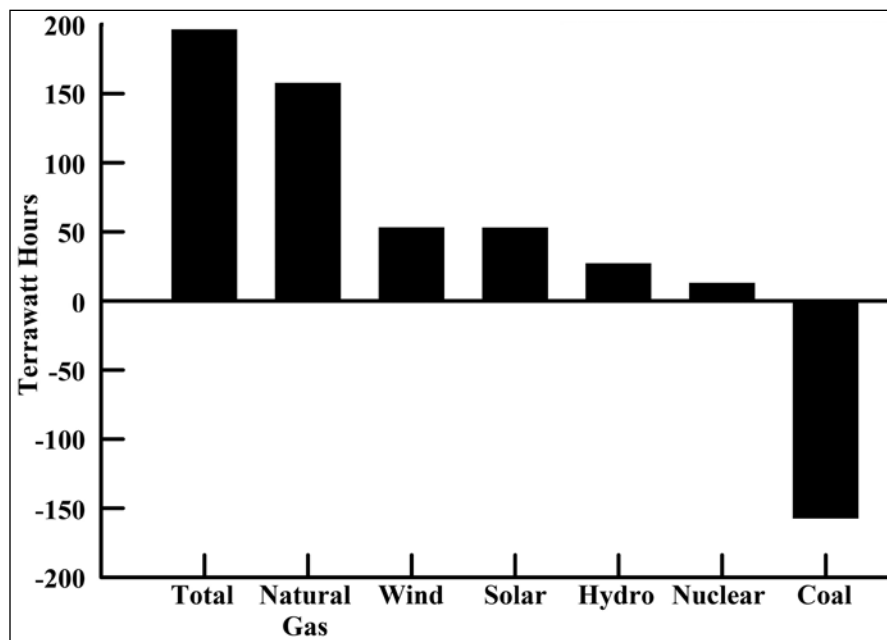


Figure 5. The four Representative Concentration Pathways showing carbon-dioxide-equivalent levels for years 2000-2100 (IPCC 2013).

Figure 6. Worldwide electricity generation change from 2017 to 2018 (International Energy Agency 2019).



as the Canaveral National Seashore may never be nourished. Only the 665 miles of sandy beaches that are state and local responsibilities are analyzed in this paper. Table 1 shows $h_s + B$, W_s , and L values for each county.

It is assumed that the entire Florida sandy coast will be nourished in the future except for the portions owned by the federal government. However, this is unlikely, making results quite conserva-

tive. That is, projected shoreline accretion due to beach nourishment will be greater than presented because beach nourishment will be more concentrated than assumed. Only about 40% of the Florida coast was nourished from 1988 to 2017 (FDEP a, b, c, d, e). Florida has parks and wildlife refuges that include about 100 miles of beaches that have never been nourished and for which there are no plans for future beach nourishment

(Florida State Parks 2019). For example, cutting and structuring St. Lucie Inlet in Martin County caused shoreline recession from 1882 to 1970 of about 1,000 to 2,500 ft that extended for 5 miles downdrift (Houston and Dean 2016). Because this recession was on shorelines of the St. Lucie Inlet Preserve State Park and the Hobe Sound National Wildlife Refuge, there have never been plans to place beach nourishment.

Sea level rise

The IPCC is an intergovernmental body of the United Nations dedicated to providing the world with a scientific view of climate change, its impacts, and possible response options. The U.S. government was the main force in forming the IPCC as an autonomous intergovernmental body to produce reports that had the backing of the leading scientists worldwide. The IPCC is the definitive source for sea level rise projections. Its 2013 projections were made by 71 of the world's greatest experts on all aspects of sea level rise, had exhaustive detailed justifications, and were peer-reviewed by hundreds of other experts (IPCC 2013). IPCC is scheduled to have new climate change projections in 2022, but in September 2019 published interim sea level projections that included the latest knowledge of ice melting in Antarctica (IPCC 2019). Others have published sea level projections, but Houston (2016a) demonstrated that these projections were weakly justified compared to IPCC projections or flawed.

IPCC sea level rise projections are based on IPCC's four Representative Concentration Pathways (RCPs). RCPs are greenhouse gas concentration trajectories that describe different climate-scenario futures (Figure 5). The four RCPs (RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5) are labelled after possible radiative forcing values in the year 2100 (2.6, 4.5, 6.0, and 8.5 watts per meter squared).

IPCC (2019) will be used to determine shoreline change from 2020 to 2100 for all four IPCC scenarios and for the upper confidence level of scenario RCP 8.5 (designated RCP 8.5+). RCP 8.5+ is included because sea level rise based on it is often cited. Increased Antarctic ice melting determined by IPCC (2019) mainly affects RCP 8.5 and RCP 8.5+, increasing them about 4 inches and 4.7 inches respectively compared to IPCC

(2013) projections. The most likely rises projected by IPCC (2019) for RCP 2.6 and RCP 4.5 are about 0.4 inches less and 0.8 inches greater respectively than IPCC (2013) projections. IPCC (2013) projected an RCP 6.0 level only 2 cm (0.8 inches) greater than its RCP 4.5 level in 2100. IPCC (2019) does not provide a projection for RCP 6.0, likely because it is so close to the RCP 4.5 projection. However, for completeness, it is assumed the RCP 6.0 projection remains 0.8 inch greater than the RCP 4.5 projection.

The likelihood of the occurrence of scenario RCP 8.5 warrants discussion. RCP 8.5 is a highly coal-intensive scenario that assumes coal usage in 2100 is seven times greater than its usage in 2013, and technology advancements to the year 2100 to reduce carbon emissions are minimal (Riahi *et al.* 2011). However, worldwide coal use to generate electricity peaked in 2007 and has been dropping rapidly (Figure 6). The International Renewable Energy Agency (2018) projects that coal usage will decline 85% by 2050. There already have been significant technology advancements. Fracking technology has made the cost of natural gas (with 40%-45% of the carbon emissions of coal per energy output) much cheaper than coal and other advances have made unsubsidized solar and wind energy now the cheapest providers of new bulk energy in almost all major economies including China and India (Institute for Energy Economics and Financial Analysis 2018). In 2019, 46% of all new U.S. electric plants used wind generation, 34% gas, 18% solar, 2% other renewables, and 0% coal (U.S. Energy Information Administration 2019). Ritchie and Dowlatabadi (2017) concluded that RCP 8.5 with its “vast future coal combustion is exceptionally unlikely. Therefore, RCP 8.5 should not be a priority for future scientific research or a benchmark for policy studies.” Despite the fact that RCP 8.5 is “exceptionally unlikely” to occur, sea levels based on it and the even more unlikely upper confidence level, RCP 8.5+, are presented.

Projections in this paper are made from 2020 to 2100. IPCC (2013, 2019) projections are from 1986-2005 to 2100. However, Table AII.7.7 of IPCC (2013) has projections that show sea level in 2020 will have risen 8 cm (about 3 in) relative to 1986-2005. Satellite altimeter measurements show the same sea level rise of about 8 cm from late 1992 to 2018

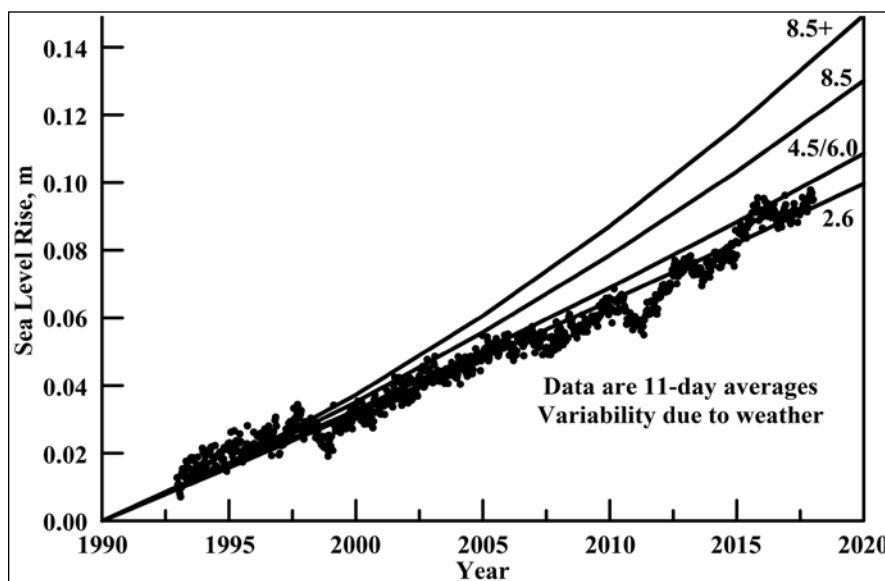
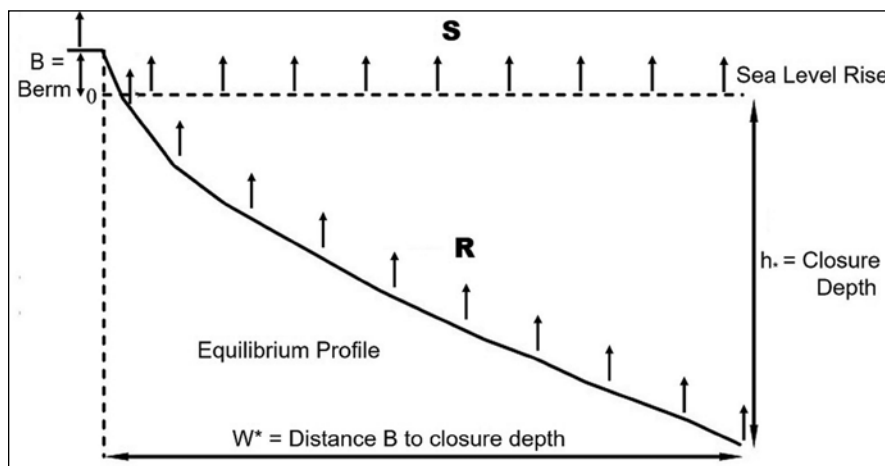


Figure 7. Satellite altimeter measurements shown from late 1992 to 2018 (University of Colorado 2019) compared to IPCC (2019) projections from 1990-2020.

Figure 8. Equilibrium profile rising at the same rate as sea level.



(University of Colorado 2019). The Florida coast is subsiding at about 0.5 mm/yr, increasing relative sea level rise by 4 cm (1.6 inches) from 2020 to 2100 (Houston and Dean 2014; Houston 2015; Houston 2017). Therefore, IPCC (2019) projections are decreased by 8 cm when taken from 2020 to 2100 rather than 1986-2100 and increased by 4 cm when ground subsidence is included. Table 2 shows projections from 2020-2100 with ground motion included and using the most likely IPCC values for each scenario and the upper confidence level of RCP 8.5 (RCP 8.5+).

A recent paper (Shepherd *et al.* 2019) notes that measurements of ice loss from Greenland from 1992-2018 show a loss equivalent to a sea level rise of 1 cm (0.4 inches) over the 27-year period. The paper says that this is near the upper level of

IPCC projections of Greenland’s contribution to sea level rise and speculates that this could increase 2100 projections for the “central estimate” (RCP 4.5/RCP6.0) by 5 to 12 centimeters (2-5 inches). IPCC will evaluate this possibility for its next projections in 2022, but its 2019 projections are used in this paper.

Satellite altimeters have made the best measurements of worldwide sea level rise since they began operations in late 1992 (University of Colorado 2019). These measurements agree well with tide gauge recordings (Dean and Houston 2013). However, altimeter measurements have major advantages over tide gauge recordings in determining global sea level rise. There are a limited number of tide gauges and they are not uniformly distributed over the oceans, but concentrated in the northern hemisphere near populated

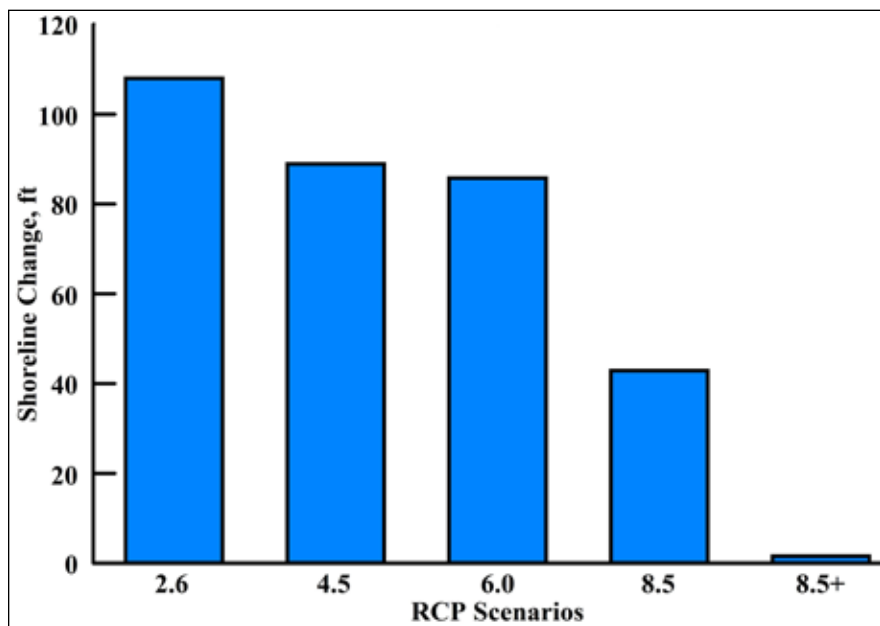
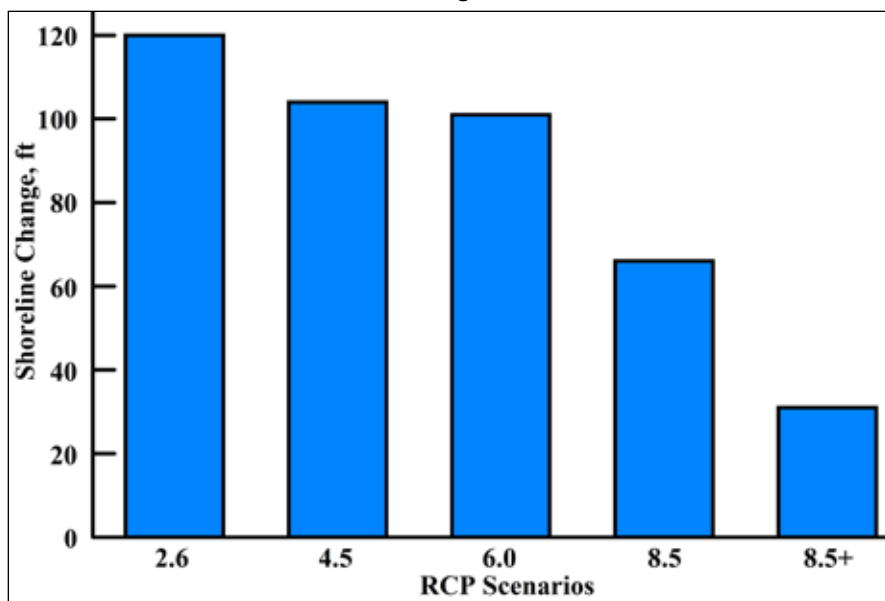


Figure 9. Shoreline change from 2020-2100 on Florida's east, southwest, and Panhandle shorelines as nourishment at the rate from 1988-2017 competes with sea level rise projected by IPCC (2019).

Figure 10. Shoreline change from 2020-2100 on the Florida east coast shoreline for the same conditions as Figure 9.



areas. They measure relative sea level rise that includes vertical motions on the land on which they rest. These vertical motions are often not accurately known. There also are decadal and multidecadal sea level oscillations that affect the determination of worldwide sea level depending on tide gauge locations and the time periods analyzed (Houston 2016b; Iz *et al.* 2018).

Satellite altimeter measurements from 1992-2018 support the validity of the IPCC (2019) projections for scenarios RCP 2.6, RCP 4.5, and RCP 6.0 and the unlikely occurrence of RCP 8.5 and RCP

8.5+. Figure 7 compares satellite altimeter measurements from 1992-2018 to the 1990-2020 portions of IPCC (2019) projections. Sea level projections based on scenarios RCP 4.5 and RCP 6.0 are so similar during this period that they appear as a single line. Figure 7 shows that sea level rise from 1992-2018 measured by satellite altimeters lies between IPCC (2019) projections of sea level rise for scenarios RCP 2.6 and RCP 4.5/6.0, and the rise trends for these scenarios have followed the measurements. The rise trends of RCP 8.5 and RCP 8.5+ compare poorly with the measured data and are

rapidly diverging from the data. Figure 7 supports the conclusion of Ritchie and Dowlatabadi (2017) that scenario RCP 8.5 is "exceptionally unlikely," and clearly scenario RCP 8.5+ is even more unlikely.

Setting Equations (1) and (2) equal so that the effects of beach nourishment and sea level rise on shoreline change are equal and dividing by the number of years yields a nourishment volume per year to offset sea level rise as:

$$V/yr = S/yr * W_s * L \quad \text{Equation (3)}$$

Another useful equation is the sand volume that must be placed annually to compensate for shoreline recession caused by sea level rise. This is determined by solving for $in Equation (2)$ and substituting it into Equation (3), yielding:

$$V/yr = X_s/yr * (h_s + B) * L \quad \text{Equation (4)}$$

The required to advance the shoreline a distance of $is determined using Equation (1).$

$$V/yr = X_s/yr * (h_s + B) * L \quad \text{Equation (5)}$$

According to equilibrium theory, after a couple of winter seasons beach nourishment sand spreads along the equilibrium profile and raises it uniformly. Figure 8 visualizes Equation (3), where the volume per year of beach nourishment placed is sufficient to raise the profile, R/yr , such that it is equal to the rise in sea level, S/yr , thereby offsetting sea level rise. If S/yr is greater than R/yr , the shoreline will erode, if S/yr equals R/yr the shoreline will be stable, and if S/yr is less than R/yr , the shoreline will accrete.

It is useful to make simple calculations before detailed calculations are made to get an idea of magnitudes. Suppose sea level rises 1 ft from 2020 to 2100. W_s averages about 1,140 ft along Florida's coasts and the shoreline length is about 3,513,000 ft (665 miles). The rise is over 80 years, and Equation (3) gives an average annual sand volume of about 1.85 million yd^3/yr is required to offset a sea level rise of 1 ft. However, 6.51 million yd^3/yr of beach nourishment were placed on Florida coasts from 1988-2017 (Figures 2-4). Dividing 6.51 by 1.85 and multiplying by 1 ft gives an estimate that beach nourishment at the past rate can offset a sea level rise of about 3.52 ft from 2020 to 2100. Sea level rise projected for scenario RCP 8.5+ is 3.48 ft (Table 1), so the past nourishment rate will offset on average the rise for all scenarios and for

RCP 8.5+. However, as will be seen in detailed calculations done by county, the past nourishment will not offset sea level rise for all scenarios for all regions and counties. Moreover, this simple calculation was for nourishment of 100% of the shoreline. If only the 40% of shoreline that has been nourished in the past were nourished in the future rather than spreading the nourishment over 100% of the shoreline, beach nourishment could offset a considerably higher sea level rise than 3.52 ft.

Equations (1) and (2) are used to determine shoreline changes on the overall shorelines of the East, Southwest, and Panhandle coasts and for each of their counties from 2020 to 2100 due to beach nourishment at the 1988-2017 rate and for each IPCC sea level rise scenario. Then the shoreline changes due to beach nourishment and sea level rise are combined to determine overall shoreline changes.

RESULTS

Figure 9 presents the average shoreline change from 2020 to 2100 for all 665 miles of Florida's sandy coast. The shoreline will advance on average for all scenarios and for RCP 8.5+, as was indicated by the simple calculation of the last section. As will be seen, the shoreline will not advance in all counties for all scenarios. Figure 10 shows results for East coast counties that are similar to those shown in Figure 9.

Although east coast shorelines advance on average for all scenarios and RCP8.5+, all county shorelines do not advance. For example, Table 3 shows Flagler and Volusia counties recede for all scenarios. Flagler County has never been nourished as of the end of 2019 (Figure 2), but has signed a 50-yr beach nourishment agreement with the Corps of Engineers (2018). Volusia County has had the least beach nourishment among nourished east coast beaches (Figure 2), but is conducting a major measurement program to aid in determining how to best maintain its beaches (Volusia County 2019). Nassau, Brevard, Indian River, St. Lucie, Martin, Palm Beach, and Broward counties have shorelines that are projected to advance for all scenarios. Inlets modified for navigation caused on average over 250 ft of shoreline recession on these shorelines before 1970, and much of the nourishment placed was to mitigate

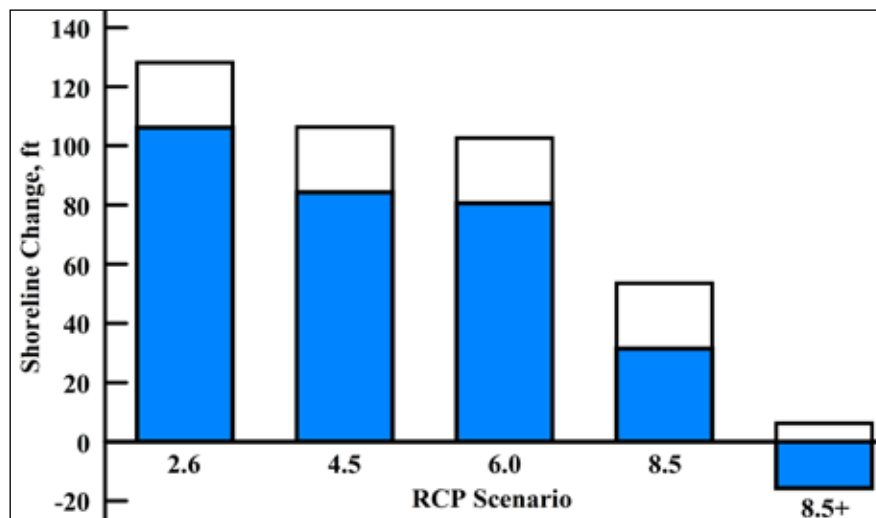


Figure 11. Shoreline from 2020-2100 on the Florida southwest shoreline. The solid bars are for beach nourishment at the 1988-2017 rate for all counties and the white bars for a 2003-2017 rate for Charlotte and Lee Counties and a 1988-2017 rate for the other counties.

Figure 12. Colored bars show shoreline change from 2020-2100 on the Florida Panhandle. White bars show the change if Franklin County is not nourished.

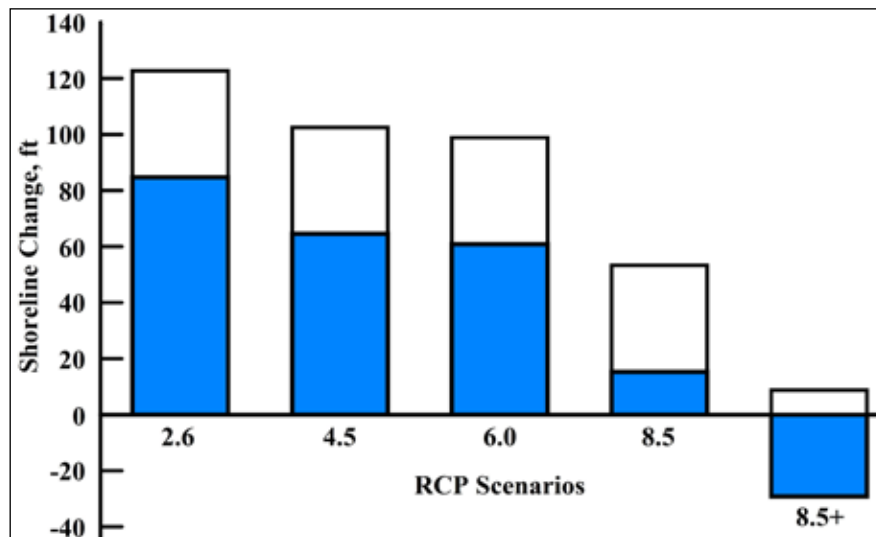


Table 2.

Sea level rise from 2020 to 2100 including Florida ground subsidence (IPCC 2013, 2019)

Scenario	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5	RCP 8.5+
Rise (ft)	1.28	1.67	1.74	2.62	3.48

this past shoreline recession (Houston and Dean 2016). Because inlets will impact shorelines much less in the future than the past as a result of shoal stability and mechanical bypassing of sand at inlets, these counties can reduce future nourishment rates and still offset sea level rise. The shoreline for Nassau County, in particular, advanced significantly because its past nourishment rate was abnormally high due to large quantities of sand dredged for a navigation channel

(to what is now the Trident submarine base at Kings Bay) that were subsequently bypassed to county beaches. Because seven of the 12 counties can reduce past nourishment rates for all scenarios and St. Johns, Duval, and Dade counties for all scenarios except the very unlikely RCP 8.5+, funds would be available for Flagler and Volusia counties to increase beach nourishment.

Figure 11 shows results for southwest coast counties. The solid bars show shore-

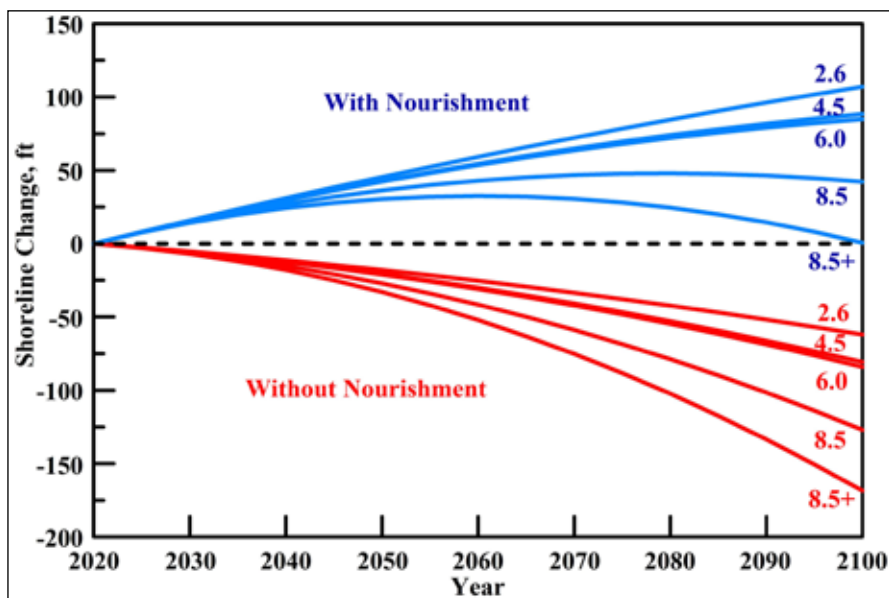
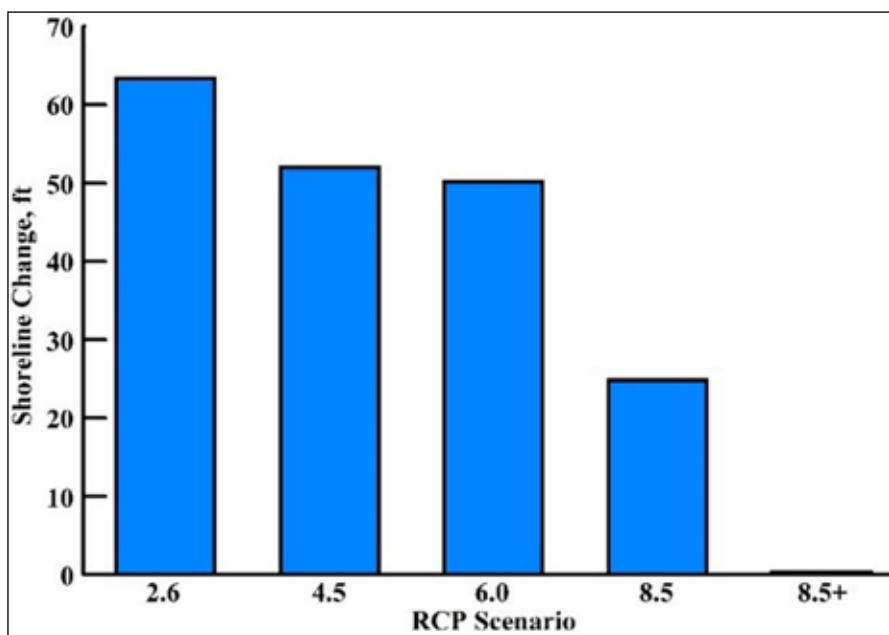


Figure 13. Shoreline change on the Florida shoreline with and without beach nourishment.

Figure 14. Shoreline change with beach nourishment placed at half the 1988-2017 rate and Florida parks and wildlife reserves not being nourished.



line change for all six counties with the 1988-2017 rate of nourishment. This rate would have to be increased by less than 10% to offset sea level rise for RCP 8.5+. In addition, Charlotte and Lee counties were late to using beach nourishment, and their rate of nourishment from 2003 to 2017 was over 40% greater than their rate from 1988 to 2002. If it is assumed that the rate from 2003 to 2017 is the more appropriate past rate for the two counties, the white bars of Figure 11 show that southwest shorelines would advance for all scenarios. This illustrates that a 30-yr representation of the past rate may be too long a period for some counties because

their rates of beach nourishment have increased.

As was the case for the east coast, shoreline change will not be uniform among the counties in the southwest. Table 4 shows Pinellas, Manatee, and Sarasota counties have advancing shorelines for all scenarios. Future shoreline change for Manatee County is high because its shoreline receded over 350 ft from 1874 to 1974 along about 30,000 ft of shoreline from Monuments R12-R41 due to impacts of the Tampa Bay entrance (Absalonsen and Dean 2010). This recession led to the 50-yr Manatee County

Shore Protection Project that started in 1993 with significant beach nourishment to mitigate the past recession. Charlotte, Lee, and Collier counties have advancing shorelines except for RCP 8.5 and RCP 8.5+. Again, future nourishment rates can be reduced in Pinellas, Manatee, and Sarasota counties and increased in Charlotte, Lee, and Collier counties if RCP 8.5 and RCP 8.5+ were to occur.

Figure 12 shows projected shoreline change for Panhandle coast counties. The solid bars represent shoreline change if all counties are included. The white bars represent shoreline change if Franklin County is not nourished. Franklin County is lightly populated, has never had beach nourishment, and there are no plans for future nourishment. The county shoreline has receded 62 ft on average from 1976 to 2007 (Absalonsen and Dean 2010). Whether Franklin County should ever be nourished is a policy issue that will face Florida.

Table 5 shows that Escambia/Santa Rosa and Bay counties shorelines will advance for all scenarios. Escambia/Santa Rosa County has placed large volumes of beach nourishment to mitigate significant past erosion due to dredging and offshore sand disposal at Pensacola Pass (Figure 4; Browder and Dean 1999). Bay County has had significant beach nourishment to mitigate the cutting of the St. Andrews Bay entrance (Figure 4; Houston 2017). Walton, Gulf, and Franklin have projected shoreline recession for all scenarios. Walton County has had the least beach nourishment of the 28 Florida counties that have been nourished (Figure 4), but has a planned 50-yr nourishment project in partnership with the Corps of Engineers (FDEP 2018e). Gulf County had a single nourishment project from 1988-2017 that was placed on a very rapidly eroding shoreline and Franklin County has never been nourished.

DISCUSSION

Shoreline changes in Figures 9-12 and Tables 3-5 have uncertainties. It has been assumed that nourishment rates and projected IPCC sea level rises are givens, so shoreline change uncertainties in Equations (1) and (2) arise from uncertainties in closure depth and distance to closure depth. From Houston and Dean (2014), it is assumed that $h_{c,B}$ has an uncertainty of ± 1 m (3.28 ft) and W_c has the same percentage uncertainty as $h_{c,B}$, because

its uncertainty is directly related to h_s+B uncertainty. Standard propagation of errors is then used to combine uncertainties in shoreline changes from Equations (1) and (2) and volume changes in Equations (4) and (5). Percentage uncertainties vary somewhat with h_s+B and W_s , but shoreline changes in Figures 9-12 and Tables 3-5 have uncertainties of approximately 25% and volumes uncertainties of about 30%.

The annual beach nourishment volume for which a county has a shortfall or surplus in offsetting sea level rise from 2020-2100 for each IPCC scenario can be determined using Equations (4) or (5), Table 1, and Tables 3-5. For example, from Table 3 the Flagler County shoreline will erode 60 ft from 2020 to 2100 for scenario RCP 4.5. From Table 1, $h_s+B = 27.3$ ft and $L = 95,000$ ft. Substituting these values into Equation (4) with an 80-yr length of time and converting from ft^3 to yd^3 yields a rate of nourishment of about $72,000 \pm 22,000$ yd^3/yr (uncertainty of 30%) that would have to be placed to offset RCP 4.5. Flagler County has a recent agreement with the Corps of Engineers to place 1.6 million yd^3 of sand over a 50-yr period along about 2.6 miles of shoreline (15% of the county's shoreline) or 32,000 yd^3/yr (Corps of Engineers 2018).

Sarasota County is a second example of use of Equation (5), Table 1, and Table 4. From Table 4, the county's shoreline would widen 10 ft from 2020-2100 for RCP 8.5+. From Table 1, $h_s+B = 21.9$ ft and $L = 174,000$ ft. Using Equation (5), Sarasota has an excess placement volume of about $17,600 \pm 5,300$ yd^3/yr for RCP 8.5+. From Figure 3, Sarasota placed about 278,000 yd^3/yr from 1988-2017, so the excess is only 6% of its past nourishment rate.

The shoreline changes in Tables 3-5 are countywide averages, and shoreline change details within a county can differ substantially from the average. For example, jetties at inlets or other interruptions of longshore transport can cause updrift accretion with sand gains that equal sand losses due to downdrift recession. When averaged over the county, there is no net loss, but beach nourishment has to mitigate the downdrift recession. It has been assumed that inlet management plans have been implemented, but only about a third of the plans have been implemented. However, it is a state requirement

Table 3.

Shoreline change for East coast counties for RCP scenarios, rounded to the nearest 5 ft, with beach nourishment at the 1988-2017 rate

County	2.6	4.5	6.0	8.5	8.5+
Nassau	410	390	390	350	300
Duval	75	50	45	- 5	- 55
St. Johns	85	65	65	20	-15
Flagler	-45	-60	-65	-95	-130
Volusia	-55	-80	-85	-130	-180
Brevard	130	115	110	80	45
Indian River	110	100	95	65	35
St. Lucie	110	90	90	50	15
Martin	260	245	245	205	170
Palm Beach	235	220	220	185	150
Broward	95	80	80	55	30
Dade	95	75	70	25	-20

Table 4.

Shoreline change for Southwest coast counties for RCP scenarios, rounded to the nearest 5 ft, with beach nourishment at the 1988-2017 rate

County	2.6	4.5	6.0	8.5	8.5+
Pinellas	155	130	130	80	35
Manatee	480	460	455	415	380
Sarasota	105	85	85	45	10
Charlotte	30	5	0	-55	-110
Lee	40	15	53	-40	-95
Collier	45	20	15	-35	-90

Table 5.

Shoreline change for Panhandle coast counties for RCP scenarios, rounded to the nearest 5 ft, with beach nourishment at the 1988-2017 rate

County	2.6	4.5	6.0	8.5	8.5+
Escambia/Santa Rosa	205	185	185	145	105
Okaloosa	55	35	35	-10	-50
Walton	-40	-55	-60	-105	-145
Bay	290	275	270	230	195
Gulf	-15	-40	-45	-110	-175
Franklin	-65	-85	-85	-130	-175

to place beach-quality sand from inlet construction or maintenance on downdrift beaches, so bypassing is occurring even if plans are still to be implemented. In addition, "hot spot" erosion areas are typical along coasts, but their cause is usually not known. They need beach nourishment even if a county's shoreline is accreting on average. Beach nourishment in the past has typically addressed these situations and will need to do so in the future. Therefore, nourishment may be needed to more than offset sea level rise, and the volume surpluses may not be as great as the calculations indicate. Similarly, volume deficits may not be quite large enough.

The beach nourishment density per year required to offset RCP 8.5+ on the

entire Florida shoreline is obtained by dividing both sides of Equation (3) by L , dividing 3.48 ft by 80 yrs to obtain S/yr in ft/yr , setting $W_s = 1,040$ ft., and converting ft^3 to yd^3 . The result is a density per year of about 1.7 $\text{yd}^3/\text{ft}/\text{yr}$. This is not a large density for nourished beaches. For example, 40% of the Florida shoreline (or 1.4 million ft) was nourished from 1988 to 2017 with sand placed at a rate of 6.5 million yd^3/yr , resulting in a density per year of 4.6 $\text{yd}^3/\text{ft}/\text{yr}$. In the Flagler County example, the sand will be placed over a 50-yr period on 2.6 miles at a modest rate of 2.3 $\text{yd}^3/\text{ft}/\text{yr}$. In the Sarasota example, less than 25% of Sarasota's 174,000 ft shoreline has been nourished (Table 1), so about 43,500 ft was nourished with a nourishment rate of 278,000 yd^3/yr , or a density per year of about 6.4 $\text{yd}^3/\text{ft}/\text{yr}$.

Beach nourishment is critical to Florida as seen in Figure 13. At the past nourishment rate, the shoreline will not only advance for all scenarios, but will accrete about 85-110 ft for likely scenarios RCP 2.6, RCP 4.5, and RCP 6.0 from 2020-2100 and still be accreting in 2100. However, without beach nourishment, the Florida coast would recede for all IPCC scenarios, even the most benign RCP 2.6 scenario. In addition, Figure 13 shows that it would not be until about 2065 before the average shoreline would slowly narrow for RCP 8.5+, and this would be hardly noticeable.

Much of Florida's beach nourishment has been placed adjacent to inlets and bay entrances to mitigate past shoreline recession produced by navigation projects. Counties in Tables 3-5 with advancing shorelines for all scenarios, have large past beach nourishment rates that were needed to mitigate the inlet impacts. With inlets now taking much less sand out of the littoral zone, after inlet bypassing plans are all put completely in effect, these counties can reduce past nourishment rates in the future and still offset sea level rise. Other counties that have received relatively little (Volusia, Walton, and Gulf counties) or no (Flagler and Franklin) past beach nourishment will require increased rates of nourishment to offset sea level rise. Therefore, the pattern of beach nourishment among Florida counties will change in the future.

The equilibrium profile analysis assumes that future shoreline effects of inlets and longshore transport are small compared to beach nourishment and sea level rise. This assumption is good for the east and southwest coasts where beach nourishment dominated shoreline change from 1970 to 2019, causing average shoreline advance of over 100 ft (Houston 2015, 2019). However, the assumption must be modified for part of the Panhandle coast.

Longshore transport rather than beach nourishment, sea level rise, and inlets has dominated shoreline change from 1970 to 2019 in Gulf and Franklin counties (Houston 2017). Portions of the St. Joseph Peninsula in Gulf County have eroded at the remarkable rate of 50-70 ft/yr since 1857 (Absalonsen and Dean 2010). This erosion is due primarily to longshore losses of 298,000 yd³/yr off ends of the Peninsula (Houston 2017). In order to

remain stable, the Gulf County shoreline would require beach nourishment to offset the longshore losses in addition to losses due to sea level rise. Parts of this shoreline have been armored and a feasibility study is being conducted to consider further armoring (FDEP 2018e). Similarly, St. George Island in Franklin County loses 127,000 yd³/yr to longshore transport off the Island ends (Houston 2017). The county is lightly developed, has never been nourished, and has no plans for nourishment. A stable shoreline would require offsetting both sea level rise and longshore losses.

The sea level rises in Table 1 are for most likely values for each scenario and the upper confidence level of RCP 8.5. Because RCP 8.5 is "exceptionally unlikely" (Ritchie and Dowlatabadi 2017) and RCP8.5+ even more unlikely as discussed in the Approach section, a more reasonable upper level of the rise from 2020-2100 is the upper confidence level of RCP 6.0. Using IPCC (2019) and the approach described to obtain Table 1, the upper confidence level of RCP 6.0 is a rise from 2020 to 2100 of about 2.30 ft. The approach presented can be used to determine shoreline change in each county for this upper level rise.

Although beach nourishment can offset sea level rise from 2020 to 2100 and beyond, there may be challenges obtaining sufficient sand. However, it is unlikely that the 100 miles of beaches (about 15% of Florida's beaches) in Florida coastal parks and wildlife reserves that have not been nourished in the past will be nourished in the future (Florida State Parks 2019). Figure 14 shows that the past beach nourishment rate can be cut in half and still offset sea level rise if these parks and wildlife reserves are not nourished in the future. Moreover, about 45% of Florida beaches are not within state parks and have never been nourished. Beach nourishment is unlikely to be economically justifiable for some of these beaches, thereby further reducing beach nourishment volumes required to offset sea level rise. Retreat is likely the most viable option for shorelines where beach nourishment cannot be justified economically.

Opponents of the use of beach nourishment sometimes argue that it is a waste of money because there is no use fighting "Mother Nature." However, inlets modified by humans for navigation

caused more sand loss in the littoral zone before 1970 than has been gained from 1970-2020 through beach nourishment placed to mitigate the loss. Increased sea level rise is caused by increased global warming that is in turn caused by increased emissions of greenhouse gases by humans. Therefore, the plight of beaches in the past was largely caused by humans and the plight in the future also will largely be caused by humans, not "Mother Nature." Moreover, far from being a waste of money, beach nourishment in Florida has had a tremendous return on investment due to wider beaches attracting tourists and protecting infrastructure from damage (Houston 2018).

There will be significant coastal problems not related to the open coast beach itself due to increased sea level rise. Florida back bay areas are low-lying, and currently during the highest tides there is significant back bay flooding in areas such as Miami Beach and Key Largo. Back bay flooding will spread as sea level rises and become a major problem throughout coastal Florida. Saltwater intrusion into freshwater aquifers is a problem now in south Florida and will worsen. Wetlands will likely be unable to keep up with sea level rise and will drown, causing significant environmental impacts.

CONCLUSIONS

Beach nourishment is powerful. It dominated shoreline change on the Florida shoreline from 1970 to 2019. If continued at a rate from 1988 to 2017, it can offset all IPCC sea level rise scenarios from 2020 to 2100, including the upper confidence level of the worst scenario. However, without beach nourishment, the Florida coast would recede for all IPCC scenarios. Therefore, beach nourishment is critically important to maintaining Florida shorelines.

Beach nourishment placement among counties in the future will differ from the past. Much of the beach nourishment placed in the past was to mitigate shoreline recession caused by sand loss due to inlet modifications for navigation purposes. However, inlet impacts have moderated since 1970 and less nourishment sand will be required in the future in counties impacted significantly in the past. Other shorelines that have received little or no beach nourishment in the past will require increased rates of nourishment in the future to offset sea level rise.

Satellite altimeter recordings of sea level rise from 1992 to 2018 show a rise that is between the 1992-2018 portion of IPCC (2019) projections for 1990 to 2020 based on scenarios RCP 2.6 and RCP 4.5/6.0. If this trend continues, the 2020-2100 rise will be 1.3-1.7 ft. A reasonable upper level of sea level rise from 2020-2100 may be 2.3 ft, which is the projected rise for the upper confidence level of IPCC scenario RCP 6.0.

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