



Quantifying Multi-Decadal Salt Marsh Surface Elevation and Geodetic Change: The South Carolina Geological Survey SET Network

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Abstract

In 1998, the South Carolina Geological Survey (SCGS) established a state-wide coastal Surface Elevation Table (SET) network to document geodetic elevation changes (uplift or subsidence) at different spatial resolutions, quantify elevation change on salt marsh platforms over time, and compare the rate of surface elevation change (REC) at each station to the rate of local relative sea-level rise (RSLR). Analysis of short- and long-term (4 to 22+ year) datasets from 21 SCGS SET stations shows that rates vary widely, from -2.30 to $+10.17$ mm/yr. The 22+ year length of record on the oldest SCGS SET datasets reveal non-linear REC trends, with short-term trends often above or below the long-term trendline. When compared to a 100-year RSLR trend of 3.36 ± 0.19 mm/year at NOAA gauge 8,665,530 (Cooper River Mouth, Charleston Harbor), 11 stations had higher rates, five were lower, and five had overlapping confidence intervals. With a shorter 23-year record, only two stations would have higher rates. All SCGS SET stations are situated high in the tidal frame. There are no discernible associations between SET positions relative to mean high water (MHW) and REC. Long-term (1998–2021) geodetic elevation data available for six of the original stations indicate some geodetic elevation loss. Data for these original stations, and nine upland benchmarks surveyed in 2022, indicate possible impacts from the underlying Garner-Edisto fault. These findings have implications for other SET programs using similar methods to quantify vertical change over decadal time spans.

Keywords Salt marsh · Surface elevation table (SET) · Geodetic data · Global navigation satellite system (GNSS) · Surface elevation change · Relative sea-level rise (RSLR)

Introduction

Salt marshes are intertidal ecosystems found along low-energy coasts in temperate and high latitudes worldwide. Often located in sheltered areas behind barrier islands or in estuaries, they occupy distinct elevation ranges that vary based on tidal regime (Redfield 1972; Brooks et al. 2021) and are thought to have established along the Atlantic Coast of North America in tandem with a decreasing rate of local relative sea-level rise (RSLR—land subsidence or uplift plus eustatic sea-level change) approximately 4.5–3 ka (Kraft

1971; Kirwan et al. 2016; FitzGerald and Hughes 2019). Salt marshes are dynamic, functioning through an interaction of complex biological and physical influences related to vegetation, sediment transport, marsh platform elevation, and exposure to physical influences such as waves and tides (Möller et al. 1999; Morris et al. 2002; Erwin et al. 2006; Fagherazzi et al. 2012; Ganju et al. 2015). Salt marsh plant species are sensitive to rising sea levels and changes in inundation regimes (Redfield 1972; Niering and Warren 1980; Christiansen et al. 2000; Lefeuvre et al. 2003), which is significant in part because marsh platforms gain elevation by trapping and accreting sediment on their surface and building biomass belowground (FitzGerald and Hughes 2019).

As global sea-level rise (SLR) accelerated over the past 200 years (Donnelly et al. 2004; FitzGerald and Hughes 2019), coastal marshes adapted to increasing inundation by building the elevation necessary for maintaining favorable hydrologic conditions or migrating landward to areas of slightly higher elevation (Redfield 1972; Gardner and Porter 2001; Lynch et al. 2015). With a predicted global

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acceleration of SLR over the coming decades (Carey et al. 2017; Sweet et al. 2022), many marshes may be at risk of becoming increasingly fragmented and converting to shallow open water or intertidal mud flats if elevation gain does not meet or exceed RSLR (Morris et al. 2002; Pendleton et al. 2012; Best et al. 2018; Cahoon et al. 2019). The loss or impairment of salt marshes would reduce or limit the vital roles that they play in biological productivity, stormwater control, carbon sequestration, and a host of other ecosystem services (Kirwan and Murray 2008; Kirwan and Temmerman 2009; Hopkinson et al. 2012; Belknap and Kelley 2021). Conversely, SLR could increase accommodation space for coastal wetlands and mangroves if sedimentation keeps pace with the volume and elevation of space made available for mineral and organic sediment (McIvor et al. 2013; Törnqvist et al. 2021). The long-term response of the world's salt marshes to SLR is largely unclear, hinging on variables that are site-specific and challenging to predict (Best et al. 2018). However, data from Surface Elevation Table (SET) stations provide context for how marsh platform elevation changes in response to these variables.

SCGS SET Network

Field-based SET monitoring methodology is used worldwide to quantify marsh platform elevation changes and provide insight into possible responses to different SLR scenarios (Lynch et al. 2015; Carey et al. 2017; Raposa et al. 2017; Cahoon et al. 2019). The South Carolina Geological Survey's (SCGS) SET network was established in the late 1990s to (1) document geodetic elevation changes (uplift or subsidence) at different spatial resolutions, (2) quantify surface elevation change on salt marsh platforms over time, and (3) compare the rate of surface elevation change (REC) at each station to the rate of local RSLR. The SCGS SET project methodology has incorporated both the original SET instrument design and the Rod Surface Elevation Table (RSET; Cahoon et al. 2002), along with geodetic surveying, to address project objectives (Doar and Luciano 2022). Herein, the term "SET" is used generically for both the original SET and the RSET unless otherwise noted. The SCGS SET network ranges geographically from South Carolina's border with North Carolina to the Georgia state line. The network is sub-divided, from north to south, into the Long Bay, Cape Romain, Charleston, Ashepoo-Combahee-Edisto (ACE) Basin, and Port Royal Sound compartments (Fig. 1). The network expanded from an initial ten stations in 1998, with an eleventh installed in 2000 (Fig. 2), to 26 by 2022. A majority of the initial 11 stations were converted to RSET in 2009 (Table 1). Since 2009, all new stations have been installed as RSETs. Five of the initial 11 stations were lost to shoreline erosion and creek bank failure, burial, or material failure (Doar and

Luciano 2022). As of 2022, six of the original SET mounts were still in place and are referred to herein as "survivor stations"—of these, only Station 10 (now ACEWI3) has ongoing SET data collection and no RSET replacement.

Physical Setting

All SCGS SET stations are situated in tidal salt marshes that range between 0.2 and 24 km from the Atlantic Ocean (Fig. 1). Station sites were selected with consideration for position within the tidal frame, distance to creeks, vegetation type, and ease of access. Geomorphic setting varies but can be broadly classified into estuarine and backbarrier marsh platforms, levees, and a revegetated spoil area along the Atlantic Intracoastal Waterway (AIWW) (Table 1). The tidal regime is semi-diurnal and mesotidal (Hayes 1994) with an average range of 1.5 m at the northernmost extent of the network near Little River Inlet, South Carolina, to 2.0 m near Savannah River, Georgia. SET stations within the same regional compartments are assumed to experience similar tidal conditions.

South Carolina's coastline varies geologically and geomorphically, with mainland-attached Pleistocene barriers in the northern part of the state (Long Bay) giving way to younger Holocene-aged drumstick barrier islands southward toward the Santee River Delta and Cape Romain compartment (Hayes et al. 1979; Hayes 1994; Fig. 1). This geography results in small, isolated patches of salt marsh in the Long Bay compartment and larger, interconnected marshes to the south. The Santee is the only river in South Carolina that has historically provided large volumes of sand to the coastline (Griffin 1981) and may control the change of barrier island morphology south of its mouth. The central and southern sections of coastal South Carolina (southern Cape Romain, Charleston, ACE Basin compartments) (Fig. 1) are characterized by a transition from Holocene drumstick barrier islands to barrier islands separated by ebb-dominated tidal inlets and backed by Sea Islands (Hayes and Michel 2007), with geomorphic control related to sediment source as well as inlet and ebb-tidal delta dynamics (FitzGerald 1984; Moslow and Tye 1985). The Port Royal compartment is characterized by composite Pleistocene and Holocene-aged Sea Islands (Doar and Koch 2004).

Most SCGS SET sites are dominated by *Spartina alterniflora*, although variability in vegetation type and distribution exists at several locations (Table 1). The ideal tidal range for *S. alterniflora* is between mean high water and 0.7 m below mean sea level (Bertness 1991; Landin 1991); however, tidal range does not necessarily dictate the occurrence of *S. alterniflora* (McKee and Patrick 1988). *S. alterniflora* can reach heights of 1.5–2.4 m (tall form) adjacent to tidal creek banks, and a shorter, stunted form of *S. alterniflora* (short form) can colonize the

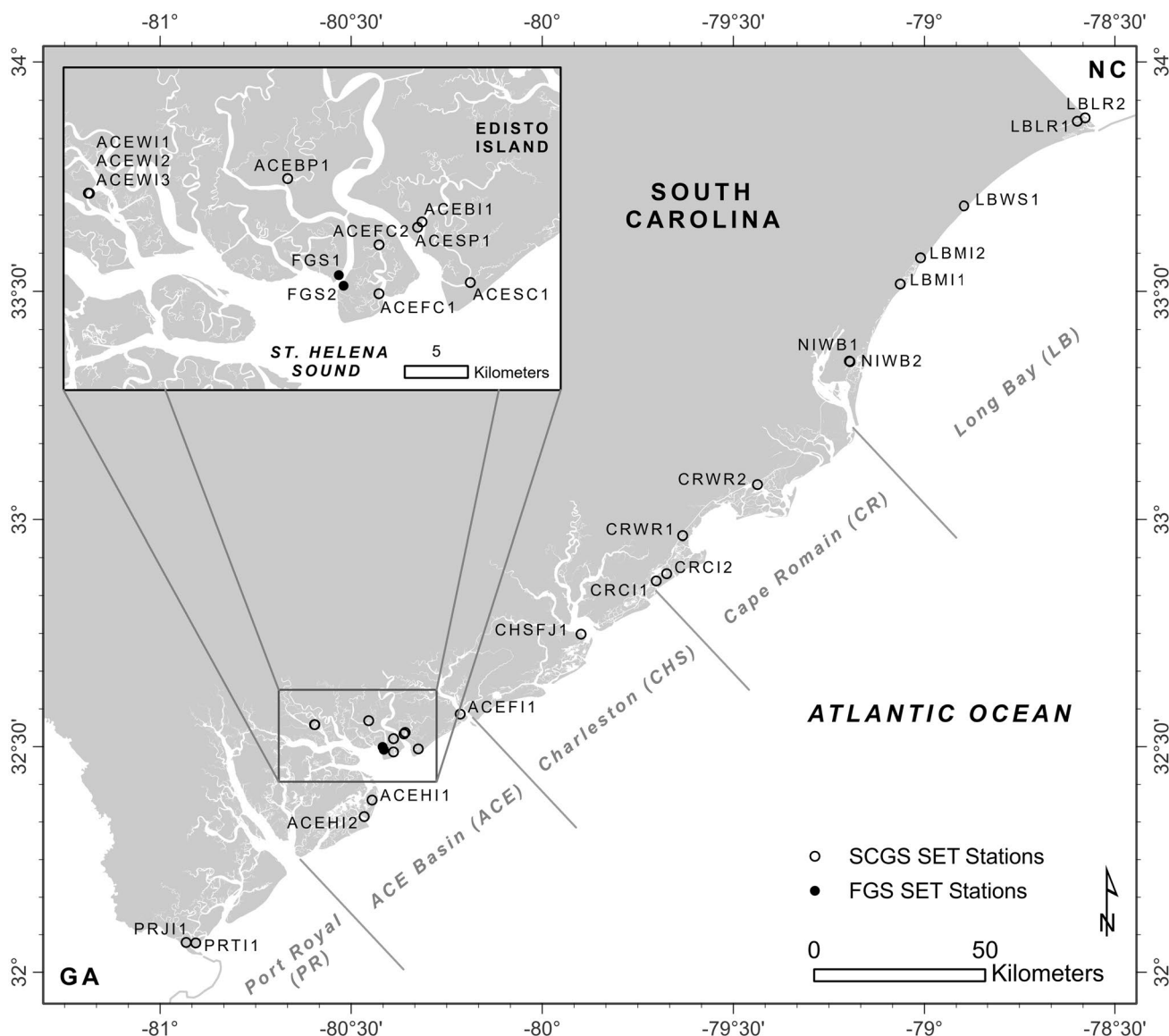


Fig. 1 Geographic distribution of the South Carolina Geological Survey (SCGS) SET network as of 2022. The inset map details the locations of SETs within the center of the ACE Basin National Estuarine Research Reserve (NERR). Two Florida Geological Survey (FGS)

stations (FGS1 and FGS2) were measured between 1997 and 2001 (Doar and Luciano 2022). Data for a subset of the network (21 of a total of 26 stations) were considered for this study

interior of marsh platforms where nutrient availability, sediment deposition, and pore water exchange tend to be lower than areas adjacent to the creek bank (Leonard 1997; Sanger and Parker 2016). Other common salt marsh species in coastal South Carolina are *Juncus roemerianus*, *Salicornia virginica*, *Batis maritima*, *Borrchia frutescens*, and *Iva frutescens*. These species progressively colonize less inundated or higher elevations of the marsh compared to *S. alterniflora* (Sanger and Parker 2016).

Research Goals

This study considers surface elevation change (change in the height of the marsh surface over time, hereafter referred to as REC) data from 21 SCGS SET stations and several vertical control (geodetic) datasets collected throughout the life of the project. The total length of record for both SET and geodetic control data provides the opportunity to examine short-term changes and long-term trends. The questions addressed herein are the following:

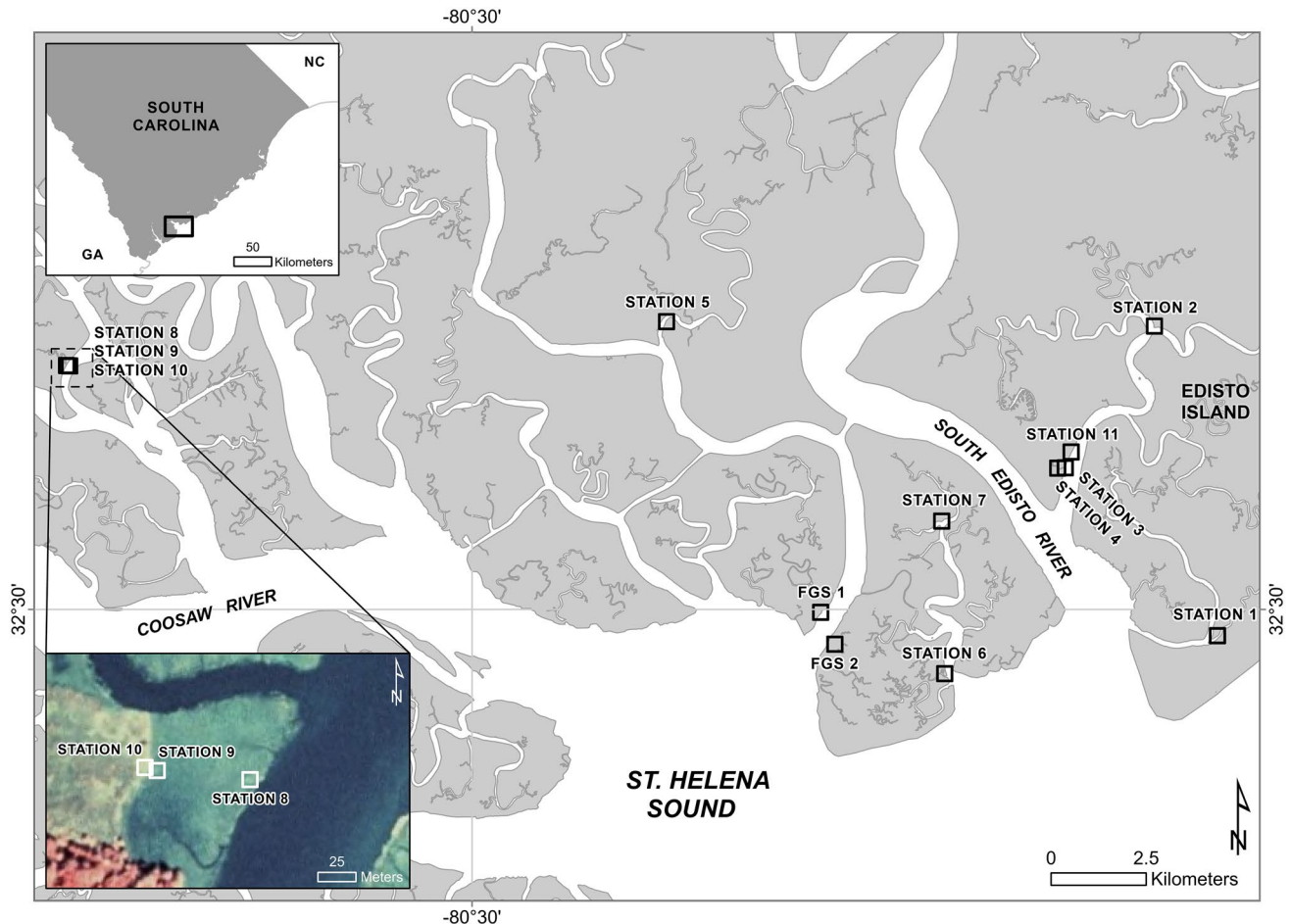


Fig. 2 Initial SCGS and FGS SET stations constructed in the ACE Basin NERR. Data were collected from these stations, installed using the original SET design, from 1998 to 2009, except for FGS1 and FGS2 (defunct by 2002), and Station 10, which is still measured as

ACEW13. Stations 1, 4, 5, 6, 7, 8, and 11 were updated to RSET in 2009. Station 9 was updated in 2017. Inset map imagery is from 1999 (SCDNR 1999)

- (1) What, if any, measurable geodetic displacement is occurring in coastal South Carolina? How does it compare with estimates for the NOAA tide gauge at Charleston Harbor, SC?
- (2) On a broad scale, are South Carolina's marshes keeping up with RSLR?
- (3) How do RECs vary spatially?
- (4) Is there a connection between REC and the orthometric elevation of the stations relative to tidal range?

Methods

Geodetic Control

In 1998, the South Carolina Geodetic Survey produced a geodetic elevation control survey on the ten original SCGS SET stations in the ACE Basin using the Height

Modernization (HeightMod) standard base station and rover technique (Zilkoski et al. 1997). This methodology was repeated in 2001 for Station 11, and again in 2005 for the original array. Since 2011, geodetic control has been obtained with a single rover using a Trimble Real-Time Kinematic (RTK) Global Navigation Satellite System (GNSS) receiver connected to a Virtual Reference Station (VRS) Network operated by the South Carolina Geodetic Survey (Lapine and Wellslager 2007; Doar and Luciano 2022). This RTK-VRS technique provides sub-centimeter positional accuracy without a physical base station through real-time corrections relayed to the rover via a wireless connection and has a 95% confidence interval (CI) of ± 2.0 cm, with ± 0.5 cm resolution possible (Zilkoski et al. 1997).

For conclusive long-term comparisons, the variation in the ellipsoidal data for a specific site should exceed the accuracy limitations of the instrumentation and technique used

Table 1 Length of record, rate of elevation change (REC, or rate), and setting information for the 21 SCGS SET stations considered for this study. Stations are listed in order from north (top) to south (bottom). Tidal range values were estimated using NOAA's VDatum (Vertical Datums Transformation) tool

SET ID	SET name	Length of record (years)	Orthometric elevation (m NAVD88)	Rate (mm/yr)	SE (mm/yr)	Estimated tidal range (m)	Dominant vegetation	Geomorphic setting
LBLR2	Little River, North	8.74	0.559	6.55 ± 0.33	0.76	1.40	<i>S. alterniflora</i>	Estuarine
LBLR1	Little River, South	8.74	0.439	1.88 ± 0.62	1.37	1.02	<i>S. alterniflora</i>	Estuarine
LBWS1	Withers Swash	8.66	0.629	9.75 ± 0.66	1.64	1.52	<i>S. alterniflora</i>	Estuarine
LBMI2	Murrells Inlet, North	8.67	0.432	-2.27 ± 0.62	1.37	1.10	<i>S. alterniflora</i>	Estuarine
LBMI1	Murrells Inlet, South	8.67	0.355	6.51 ± 0.86	2.05	0.92	<i>S. alterniflora</i>	Estuarine
CRWR2	Clubhouse Creek	8.77	0.374	3.44 ± 0.90	2.15	0.93	<i>S. alterniflora</i>	Estuarine
CRWR1	Venning Creek	8.78	0.652	2.07 ± 0.37	1.00	1.52	<i>S. alterniflora</i>	Spoil/moved earth
CRCI2	Capers Island, North	11.28	0.568	2.87 ± 0.50	1.44	1.38	<i>S. alterniflora</i>	Backbarrier
CRCI1	Capers Island, South	11.28	0.630	4.97 ± 0.36	1.06	1.47	<i>S. alterniflora</i>	Backbarrier
ACEFI1	Fig Island	12.45	0.667	6.65 ± 0.63	1.65	1.60	<i>S. alterniflora</i>	Estuarine
ACEBP1	Bennetts Point ^a	22.90	1.115	4.46 ± 0.24	1.03	1.83	<i>S. alterniflora</i>	Estuarine
ACEW13	Williman Island, High	22.76	1.146	-2.30 ± 0.18	0.75	2.01	<i>B. frutescens</i>	Estuarine
ACEW12	Williman Island, Middle	4.080	0.804	2.93 ± 0.36	0.68	2.01	<i>S. alterniflora</i>	Estuarine
ACEW11	Williman Island, Low ^a	22.76	0.892	10.17 ± 0.39	1.59	2.01	<i>S. alterniflora</i>	Estuarine
ACEBI1	Bailey Island ^a	21.69	0.944	4.20 ± 0.54	0.67	1.85	<i>S. alterniflora</i>	Estuarine
ACESP1	St Pierre Creek ^a	22.90	0.924	4.12 ± 0.29	1.30	1.84	<i>S. alterniflora</i>	Estuarine
ACEFC2	Fish Creek, Upper ^a	22.90	0.927	3.41 ± 0.32	1.36	1.81	<i>S. alterniflora</i>	Estuarine
ACESC1	Scott Creek	11.77	0.931	4.80 ± 0.41	1.30	1.82	<i>S. alterniflora</i> , <i>S. virginica</i>	Backbarrier
ACEFC1	Fish Creek, Lower	12.50	0.797	3.15 ± 0.86	2.67	1.80	<i>S. alterniflora</i>	Estuarine
ACEHI1	Hunting Island, North	11.18	0.671	-0.84 ± 0.32	0.93	1.79	<i>S. alterniflora</i>	Backbarrier
ACEHI2	Hunting Island, South	11.18	0.865	6.18 ± 0.33	1.03	1.86	<i>S. virginica</i> , <i>B. maritima</i>	Backbarrier

^aStation converted from original SET design to RSET in the same measurement plot (see Doar and Luciano 2022)

(Geoghegan et al. 2008). For sites in South Carolina, where estimated rates of regional land motion are low (0–2 mm/yr; Karegar et al. 2016) or not as readily detectable as in other areas that are either tectonically active or known to be experiencing subsidence (i.e., California, Louisiana), a multi-decadal dataset is required to make interpretations at the resolution available given the survey methods used. For this study, 1998 and 2001 HeightMod data collected by the South Carolina Geodetic Survey were compared to

RTK-GNSS data collected in 2021 by SCGS for the six survivor stations (Stations 3, 4, 5, 7, 10, and 11; Table 2). Comparison procedures followed those outlined in Geoghegan et al. (2008) for long-term geodetic change analysis using ellipsoidal measurements. Geodetic data collected on the original SET array using HeightMod were formally included in the National Geodetic Survey (NGS) Integrated Database, or “bluebooked,” allowing for the data to be updated with newer realizations. The ellipsoidal values in the NGS

Table 2 Station names, PIDs, and ellipsoidal information for the NGS benchmarks and SCGS survivor SET stations used for geodetic analyses

SCGS station name	NGS station name	NGS PID	Time span	Total change ellipsoid height (mm)	Rate of change (mm/yr)
Station 3	WELL PIPE F	AI7202	12/1998–8/2021	61.68	-2.74 ± 0.10
Station 4	WELL PIPE E	AI7201	12/1998–6/2021	64.20	-2.84 ± 0.08
Station 5	WELL PIPE L	AI7196	12/1998–6/2021	76.86	-3.42 ± 0.09
Station 7	WELL PIPE B	AI7198	12/1998–9/2021	51.43	-2.24 ± 0.09
Station 10	WELL PIPE I	AI7205	12/1998–8/2021	68.22	-3.00 ± 0.09
Station 11	WELL PIPE M	DH9531	11/2001–6/2021	70.45	-3.57 ± 0.10
CK5700	2115	CK5700	6/2004–4/2022	56.87	-3.19 ± 0.11
DH6978	SCW1	DH6978	11/2004–5/2022	85.00	-4.85 ± 0.12
CK1770	Y 109	CK1770	5/2006–4/2022	57.65	-3.62 ± 0.13
DH9514	NERRS ACE BASIN	DH9514	5/2006–4/2022	39.80	-2.49 ± 0.12
CK1442	B 108	CK1442	8/2000–4/2022	43.17	-2.43 ± 0.11
DG6101	CASSENA	DG6101	6/2004–4/2022	36.00	-2.02 ± 0.11
CK2315	7 165	CK2315	8/2000–4/2022	25.68	-1.19 ± 0.09
DG6124	SIP	DG6124	6/2004–4/2022	19.75	-1.11 ± 0.11
CK2336	866 8146 TIDAL 5	CK2336	12/1999–4/2022	63.50	-2.50 ± 0.09

databases have been updated to NAD 83 (2011). The SCGS 2021 RTK-VRS data were collected in the same realization. To assist in validating the results of the SET-specific analyses, nine upland (non-marsh) NGS benchmarks

located in or adjacent to the ACE Basin (Fig. 3; Table 2) were surveyed in early 2022 by SCGS using the RTK-VRS method. Five 5-min and two 10-min occupations were collected for each benchmark. Data were collected before noon

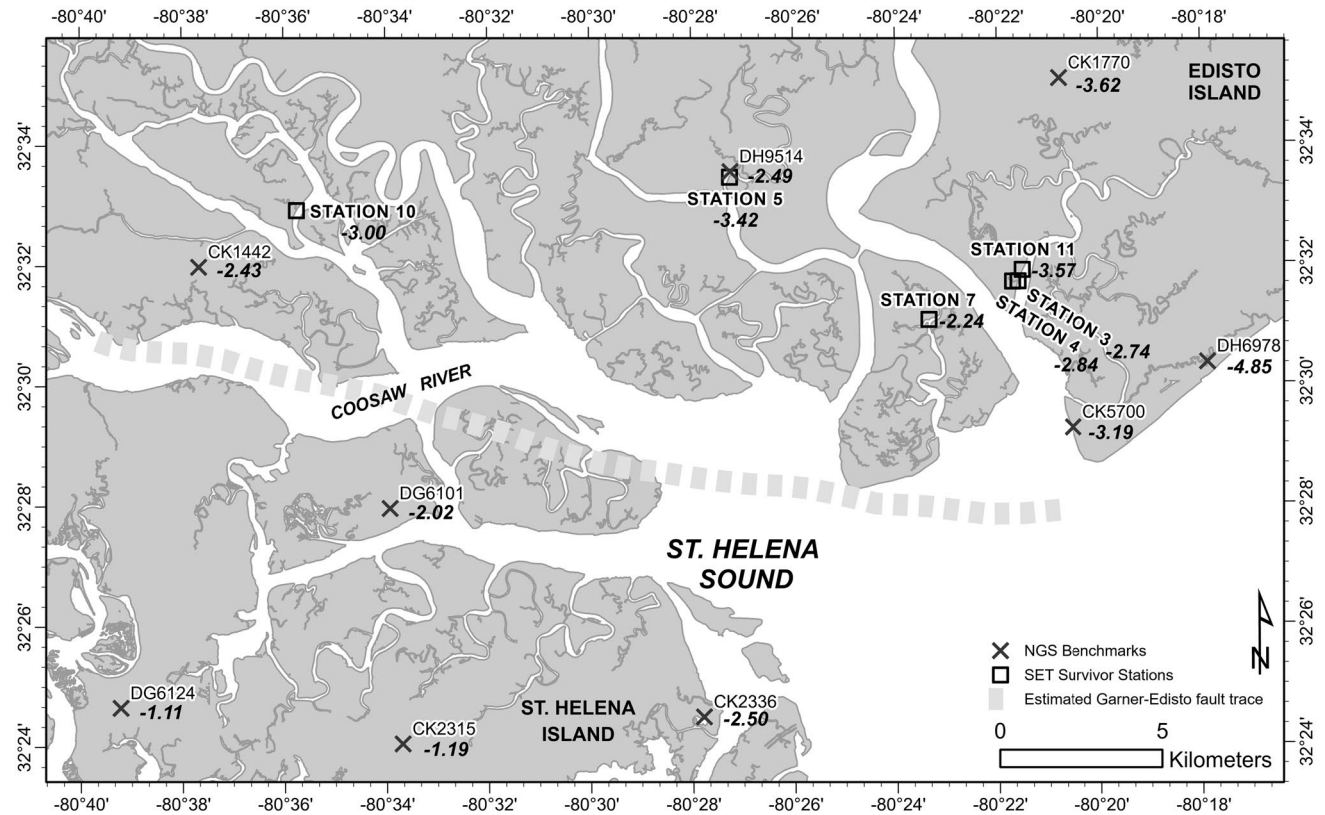


Fig. 3 Distribution of upland benchmarks and survivor SET stations used for geodetic analyses, with associated rates of change in italics (mm/yr). Upland benchmarks are designated by NGS Permanent

Identifier (PID)—a 6-character alphanumeric ID associated with a survey mark. The estimated trace of the Garner-Edisto fault is based on SCGS mapping in the area

during two observation windows (3:00 AM–6:00 AM; 8:00 AM–11:00 AM) to limit atmospheric disturbances. Data were grouped by session, each session was filtered to remove extreme outliers, and the remaining data were averaged to produce an ellipsoid height. These data were then compared to the adjusted ellipsoid heights from the NGS database. Rates of geodetic elevation change from the survivor stations and benchmarks were calculated by dividing the change in ellipsoidal values (in meters) by the time (in years) between the original measurement and the 2021 or 2022 measurement (Table 2). A 2018 RTK-VRS geodetic dataset, the first to measure the entire existing SCGS SET network beyond the ACE Basin, was used separately to determine if orthometric elevation of the salt marsh platform changes latitudinally within the SCGS SET network.

Marsh Platform Elevation (SET) Data

SET data were collected following the methodologies and protocols outlined by Lynch et al. (2015). SCGS collects SET data quarterly (February, May, August, and November) to capture seasonal variability (Doar and Luciano 2022). A minimum of 4 years of data were collected before representative linear elevation trends were determined, since sites are known to experience an early period of general rate instability (Lynch et al. 2015). The length of record and date of first measurement for each SCGS SET dataset varies by station; however, the final measurements for all 21 stations used in this study were collected in November–December 2021 (Figures S1–S20).

As detailed in Doar and Luciano (2022), the REC for each station was calculated by averaging 36 pin datapoints collected during each measurement to produce a single value for that station in time. Standard error (SE) was calculated, and when multiple sets of data over time were collected and processed, both the elevation and error values were plotted along with a linear regression trendline. A 95% confidence interval (CI) was calculated for each station's data to allow comparison to datasets from other sources. These values were converted to NAVD88 orthometric elevation using geodetic data, taking station-specific geometry (difference in elevation between the geodetic reference point and the marsh platform surface) into account (Doar and Luciano 2022). Sediment accumulation data (as outlined by Lynch et al. 2015) were not collected from the SCGS SET network due to early difficulties with the longevity of powdered feldspar (applied as a contrast layer) in the field caused by bioturbation.

RSLR

Methodologies developed by NOAA's National Estuarine Research Reserves (NERRs), based on Cahoon et al. (2019), were used to evaluate whether stations are keeping pace with

RSLR. NOAA gauge 8,665,530 in Charleston Harbor, SC, was used as the primary RSLR reference. It has a long-term (120-year) RSLR trend of 3.36 ± 0.19 mm/yr based on mean-sea level (MSL) data (NOAA 2021a). Using a shorter-term subset (1999 to 2022) of data from this gauge, a 23-year trend (capturing the duration of this project) of 7.86 ± 0.59 mm/yr was calculated by SCGS and used for comparison with SET REC data. Vertical Land Motion (VLM) estimates from Zervas et al. (2013) for NOAA gauge 8,665,530 were used for comparison to geodetic elevation data collected by SCGS on survivor stations and NGS benchmarks.

Inundation and Tidal Range Estimates

NOAA's Vertical Datum Transformation (VDatum) tool was used to vertically transform each SET station's orthometric elevation to elevations relative to mean high water (MHW) and mean low water (MLW) based on horizontal and vertical control (x , y , and z positional data) (White et al. 2016). Results were used to approximate each station's location within the tide cycle, inundation at average high tides, and exposure at average low tides. The SE for VDatum is ± 15 cm for all MHW and MLW estimates.

Results

Geodetic Data

Comparison of adjusted ellipsoidal data from the 1998 and 2001 HeightMod datasets to the 2021 RTK-VRS dataset for the six survivor stations (Fig. 3; Table 2) showed long-term elevation loss, with values ranging from -51.43 mm (Station 7) to -76.86 mm (Station 5). These values convert to rates of -2.24 ± 0.09 mm/yr and -3.42 ± 0.09 mm/yr, respectively. Station 11 has the highest rate of loss, at -3.57 ± 0.10 mm/yr. RTK-VRS data collected on the nine NGS upland benchmarks also record elevation loss, with values ranging from -19.75 mm (DG6124) to -85.00 mm (DH6978) (Fig. 3; Table 2). These values convert to rates of -1.11 ± 0.11 mm/yr and -4.85 ± 0.12 mm/yr (Fig. 3; Table 2). The rates of elevation change calculated from ellipsoidal values for the survivor stations and NGS benchmarks were compared to an estimated -1.24 ± 0.07 mm/yr for NOAA gauge 8,665,530 (Zervas et al. 2013). For all survivor stations in the ACE Basin compartment, the rate of geodetic elevation change was higher than the estimate from gauge 8,665,530. Two benchmarks south of St. Helena Sound, DG6124 and CK2325, have rates less than the estimate (Fig. 3; Table 2). A more detailed discussion about the rates at these two NGS benchmarks is included in the "Discussion" section.

Geodetic data collected by SCGS in 2018 and 2021, which was used to back-calculate platform elevation at each SET over time using changes in surface elevation data, shows that orthometric elevation of the salt marsh platform at SCGS SET stations generally increases from north to south (Fig. 4; Table 1). Orthometric elevation values correlate with tide range values calculated from VDatum ($P < 0.00001$; $r^2 = 0.7782$), with higher elevations in areas with larger tidal ranges (ACE Basin) and lower elevations in areas with smaller tidal ranges (Long Bay and Cape Romain) (Fig. 5).

REC, Inundation, and Tidal Range Estimates

Analysis of SET data shows that 18 stations have long-term marsh platform elevation gain (positive REC), and three have long-term loss (negative REC) (Table 1). The highest positive REC is +10.17 mm/yr (ACEWI1). The highest negative REC is -2.30 mm/yr (ACEWI3, also known as Station 10). RECs vary throughout the network and are variable within each geographic compartment.

Position in Tidal Range

To estimate inundation, the positions of SET stations relative to MHW and MLW were calculated using geodetic and calculated orthometric data and VDatum (White et al. 2016). The elevations are between 0.23 m below MHW and 0.24 m above MHW, and 1.12 to 2.24 m above MLW (Fig. 5). Ten stations are positioned above MHW, and 11 stations are presumed to be inundated during MHW.

REC Related to Tidal Position

No correlative relationship can be established between REC and position relative to mean MHW ($P = 0.938$; $r^2 = 0.0003$); however, we calculated a mean REC of +4.17 mm/yr for stations higher than MHW versus mean REC of +3.37 mm/yr for stations lower than MHW. The 11 stations where $REC > RSLR$ (Figs. 6 and 7) are situated higher relative to MHW (average of +0.037 m), while those where $REC \sim RSLR$ (average of -0.054 m) and stations where $REC < RSLR$ (average of -0.024 m; -0.088 m

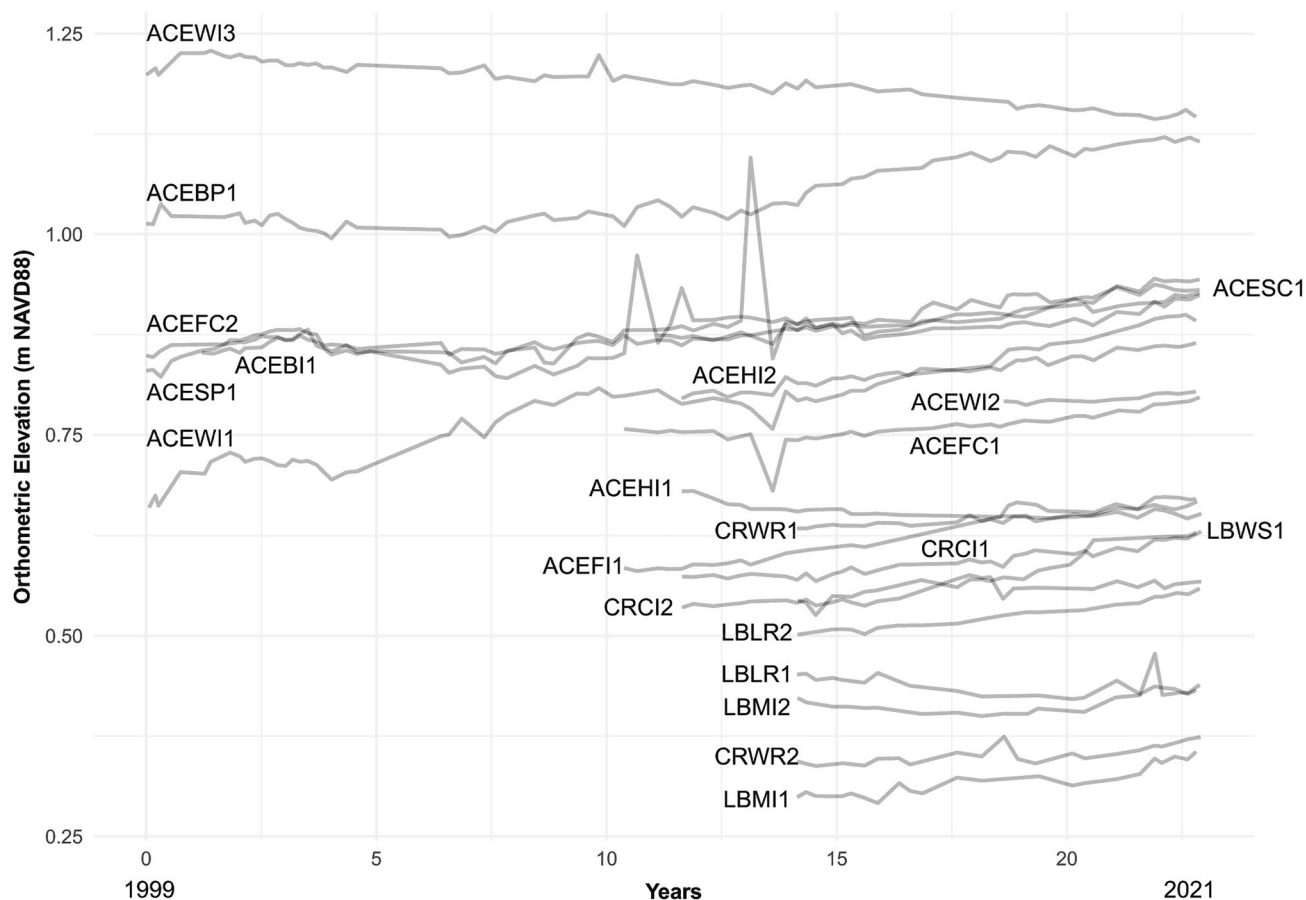


Fig. 4 Change in orthometric elevation over time for the 21 SET stations considered for this study. Stations with higher orthometric elevations tend to be in the southern part of the coast

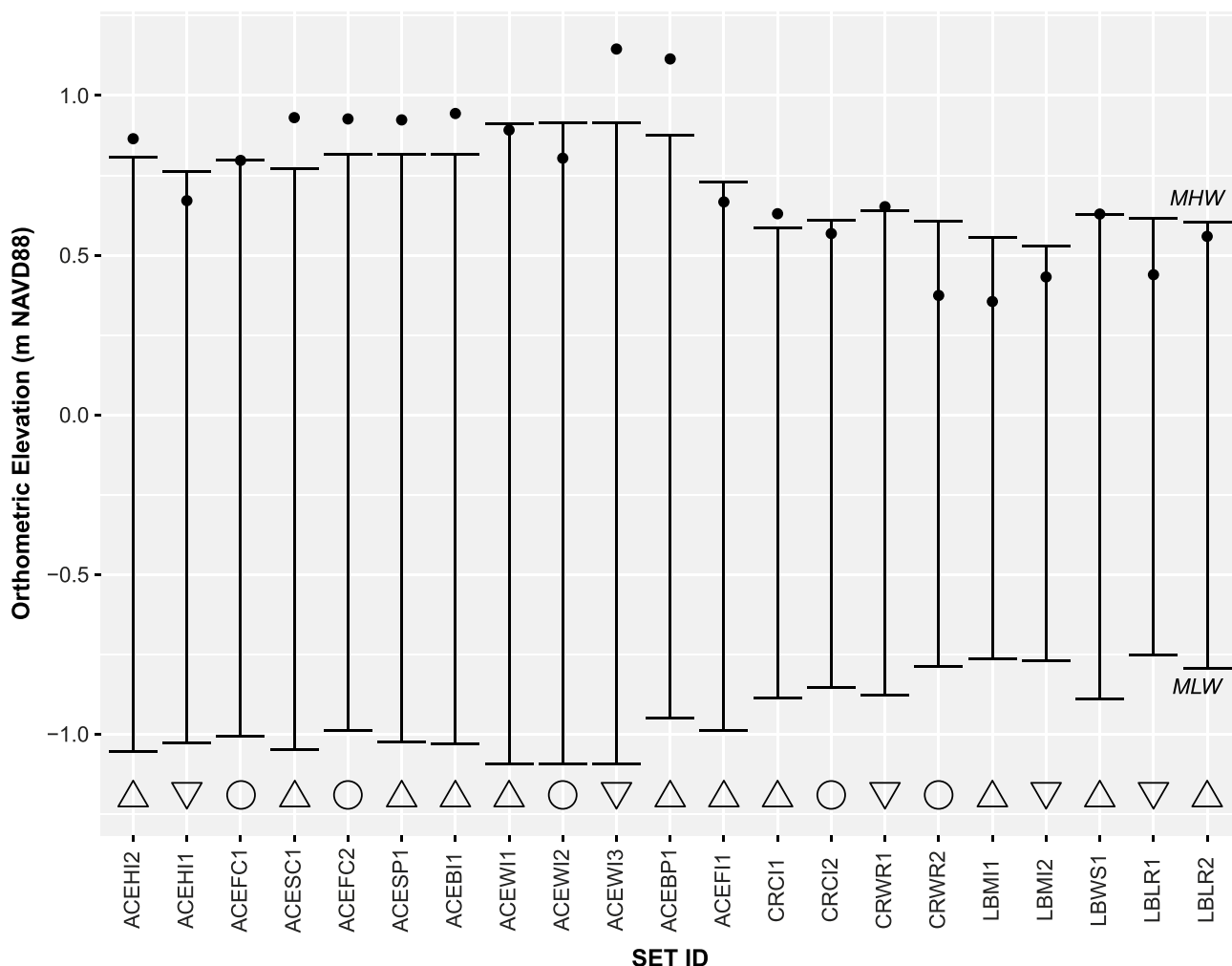


Fig. 5 Orthometric elevation values for each SET marsh platform (black dots) in relation to mean high water (MHW) and mean low water (MLW) estimates calculated using NOAA VDatum. Shapes correspond to whether a station’s REC is above, equal to, or below

the long-term RSLR rate from the Cooper River Mouth tide gauge (Fig. 6). Elevations show that SCGS SET stations exist in the upper limit of the estimated tidal frame

if ACEWI3 is not included) are situated below MHW. The negative REC associated with ACEWI3 (-2.30 ± 0.18 mm/yr) may be related to site-specific factors addressed in the “Discussion” section.

REC vs. RSLR

Compared to the 3.36 ± 0.19 mm/yr long-term RSLR rate for gauge 8,665,530, 11 SET REC values are higher, five are lower, and five have 95% confidence intervals that overlap (cannot definitively determine higher or lower) (Figs. 6 and 7). Of the 12 ACE Basin sites, seven are higher, two are lower, and three have overlapping confidence intervals. Of the four Cape Romain sites, one is keeping pace, one is not keeping pace, and two have overlapping confidence intervals. Of the five Long Bay

sites, three are higher, and two are lower. When using the 7.86 ± 0.59 mm/yr shorter-term RSLR rate from the 23-year subset of data from gauge 8,665,530, only two of the 21 stations have REC values higher than the RSLR estimate—ACEWI1 and LBWS1 (Fig. 7).

Discussion

Interpretations of Geodetic Data

The geodetic dataset collected on the entire SCGS SET network in 2018 allowed for a broad latitudinal comparison of marsh platform elevation at each site. Tidal range estimates for the 21 SET stations (Table 1) correlate with latitude (y) values ($P < 0.00001$; $r^2 = 0.6966$). Vertical (z) values for

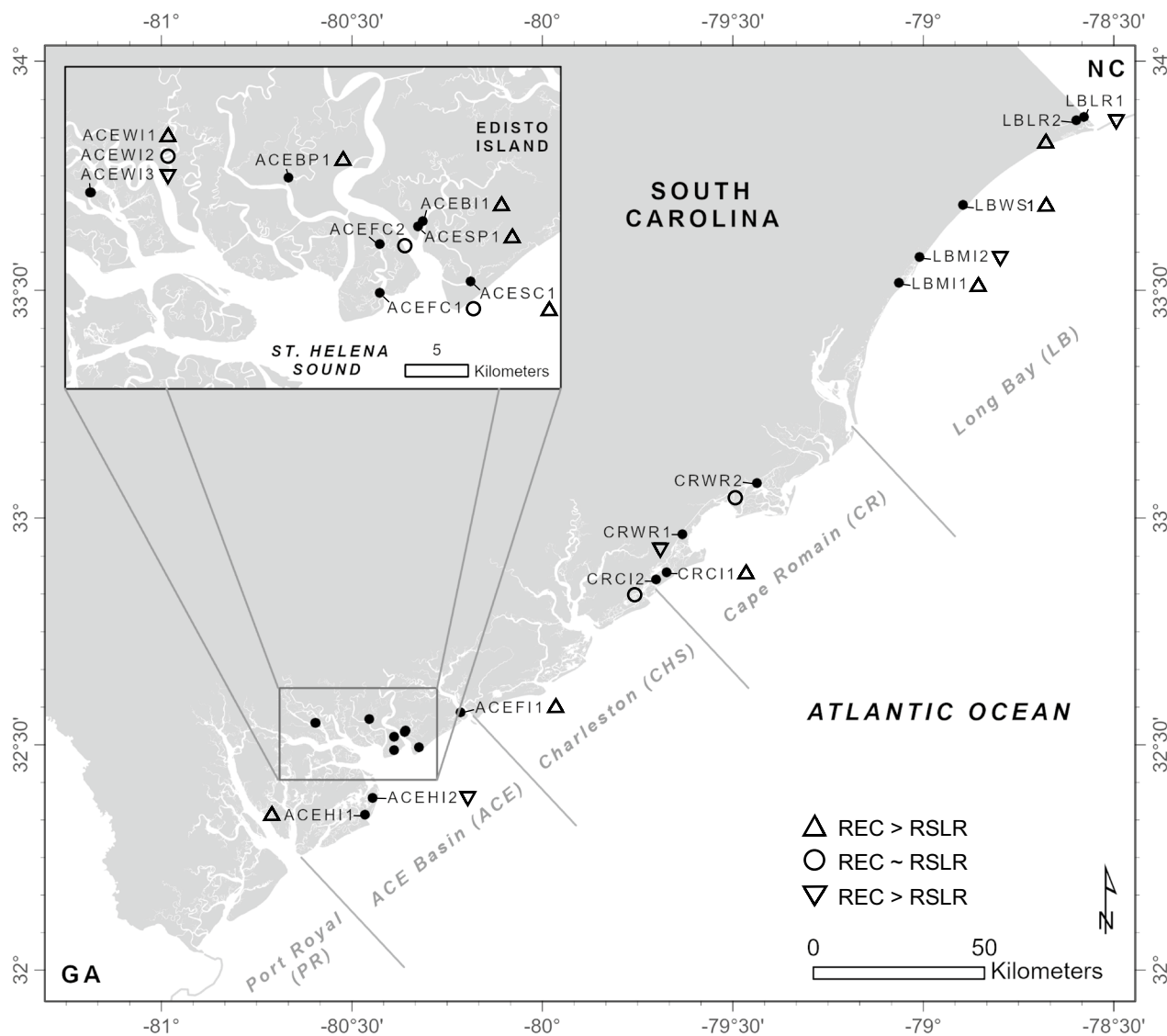


Fig. 6 REC values from SCGS SET stations compared to a RSLR rate of 3.36 ± 0.19 mm/yr (NOAA Cooper River Mouth tide gauge)

marsh platform elevation also correlate with increasing tidal range estimates ($P < 0.000001$; $r^2 = 0.7782$). Tidal range and marsh platform elevation increase moving south from the Long Bay and Cape Romain compartments to the ACE Basin (Fig. 4; Table 1).

A comparison of starting and ending ellipsoid values for the survivor stations and upland benchmarks showed elevation loss over time for all locations (Fig. 3; Table 2). To assist in interpreting the magnitude of this change, the rate of change values presented in Table 2 were modified within a fixed error margin of ± 2.0 cm (Zilkoski et al. 1997). This margin of error is a possible overestimate that considers the accuracy of the two techniques used to collect geodetic data (HeightMod for the 1998–2001 data,

RTK-VRS for the 2021 data). Geodetic change that exceeds this error margin can represent actual change. When applying the fixed error to the 20+ year length of record on the survivor stations and 2022 benchmark data, the rates of change have an estimated error of less than ± 0.14 mm/yr (Table 2). With the survivor stations exhibiting between 51 and 77 mm of total change in their ellipsoidal values, exceeding the ± 2.0 cm threshold, we conclude that our values are real indicators of long-term subsidence rates estimated at between -2.42 and -3.57 mm/yr for the ACE Basin area. Because the survivor stations are often anchored in Holocene marsh platform material, any calculated geodetic change could be a combination of shallow subsidence between the SET pipe (or rod) and deeper

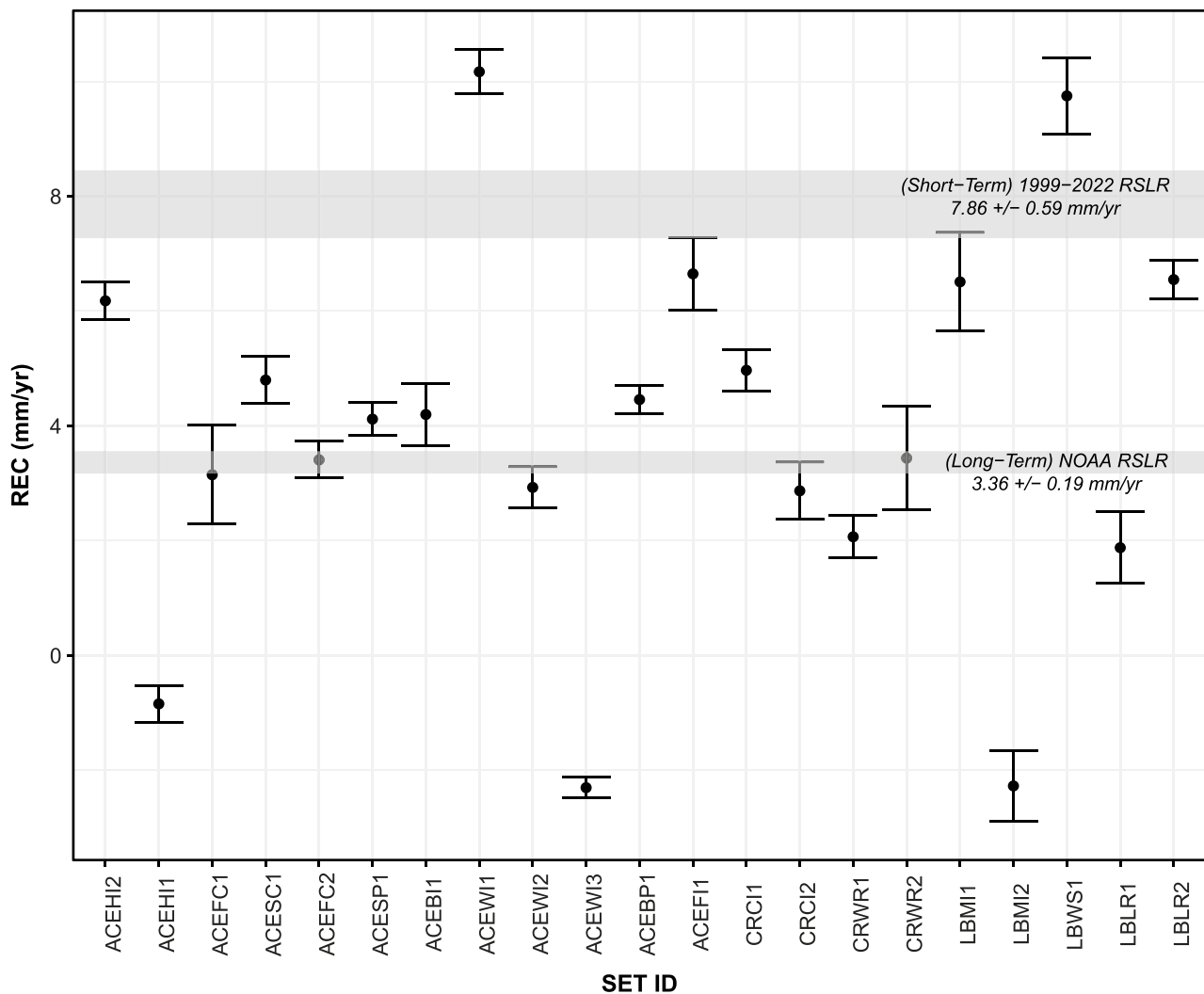


Fig. 7 REC values from SCGS SET stations compared to a relative sea-level trend (RSLR) of 3.36 ± 0.19 mm/yr (NOAA Charleston Harbor tide gauge) and a shorter-term (1999–2022) 23-year trend

calculated using data from the same gauge (7.86 ± 0.59 mm/yr) (after Cahoon et al. 2019). Confidence intervals (CIs) for each SET are displayed

“stable” substrate and subsidence of the deeper substrate. The exception to this is ACEWI3 (Station 10). This station was installed directly into Pleistocene sediments, with no Holocene sediment at the surface. The estimated geodetic change rate for ACEWI3 is -3.00 ± 0.09 mm/yr.

Upland benchmarks, measured in 2022 for geodetic comparison to the survivor stations, experienced between -19.75 and -85.00 mm of ellipsoid height change (Table 2). With four of these within or close to the ± 2.0 cm error threshold (DG6124, CK2315, DG6101, and DH9514 with -19.75 , -25.68 , -36.00 , and -39.80 mm total elevation loss, and rates of -1.11 ± 0.11 , -1.19 ± 0.09 , -2.02 ± 0.11 , and -2.49 ± 0.12 mm/yr respectively), applying the ± 2.0 cm fixed error produces the possibility of no conclusive change at these locations. The smallest geodetic elevation loss was recorded at benchmarks located south of

the survivor stations (Fig. 3). The remaining upland benchmarks have similar rates of geodetic change as the survivor stations, exceed the error threshold, and are considered real indicators of subsidence.

At regional scales, RSLR is influenced by processes including uplift and subsidence (Cahoon and Lynch 1997) and groundwater withdrawals, recharge, and aquifer compaction (Karegar et al. 2016) that can be influenced by isostatic adjustment. The International Panel on Climate Change (IPCC 2007) published a eustatic SLR rate of 1.7 mm/yr over the past century using such glacio-isostatic adjustment (GIA) models as Peltier (2004). When this 1.7 mm/yr eustatic rate is removed from the long-term Charleston Harbor tide gauge rate of 3.36 ± 0.19 mm/yr, the remaining vertical motion is approximately 1.66 mm/yr. Zervas et al. (2013) used the IPCC eustatic rate when comparing tide records

from Charleston Harbor, SC, and Ft. Pulaski, GA, and estimated a subsidence rate from GIA of -1.24 ± 0.07 mm/yr for Charleston Harbor and a -1.36 ± 0.10 mm/yr rate for Ft. Pulaski. Similarly, Karegar et al. (2016) modeled a 0 to -1 ± 0.5 mm/yr subsidence rate for the southern coast of South Carolina. When comparing our geodetic rates in this area to those publications, our southern benchmark rates of -1.11 ± 0.11 , -1.19 ± 0.09 , and -2.02 ± 0.11 mm/yr are similar. The differences in the published subsidence rates from the tide gauges (e.g., Zervas et al. 2013), the modeled subsidence rates (e.g., Karegar et al. 2016), and our geodetic elevation data show that there are continuing disagreements with the rates interpreted from different methodologies, timescales, and assumptions. Using the long-term tide gauge data produces rates averaged over a time span of 100 years (in the case of the Charleston NOAA gauge 8,665,530). This linear relative sea level trend averages through short-term fluctuations, both positive and negative, over the duration of the dataset. Subsampling this dataset and applying the published eustatic sea-level rates (e.g., 1.7 mm/yr; IPCC 2007) can produce an estimated subsidence rate lower than estimated by Zervas et al. (2013) or when using the number included for the 24-year rate (7.86 ± 0.59 mm/yr), results in 6.16 mm/yr remaining to be explained.

Differences between these rates and the higher change rates found at benchmarks on the northern side of the ACE Basin could relate to a regional east–west structural feature called the Garner-Edisto fault (Colquhoun et al. 1983; Maybin et al. 1998). This feature is projected to underly or parallel St. Helena Sound and the Coosaw River (Fig. 3). Based on borehole data collected prior to 1985, this feature was interpreted to have a south-side down subsurface stratigraphic offset at depths below 300 ft (Colquhoun et al. 1983, Plate E). Stratigraphic data collected by the SCGS in the early 2000s from shallow geological boreholes during a mapping project in the ACE Basin NERR area support the existence of the fault. These data identified Eocene (30MY) strata underlying Pleistocene (2.7MY and younger) sediments at or near MSL on the south side of St. Helena Sound and the Coosaw River with only isolated patches of Miocene sediments. North of the sound and river, Miocene (23–5.3MY) strata at least 15 m thick (often missing from the south side) were identified at or near MSL (maps and borehole logs available upon request at the SCGS). The interpretation from the SCGS borehole data is for north-side down. Therefore, the fault is interpreted as poly-phasic with pre-Miocene motion being south-side down and post-Miocene motion being south-side up, although the exact timing for both has not been determined. This fault could bound a half-graben or graben and be part of the Southeast Georgia Rift system but verifying that is beyond the scope of this investigation.

Possible implications of the placement of this fault include the south side of the fault remaining somewhat stable and locally remaining close to the modeled isostatic subsidence rate; the fault motion continuing and offsetting some subsidence on the south side and/or increasing it on the north side; or the thicker, younger sediments north of the fault compacting and locally increasing the subsidence rate. Future geodetic data collected on survivor stations and the entire SCGS SET network, including deeper RSET installations, should provide additional insight into regional-scale subsidence since we cannot extrapolate the subsidence rates calculated for this study to areas of coastal South Carolina beyond the ACE Basin.

Rates of Surface Elevation Change (REC)

RECs calculated from the 21 SCGS SET stations vary from -2.30 ± 0.18 to $+10.17 \pm 0.39$ mm/yr (Figures S1 to S20; Table 1). The stations with the highest and lowest REC are both located at Williman Island, in the ACE Basin (Fig. 1; Table 1). ACEWI3, with the highest orthometric elevation in the network at 1.146 m NAVD88, is supratidal, with a long-term REC of -2.30 ± 0.18 mm/yr. In contrast, ACEWI1, 72 m east of ACEWI3, appears to reflect a classic low marsh setting with an elevation below MHW and an REC of $+10.17 \pm 0.39$ mm/yr (Fig. 7, Table 1). ACEWI2, an interior platform station between ACEWI1 and ACEWI3, has an REC of $+2.93 \pm 0.36$ mm/yr after approximately 4 years of data collection. These three stations are experiencing different RECs despite their geographic proximity, indicating that variation in orthometric elevation and distance to creek banks may be important variables. ACEWI3 may represent an upper limit at which salt marshes can successfully establish.

The remaining 18 SET stations considered for this study fall between these values, with most having positive REC values. Interestingly, ACEBP1 currently has a similar orthometric elevation ($+1.115$ m NAVD88) and position relative to MHW ($+0.239$ m) to ACEWI3 yet has an REC of 4.46 mm/yr compared to -2.30 ± 0.18 mm/yr (Figs. 4 and 5; Table 1). As listed in Table 1, these stations also have different dominant vegetation types (*S. alterniflora* at ACEBP1 and *B. frutescens* at ACEWI3). The different REC values for these stations, despite their similar orthometric and tidal positions, indicate that other dynamics not accounted for in this study likely contribute to platform elevation gain or loss.

Reviewing the 22+ year length of record on the oldest SCGS SET datasets reveals non-linear REC trends, with short-term trends often above or below the long-term trendline (Fig. 8; S1–S20). These short-term data can be problematic for extrapolating long-term trends. For example, ACEBP1 has a long-term (22.9-year) REC of $+4.46 \pm 0.24$ mm/yr. However, if data used to extrapolate

possible future trends for this station were collected over any of several 5-year subsets of the data, the calculated REC values would be dramatically different. For 2002–2007, the REC was +1.0 mm/yr. From 2010 to 2016, the REC is estimated at +8.2 mm/yr. Other stations exhibit similar patterns (Fig. 8; S1-S20). The SE values calculated for SET REC also reveal the variability inherent in the SET data (Table 1; Fig. 8; S1-S20). Larger SE values could be related to the rugosity, or ruggedness of the microtopography at a station due to differences in plant density, changes in crab burrow density or geometry, damage from other animal disturbances, natural heterogeneity of sediment deposition, a pre-existing non-planar surface or slope below the platform such as a levee near a creek edge, or surficial disruptions from climatic events (i.e., mud cracks).

When comparing REC data between stations, an issue arises: the stations do not have identical lengths of record

because they were installed on different dates (Fig. 8: S1-S20). The stations with the longest records can provide both long- and short-term trends. The stations installed more recently provide short-term trends, similar to the subsets of the long-term datasets, and will eventually provide long-term trends. We feel that the longer the dataset, the more it smooths the rate through the shorter-term trends and better reflects the actual overall rate used for interpretations, but the short-term subsets of the data provide insights into the factors affecting change in the long-term data such as droughts, rainfall increases, variations in sea level, and biological activity.

Inundation and Tidal Range Estimates

Using VDatum provided an idea of possible inundation (or lack thereof) at MHW and elevation relative to MLW for

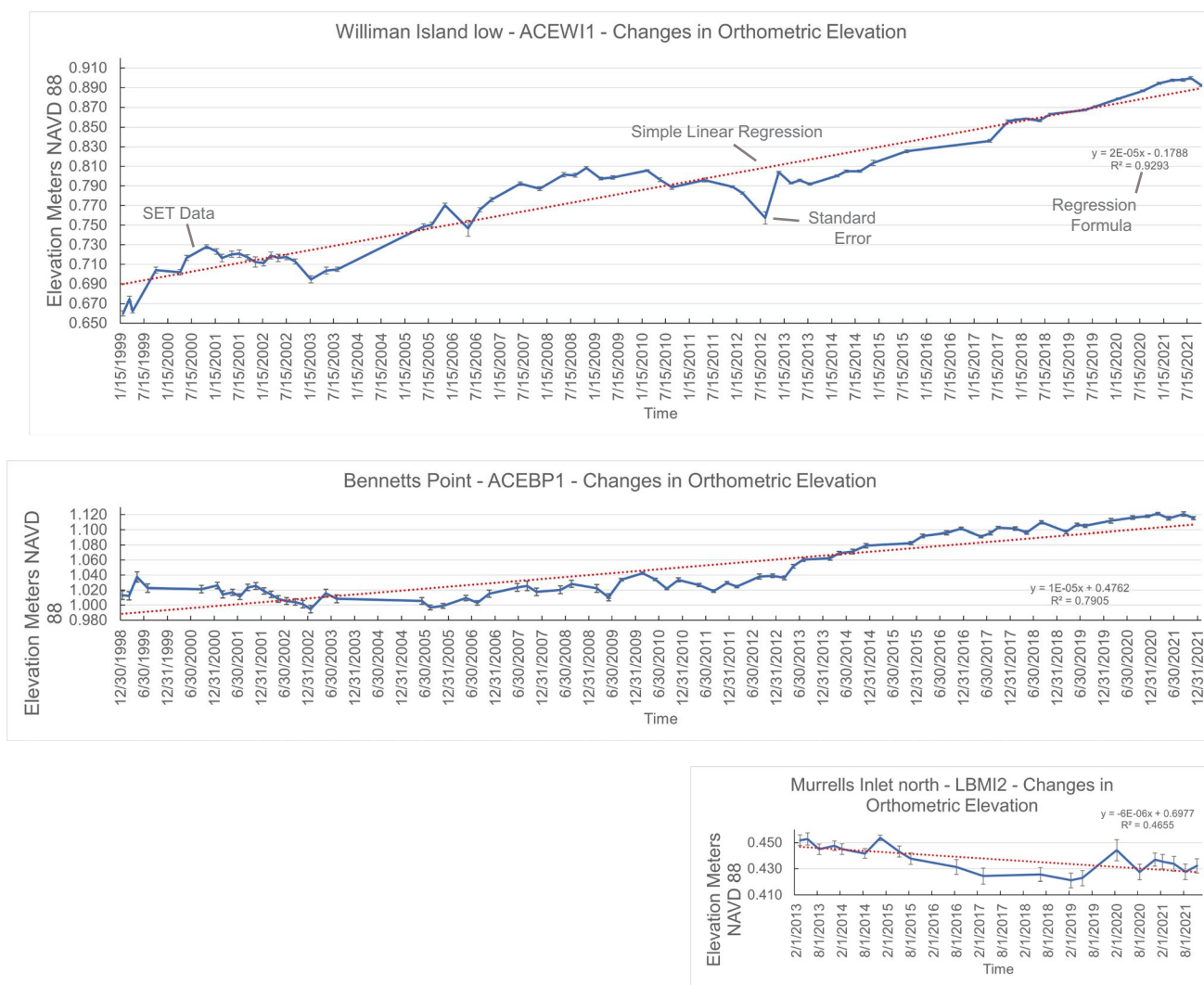


Fig. 8 Three examples of SCGS SET elevation change records, converted to orthometric elevation, without adjustment for possible isostatic change. Note the short-term variability compared to the long-term trends

each station (Fig. 5). Overall, MHW levels are higher for the ACE Basin sites than the Long Bay sites by 0.20–0.45 m. Within the ACE Basin compartment, most SET stations are above MHW, though we found no correlation between REC and location in the tidal range. Within the paired stations in Cape Romain (Capers Island—CRCI1 and CRCI2) and Long Bay (Murrells Inlet—LBMI1 and LBMI2 and Little River—LBLR1 and LBLR2), inundation or exposure at MHW again does not correlate with REC, although for each pair, one station has $REC > RSLR$ and a second station with either $REC \sim RSLR$ or $REC < RSLR$ (Figs. 6 and 7).

There are also specific situations that limit the applicability of VDatum for interpretations. For example, at LBWS1, where VDatum modeled the station position at 0.001 m above MHW, the marsh platform has been inundated more frequently and for week-long durations in recent years. LBWS1 is in a tidal salt marsh draining directly onto an ocean-fronting beach (swash), that is impacted by periodic buildup of sand due to longshore drift. When sand accumulates at the mouth of the swash, water cannot drain below mid-tide levels. The station remains inundated either partially or completely through the tide cycle. This prolonged inundation may provide increased duration for the settling of suspended sediments beyond the expected rates based on tidal position.

Since tidal flooding delivers suspended sediment to the marsh platform surface, promoting enhanced vegetation growth and increased rates of organic accumulation (Leonard 1997; Kirwan et al. 2016), it would be expected that stations experiencing a positive REC are regularly inundated at MHW. However, we found no linear relationship exists between REC and position relative to MHW. Though it is assumed that at least some suspended sediment, if not most of it, originates from adjacent tidal creeks, it may not be requisite for a station to be regularly inundated to keep pace with RSLR. Instead, delivery of sediment from below-ground biomass or punctuated climactic events (i.e., hurricanes) may play an important role (Cahoon et al. 1995; Tweel and Turner 2014). The import or export of pulses of sediment on a broad geographic scale can enhance short-term sedimentation and vertical accretion on the marsh surface, particularly in areas with higher elevation that may not be inundated daily (French and Spencer 1993; Cahoon et al. 1995; Orson et al. 1998; Carey et al. 2017; Doar et al. 2018). Storm impacts have alternatively been shown to result in negative elevation trajectories or sediment redistribution on the marsh surface (Leonardi et al. 2017; Yeates et al. 2020). Prior to 2015, no tropical storms directly affected the SCGS SET network. Since 2015, seven storms have impacted the network, as illustrated from data collected from the ACE Basin stations before and after Hurricane Irma in 2017. These data showed an overall mix of accretion, erosion,

and no long-term identifiable change in REC (Doar et al. 2018). In the future, collecting site-specific water level data could provide more information about whether REC is related to water depth, duration of flooding, or punctuated storm events, which can deliver pulses of sediment to coastal marshes and/or re-suspend sediment that is already in situ. Having nearby tide gauges, or a means of better extrapolating water level data from harmonic to non-harmonic stations, would also be useful. More research on local site-specific variables is needed to understand potential commonalities between gaining and losing stations, especially those within the same compartment.

Comparison of SET Data to RSLR

RSLR is important for interpreting SET REC values and changes in marsh platform orthometric elevation over time, particularly in locations where uplift or subsidence are significant enough to impact the long-term positions of marshes in the tidal frame. A driving question of this work was whether South Carolina's marshes will maintain their elevation above the rate of RSLR. Comparing REC data to the long-term (100-year) RSLR rate of 3.36 ± 0.19 mm/yr from NOAA gauge 8,665,530, 11 SCGS SET stations are gaining elevation ahead of RSLR, five have RECs with some statistical overlap and may or may not be maintaining their position relative to long-term RSLR, and five are not keeping pace (Figs. 6 and 7). Using a subset of the tide gauge data covering the 23-year life of the SCGS project, a short-term RSLR rate of 7.89 ± 0.59 mm/yr results. Using this short-term RSLR rate, only two SCGS SET stations have RECs that exceed the short-term RSLR (Fig. 7).

We also note that we applied the NOAA Charleston Harbor gauge RSLR and geodetic rate estimates broadly across all stations in the SCGS network, although other NOAA gauges at Springmaid Pier (Myrtle Beach) and Fort Pulaski (Savannah) may be geographically closer to some of the stations (NOAA 2021a, b, c). The relative sea-level trend for Springmaid Pier, at 4.03 ± 0.49 mm/yr, is 0.64 mm higher than the Cooper River station; the Fort Pulaski station, with an estimate of 3.44 ± 0.26 mm/yr, is only 0.05 mm higher (NOAA 2021b, c). VLM estimates from Zervas et al. (2013) are also higher at these stations (-2.34 ± 0.63 mm/yr and -1.36 ± 0.10 mm/yr, for Springmaid and Fort Pulaski, respectively). If the higher RSLR estimate from the Springmaid Pier gauge was compared to the Long Bay station REC values, it would not change any interpretations about relationships between REC values and RSLR (Figs. 6 and 7). However, as more resolution is gained for geodetic elevation change estimates over the entire network in the future, it may be worth taking these higher estimates for RSLR and VLM into consideration to fully understand if marshes in the northern part of the state are more vulnerable.

Comparing Datasets with Varying Measurement Timescales

Ideally, SET geodetic and SET data would be collected at the same time as the tide gauge data to produce parallel datasets; however, field requirements of each method make collecting original data over a wide geographical area difficult. SET data are collected quarterly, and the geodetic data is collected on an approximately 5-year cycle. Changes in the surface elevation at each station due to deposition, erosion, compaction, etc., can occur over short timescales (i.e., minutes or seconds), and collecting on a specific day (or month) versus the next day (or month) may result in slightly different data. An example of this is the variation of data collected over a single year in most of the SET datasets (e.g., S1, S8, S10, S12) resulting from seasonal changes within the marshes. The lack of the ability to collect the geodetic data at the same intervals as the SET data means that we do not know if the geodetic data may have a similar variable pattern resulting from crustal motion, groundwater extraction, sediment compaction, or isostatic adjustment.

Conclusions

We conclude that the amount of change measured in the ellipsoidal values for the ACE Basin survivor stations and NGS benchmarks indicates subsidence on the order of -2.43 ± 0.11 to -3.57 ± 0.10 mm/yr, which is higher than the -1.24 ± 0.07 mm/yr VLM estimate for NOAA gauge 8,665,530 in Charleston Harbor (Zervas et al. 2013). Based on the spatial distribution of these sites and their geodetic elevation change rates, the Garner-Edisto fault may be influencing these rates. Since the survivor stations are located on one side of the fault, the north side (Fig. 3), we cannot discern whether fault displacement has impacted SET REC in the compartment. For settings like coastal South Carolina, where regional-scale uplift or subsidence is estimated on the scale of < 1 to 2 mm/yr, decadal-scale GNSS datasets are necessary to determine if local geodetic displacement is similar using SET sites as benchmarks. Understanding potential inputs to RSLR from subsidence and uplift should also consider the location of structural features (i.e., faults), especially when interpreting regional scale datasets.

This study also found that SET RECs are highly variable latitudinally and within compartments. Orthometric elevations for the network correspond with the north–south increase in tidal height and range. REC values do not correlate with latitude. Approximately half of the stations considered (11 of 21) have an REC higher than the RSLR rate at NOAA gauge 8,665,530 in Charleston Harbor. We did not determine a link between the position

of a SET station within the tidal frame, its relationship to MHW, and REC. As noted in the literature, tidal range is a known determinant of marsh vulnerability, and marshes that exist in larger tidal frames are more resilient to SLR (Kirwan et al. 2016; Törnqvist et al. 2021). The northern SCGS stations may inherently be more vulnerable to SLR and RSLR due to a smaller tide range and lower marsh platform elevation. However, some of the stations in the Little River compartment (notably LBWS1, LBMI1, and LBLR2) also have some of the highest REC values in the network but also have some of the shortest length of records (Fig. 7: S1–S20). Additional RTK-GNSS data collection in the future will help determine geodetic elevation change trends in compartments outside the ACE Basin.

Long-term (multi-decadal) datasets are necessary to constrain true change in elevation using geodetic methods, interpreting SET data, and comparing the resulting rates to tidal gauge records. The marsh platform can be complex at small spatial scales (as exemplified by the variability of ACEWI1, ACEWI2, and ACEWI3), making it challenging to apply interpretations across even the same marsh. Site-specific impacts (i.e., increased submergence at LBWS1 due to beach dynamics, and negative REC at ACEWI3 despite or possibly because of its supratidal position and high orthometric elevation) may also influence marsh platform dynamics. SCGS SET stations are variable within their compartments in terms of REC, orthometric elevation, and vegetation, and the compartments themselves are highly variable in terms of tidal range, sediment input, and (possibly) impacts of subsidence or uplift. The shifting lateral extent of the salt marsh (i.e., upland migration and changes in creekbank location and position of the seaward shoreline) is also indicative of changing physical conditions (i.e., SLR, erosion) and should be considered when evaluating overall marsh vulnerability (Kirwan et al. 2016; Doar et al. 2019). Additional investigation is required to further understand both the myriad factors controlling elevation change in South Carolina's salt marshes, and the susceptibility of our marshes to RSLR.

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Data Availability The supporting data related to this study are available from the corresponding author, WRD, III, upon request.

Declarations

Conflict of Interest The authors declare no competing interests.

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