National Synthesis of NERR SET Data

Generated from the 2018 – 2020 project
"Is marsh surface tracking sea level change?
Developing tools and visualizations for NERRS Sentinel Site Data"
aka ***"SETr"***

Background

Can tidal wetland surfaces keep up with sea level rise? This is a critical coastal management question, around which many monitoring programs have been developed. Surface Elevation Tables (SETs) are widely used to collect data on the dynamics of tidal wetland communities, through precise measurements of marsh surface over time. Most sites within the network of 29 National Estuarine Research Reserves (NERRs) have been measuring SETs for several years, resulting in a need for tools to process, analyze, and communicate about surface elevation change. This project focused on developing such tools, within a larger workflow, and this document is a first synthesis of SET data from multiple Reserves.

Sixteen data files from 15 Reserves were submitted, containing data for 187 SETs. Information on these Reserves, number of SETs, sample dates, and the nearest NWLON station to each is given in Table 1 below. Please reference the metadata for your particular Reserve for specific information on individual SETs, such as date of first observation, geomorphic setting and dominant vegetation type, elevation of the SET receiver, etc.

Table 1. Information on contributed NERR SET data.

Reserve	State	# SETs	Nearest NWLON Station	First Sample Date	Last Sample Date	# years measured
Region: Gulf and Southeast						
APA	FL	21	8728690	2012-10-05	2018-05-02	5.57
GND	MS	15	8735180	2012-02-28	2016-11-23	4.73
GTM	FL	18	8720218	2013-06-27	2019-10-21	6.32
MAR	TX	15	8774770	2013-08-21	2019-05-02	5.70
WKB	AL	12	8735180	2015-01-07	2019-01-22	4.04
Region: Mid-Atlantic						
CBM	MD	12	8577330	2010-10-07	2016-04-27	5.56
CBV	VA	10	8638610	2009-02-09	2018-09-20	9.61

Reserve	State	# SETs	Nearest NWLON Station	First Sample Date	Last Sample Date	# years measured
DEL	DE	14	8557380	2004-06-22	2016-08-23	12.17
Region: Northeast						
GRB	NH	9	8443970	2011-08-11	2017-12-05	6.32
NAR	RI	12	8452660	2012-10-10	2018-10-17	6.02
NARUNH	RI	5	8452660	2014-06-12	2018-06-11	4.00
WEL	ME	2	8418150	2011-08-25	2018-10-16	7.14
WQB	MA	11	8447930	2013-06-25	2018-07-05	5.03
Region: West						
ELK	CA	8	9413450	2006-09-29	2018-09-18	11.97
PDB	WA	14	9449880	2002-08-18	2017-06-25	14.85
SOS	OR	9	9432780	2011-05-05	2018-06-08	7.09

The project team developed criteria for inclusion in this analysis and decided that at least 5 observations over at least 4.5 years were needed to develop an accurate depiction of trend. A total of 146 SETs had enough data for rate calculations; SETs that had less than the minimum number of observations are tallied in the column “not enough data” in the following tables, which compare rates of SET elevation change to rates of sea level rise and 19-year water-level change.

SET rates in the tables below largely reflect those that are in emergent marsh, or in a habitat that was emergent marsh and may now be transitioning to an unvegetated condition. Only two Reserves in the table below have SETs in other habitat types. All of Padilla Bay’s SETs are located in seagrass habitat; Mission-Aransas has SETs in marsh and mangroves. All SET data, regardless of habitat type that a particular SET is located in, is reported in the tables and figures below.

Statistical methodology

Rates of elevation change at each SET were generated using random-intercept linear mixed models. See Zuur et al. (2009) and Cahoon et al. (2019) for details.

Linear mixed models (LMM) extend traditional linear regression models by allowing for the inclusion of both fixed and random effects. These types of models are particularly useful when the data are structured hierarchically, as with SET data. Data for each SET is analyzed separately using pin height as the response variable; arm and pin (nested in arm) are treated as random effects; and date is considered a numeric covariate. As both the intercept and slope include random effects, methods other than least squares must be employed.

For each SET, we initially considered two LMMs, as in Cahoon et al. (2019): a LMM that includes a random intercept (with a random effects for arm and for pin nested in arm) and a LMM that includes both a random slope and a random intercept (with random effects for arm and for pin nested in arm). For many SETs, we observed that the random intercept model fit better. At other SETs, the random slope and intercept model produced better fitting models (based on AIC). However, the resulting point estimates showed only small differences between the two approaches. As the random intercept models did not require the same degree of scrutiny when model fitting, and did not cause as many script-running errors, we exclusively employed random intercept models in these automated R scripts. For more detailed analyses at a smaller level, we recommend consideration of both models.

Comparison to local long-term sea level rise

National Ocean Service's Center for Oceanographic and Operational Products' (CO-OPS) operates 210 continuous, long-term water level stations for assessing relative sea level. Water level observation stations qualify for the National Water Level Observation Network (NWLON) if they have at least 19 years of high accuracy data. For the SLR calculations listed in the table below, the *full* record of water level observations from the closest NWLON station were utilized. The SLR results for each station were compared to the CO-OPS published rates, and in all cases, the values and their estimates of variability matched. To find out more details about which NWLON station was used for each Reserve's comparisons, its period of record and distance to each Reserve, refer to the Sea Level Rise rates document.

To compare SET rates of change to SLR and 19-year water-level change, we are noting whether the confidence intervals for each rate overlap with each other. This method of comparison was chosen because different methods were used to calculate rates for sea level rise (ARIMA) and SET elevation change (LMMs), using data from different sources. We note that each individual interval has 95% confidence associated with it, and conclusions that are made based on pairwise comparison of these intervals will not necessarily be equivalent to conducting a formal hypothesis test for a difference at the 5% level (Schenker and Gentleman, 2001).

Table 2. Comparison of SET rates of elevation change to long-term SLR.

Reserve	SLR rate	# SETs	# SETs Higher		# SETs Lower		Not enough data
	long-term	total	No CI overlap	CI overlap	No CI overlap	CI overlap	
Region: Gulf and Southeast							
APA	2.23 +/- 0.64	20	8	2	9	1	0
GND	3.61 +/- 0.59	15	3	6	4	2	0
GTM	2.62 +/- 0.25	18	6	2	10	0	0
MAR	5.62 +/- 0.48	15	4	1	3	1	6
WKB	3.61 +/- 0.59	12	-	-	-	-	12
Region: Mid-Atlantic							
CBM	3.82 +/- 0.24	12	2	2	4	4	0
CBV	4.66 +/- 0.22	10	5	0	5	0	0
DEL	3.44 +/- 0.24	14	8	0	2	0	4
Region: Northeast							
GRB	2.82 +/- 0.16	9	0	0	6	1	2
NAR	2.77 +/- 0.16	12	1	0	9	2	0
NARUNH	2.77 +/- 0.16	5	-	-	-	-	5
WEL	1.88 +/- 0.14	2	2	0	0	0	0
WQB	2.86 +/- 0.17	11	2	1	2	5	1
Region: West							
ELK	1.57 +/- 0.82	8	0	5	0	3	0
PDB	1.19 +/- 0.27	14	0	0	12	1	1
SOS	1.12 +/- 0.77	9	-	-	-	-	9

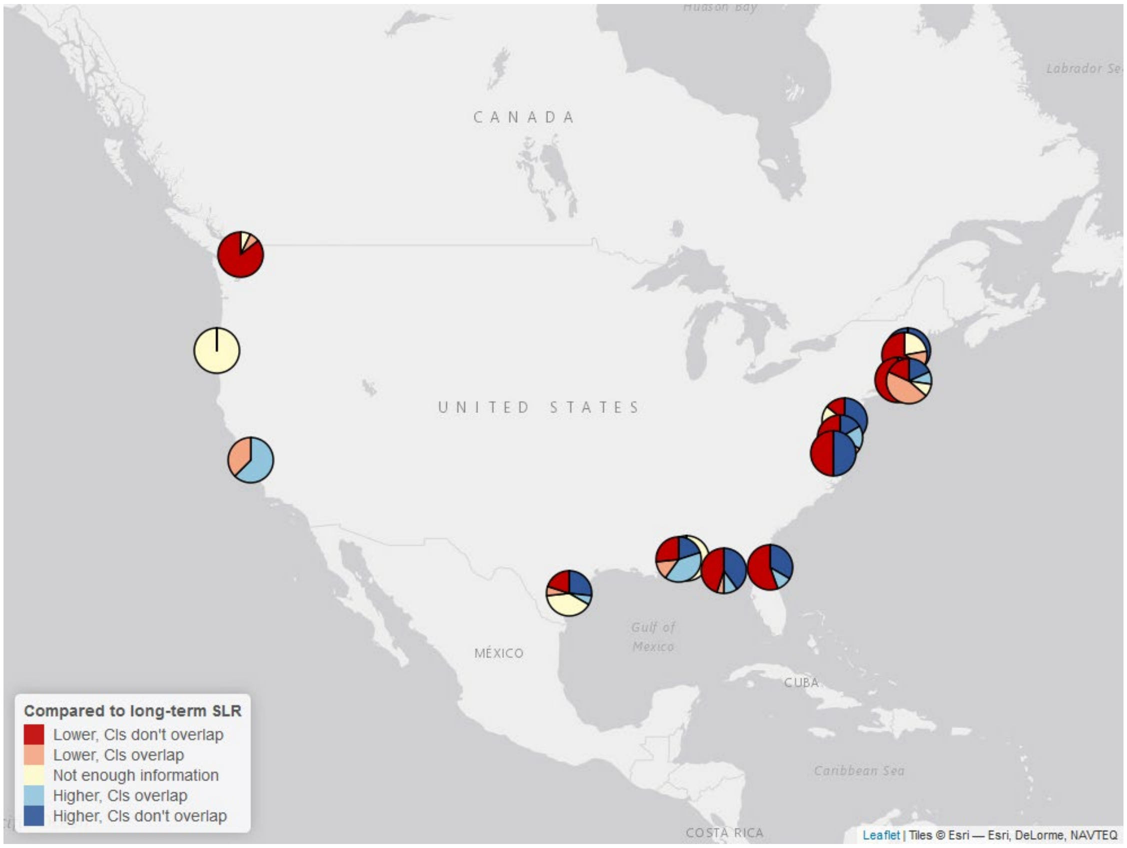

Figure 1. Proportion of SETs at each participating reserve whose rate of elevation change was greater than (blue) / less than (red) long-term sea level change at a nearby NWLON station. Shading depends on whether confidence intervals overlapped (see text for more detail; dark color = no overlapping of CIs; lighter shading = CIs overlapped).

Understanding regional trends for mean sea level and analyzing rates of marsh surface elevation change can help identify patterns to determine how resilient marshes across the nation are to sea level rise (SLR). Long term SLR rates vary regionally due to processes such as subsidence which causes increased relative SLR rates, or isostatic rebound from glaciation, which causes the land surface to rise and a decrease in relative SLR. Excessive groundwater withdrawal causing local sediment compaction or even changes in ocean surface currents can affect sea levels observed at particular locations. From scanning across regions in Table 2, it is apparent that in the US West coast Reserves; the NWLON stations are showing some of the lowest rates of SLR as compared to Reserves in the Gulf, Mid-Atlantic and Northeast. Isostatic rebound and local tectonics (i.e., uplift) are some of the factors that mitigate SLR rates in California, Oregon and Washington and contribute to lower long term SLR rates than the 20th century global average of 1.7 + 0.5 mm/yr (IPCC 2007). Cape Mendocino, California is a breakpoint for West Coast SLR rates; generally the tide gauges north of it, which are within the tectonically active Cascadia Subduction Zone, have RSLR rates that are less than global average or even falling, while those south of it show RSLR is rising (NAP 2012).

Similarly, there is variability in changes to surface elevation of wetlands at both the local and regional level due to a variety of drivers, such as human perturbations, whether systems are ocean or river driven, inundation patterns, and plant community composition. Coastal wetlands are highly dependent on river and ocean sediment delivery for vertical accretion, but a high prevalence of human diversions (e.g., dams/levees) have historically reduced overall sediment delivery to tidal wetlands (Callaway et al. 2012; Cahoon et al. 1996; Weston 2014). According to Weston (2014), many fluvial dominated systems, such as those in the Mid-Atlantic and Gulf regions, are particularly vulnerable to reduced fluvial sediment deliveries due to the prevalence of upstream dams. For instance, the Apalachicola River has nearly 60 dams trapping sediments behind them prior to entering the estuary.

Long term records of NERR SET data were relatively sparse along the US West Coast; there are 31 SETs represented here. Although South Slough NERR (SOS) collects SET data it does not yet have the prerequisite minimum five sample points necessary for inclusion in this synthesis. Interestingly Padilla Bay NERR in Washington has the second lowest long term SLR rate in this national synthesis and its SETs show some of the lowest accretion rates of all the SETs analyzed for this project. It's important to note that Padilla Bay is unique in this analysis in that the SETs are located in Submerged Aquatic Vegetated (SAV) habitat, not emergent marsh. Elkhorn Slough NERR, which is south of Cape Mendocino, has 5 of its 8 SETs showing a trend of keeping up with long term SLR, but in all 8 of its SETs analyzed for this project, none of the SET rates and associated confidence intervals are outside of the confidence limits of long term SLR. Overall, 76% of the SETs in NERRS along the US West Coast showed lower elevation gain rates than long term SLR; and for over half of these (57%), the SET rates and their confidence intervals were below and did not overlap the confidence intervals for long term SLR.

For the Gulf and Southeast coast NERRS, there is a higher density of SETs than for the West Coast and they are, like Elkhorn Slough NERR, nearly split between those where the surface elevation is increasing faster than local, long term SLR (blue and light blue) and those SETs whose elevations are falling behind SLR (red and pink). Twenty-six of the 62 Gulf region SETs that have a long enough record to be included in this analysis are not keeping pace with long term SLR (CIs don't overlap); these SETs are distributed among all of the Gulf region NERRs and aren't concentrated in one location unlike Padilla NERR on the West Coast. The long term SLR rate at Mission-Aransas Reserve in Texas is 2 mm/yr higher than that of any other NWLON station in this analysis; yet 44% of their SETs are showing elevation gain rates that are substantially higher than their local, comparatively high, long term SLR rates. Mission-Aransas has SETs in both mangrove and emergent marsh, as well as areas that are in transition between these two habitat types. A detailed examination of the results from that Reserve indicates that one of the SETs from Mud Island East where marsh is transitioning to mangroves is gaining elevation very rapidly while two other nearby SETs are not. The two NERRs in Florida that are located at approximately the same latitude but occur on opposite sides of the peninsula (GTM is on the east coast of FL) have similar, comparatively low rates of long term SLR. Both FL Reserves have 40% or less of their SETs that are showing elevation gains that are higher than long term SLR and do not overlap in confidence intervals.

Similar to the West Coast and Gulf Coast NERRs, when analyzed over the whole region, the 36 Mid-Atlantic NERRs have a nearly even split between the portion of SETs that are gaining elevation at rates that exceed long term SLR and its confidence intervals (47%) and those that generally are not keeping pace with long term SLR. The two Chesapeake Bay NERRs have long term SLR rates that are nearly 1 mm different, and in the case of Chesapeake Bay, VA, with narrow confidence intervals which is likely due to the long time record of the NWLON station, which has been in operation since 1927. However, all of the three Mid-Atlantic NERRs have narrow confidence intervals for their long term SLR rates, which is likely due to the longevity of observations at the tide stations in this region.

For the 39 SETs in Northeast NERRs, SLR rates generally decrease from south to north, and at Wells NERR in Maine, the 2 SETs that are included in this analysis have elevation gain rates that exceed the confidence intervals of the long term SLR rate- the only Reserve within this synthesis to have this promising pattern. The preponderance of red and pink shading for the three other Reserves indicate that, with the exception of Maine, the northeast SET accretion rates are generally very low. Only 16% of the SETs in the Northeast that had sufficient data to be included in this analysis had elevation change rates that were higher with non-overlapping confidence intervals with those of long term SLR rates. Conversely, over half of the Northeast SETs (55%) had elevation trends that were so low, they did not overlap the narrow confidence intervals of their nearby long term NWLON stations' SLR records.

Comparison to local 19-year water level change

National Water Level Observation Network (NWLON) stations are maintained by the National Ocean Service's Center for Oceanographic and Operational Products' (CO-OPS). In order to be considered part of the NWLON network, a station must have been in operation for at least 19 years. This 19-year requirement is due to a predictable astronomical cycle (also known as the metonic cycle) that is mostly influenced by the moon, hence it is also referred to as the lunar nodal cycle. Every 18.6 years, this cycle of tidal amplitude changes due to the orbits of the moon and earth relative to the sun, repeats. Water level changes that are calculated over a minimum of a 19-year observation period will reflect both the peak and trough of the metonic cycle; the most recent peak of the metonic cycle was in 2015. Workshop participants midway through the SETr project agreed that comparing SET rates of elevation change to 19-year water level change would be a useful shorter-term comparison than the previously described comparisons to long-term SLR. For this project, the same data used by NOAA to calculate long-term SLR was downloaded and analyzed using the same methodology (ARIMA 1,0,0; NOAA 2009) to generate rates and 95% confidence intervals for water level change. We verified that our long-term calculations matched those of NOAA before performing these shorter-term calculations. The table below summarizes these rates, CIs, and comparisons of SET rates of change to the 19-year water level changes.

Table 3: Comparison of SET rates of change to 19-year water level change

Reserve	water level	# SETs	# SETs Higher		# SETs Lower		Not enough data
	19-yr rate of change	total	No CI overlap	CI overlap	No CI overlap	CI overlap	
Region: Gulf and Southeast							
APA	5.22 +/- 2.57	20	1	4	10	5	0
GND	7.37 +/- 3.18	15	0	0	6	9	0
GTM	4.66 +/- 2.47	18	3	2	10	3	0
MAR	8.57 +/- 2.48	15	4	0	4	1	6
WKB	7.37 +/- 3.18	12	-	-	-	-	12
Region: Mid-Atlantic							
CBM	7.15 +/- 1.67	12	1	0	10	1	0
CBV	7.19 +/- 2	10	0	2	5	3	0
DEL	4.69 +/- 2.02	14	4	4	1	1	4
Region: Northeast							
GRB	4.92 +/- 1.89	9	0	0	7	0	2
NAR	4.81 +/- 1.49	12	0	1	11	0	0
NARUNH	4.81 +/- 1.49	5	-	-	-	-	5
WEL	4.54 +/- 1.99	2	0	1	0	1	0
WQB	4.32 +/- 1.56	11	0	0	2	8	1
Region: West							
ELK	5.19 +/- 1.88	8	0	0	8	0	0
PDB	3.31 +/- 2.4	14	0	0	12	1	1
SOS	2.31 +/- 2.71	9	-	-	-	-	9

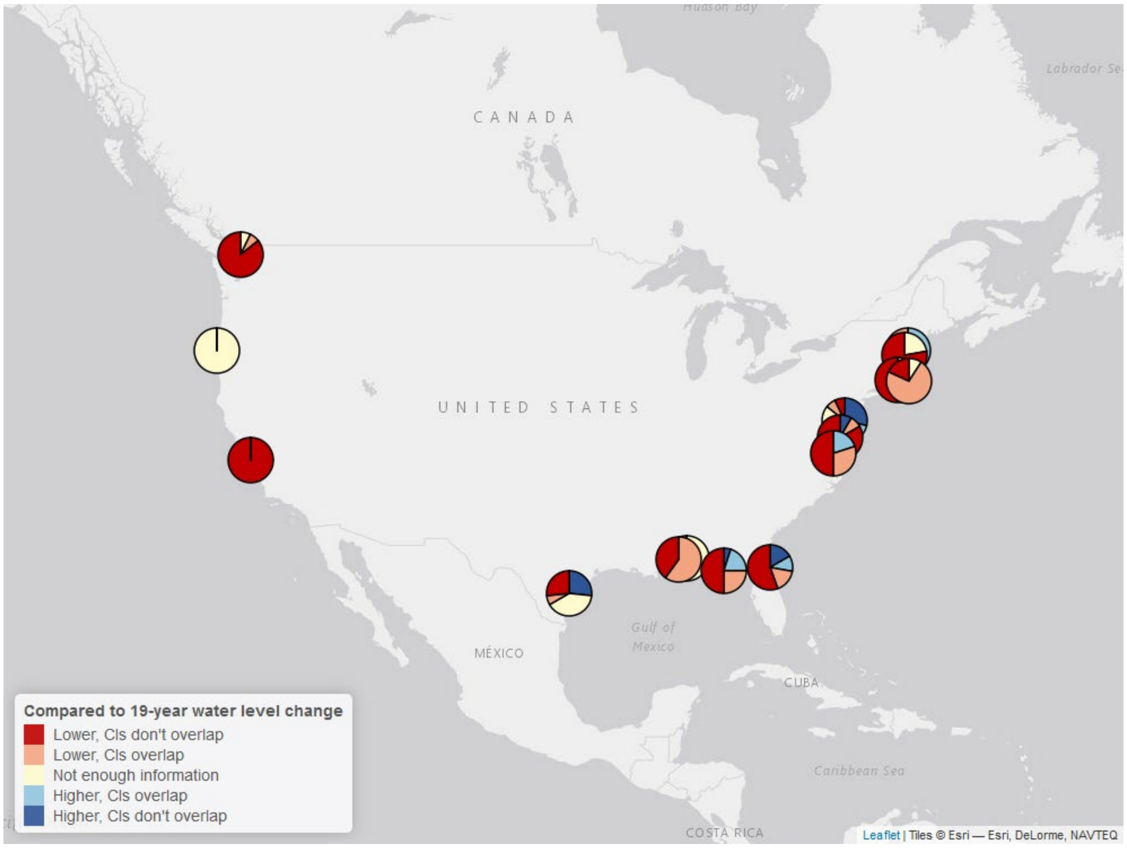

Figure 2. Proportion of SETs at each participating reserve whose rate of elevation change was greater than (blue) / less than (red) 19-year water level change. Shading depends on whether confidence intervals overlapped (see text for more detail; dark color = no overlapping of CIs; lighter shading = CIs overlapped).

Local 19-year water levels for Gulf region are 2-4 mm higher than the long term rate of the closest NWLON station, but variability is much higher as well (±/-2-2.5 mm). Given these changes with a shorter time frame for water level observations, we see a reduction in the total number of SETs reduced from 21 (34%) to only 8 (13%) whose average surface elevation gain rates and associated confidence intervals are higher than (not overlapping) average 19 year water level changes and its associated confidence intervals. For the Mid-Atlantic the local 19-year water-level changes are ~3.5 mm higher (except in Delaware where it's only 0.5 mm higher). The effect of these higher average water levels over this shorter time frame is a reduction in the number of SETs keeping pace with SLR from 15 (47%) to only 5 (16%). Local SLR rates for the Northeast and the West show none of the SETs in this dataset that can keep pace with the shorter term, but notably higher, local water level change rates.

Region-level maps, long-term SLR

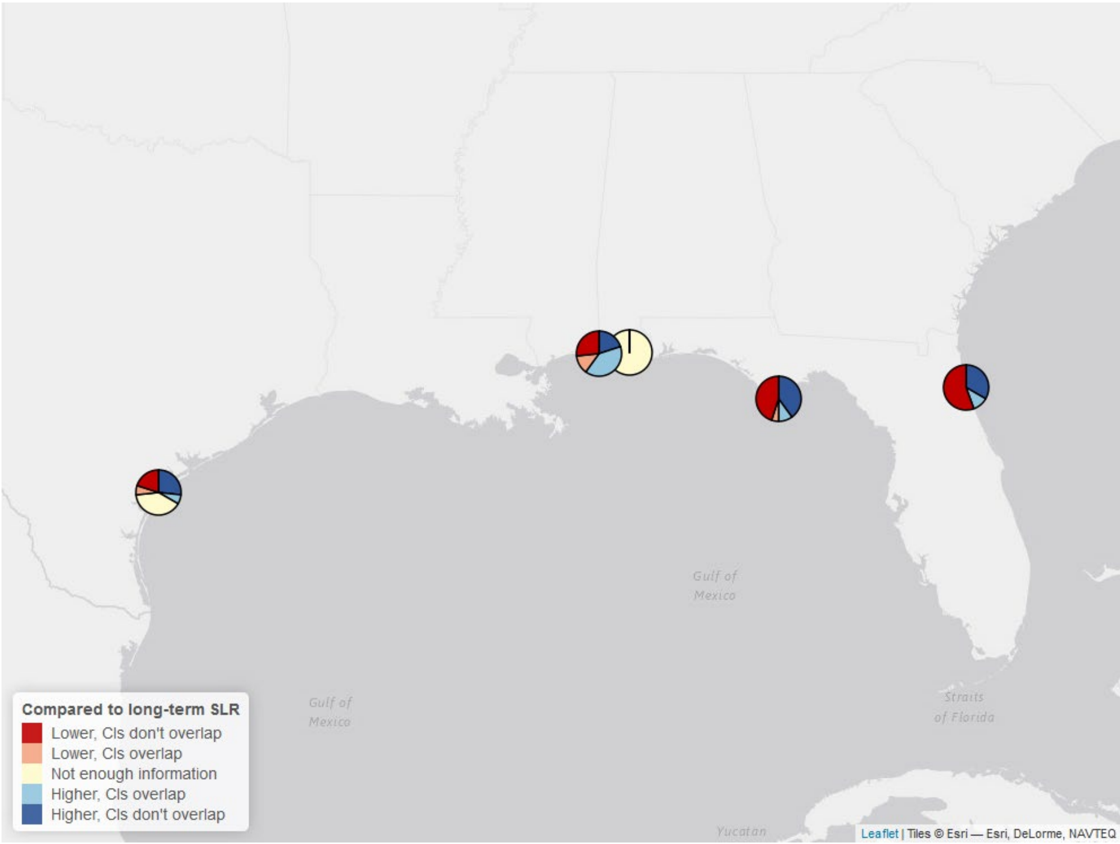

Figure 3. Gulf and Southeast region compared to long-term SLR.

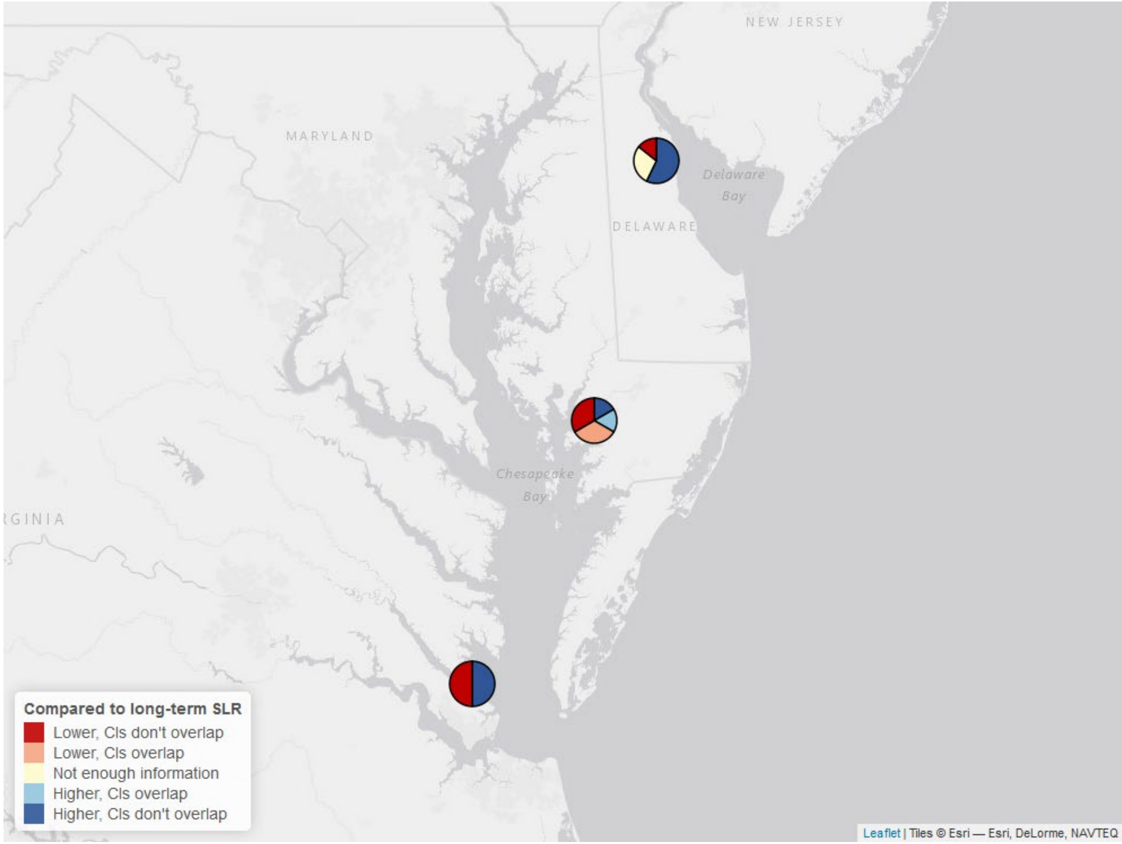

Figure 4. Mid-Atlantic region compared to long-term SLR.

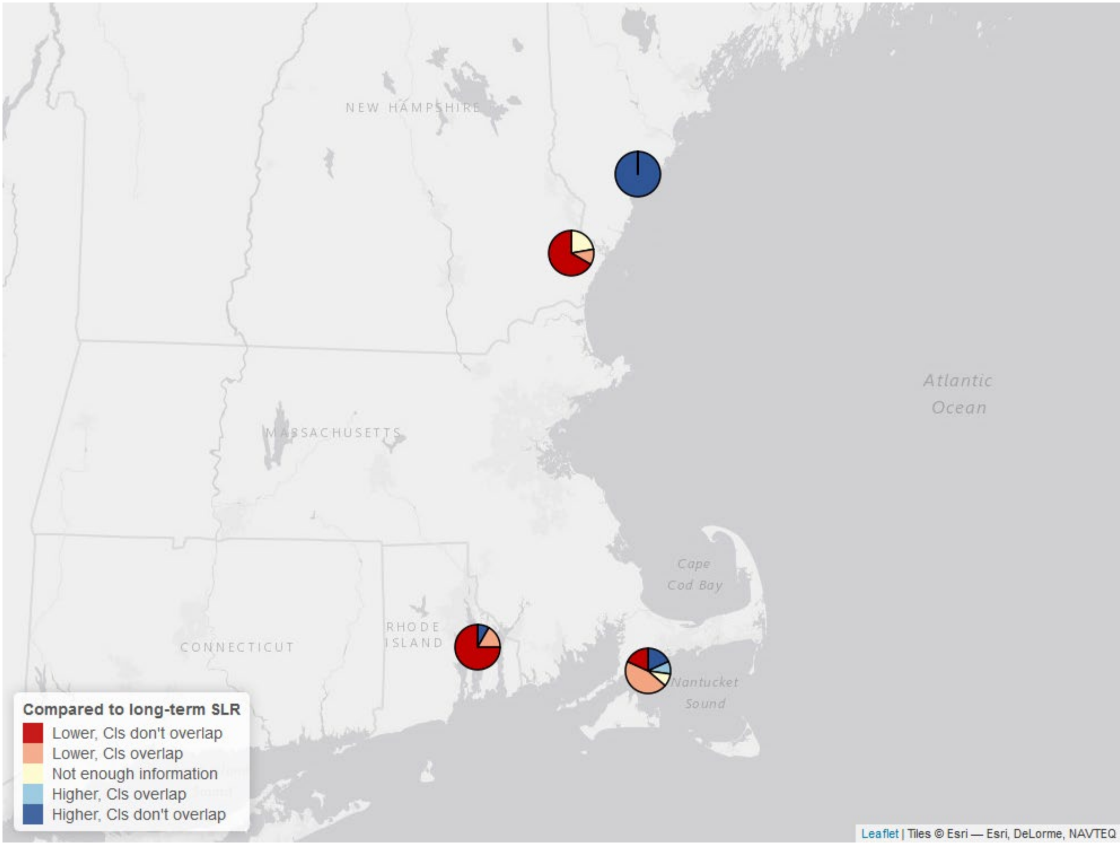

Figure 5. Northeast region compared to long-term SLR.

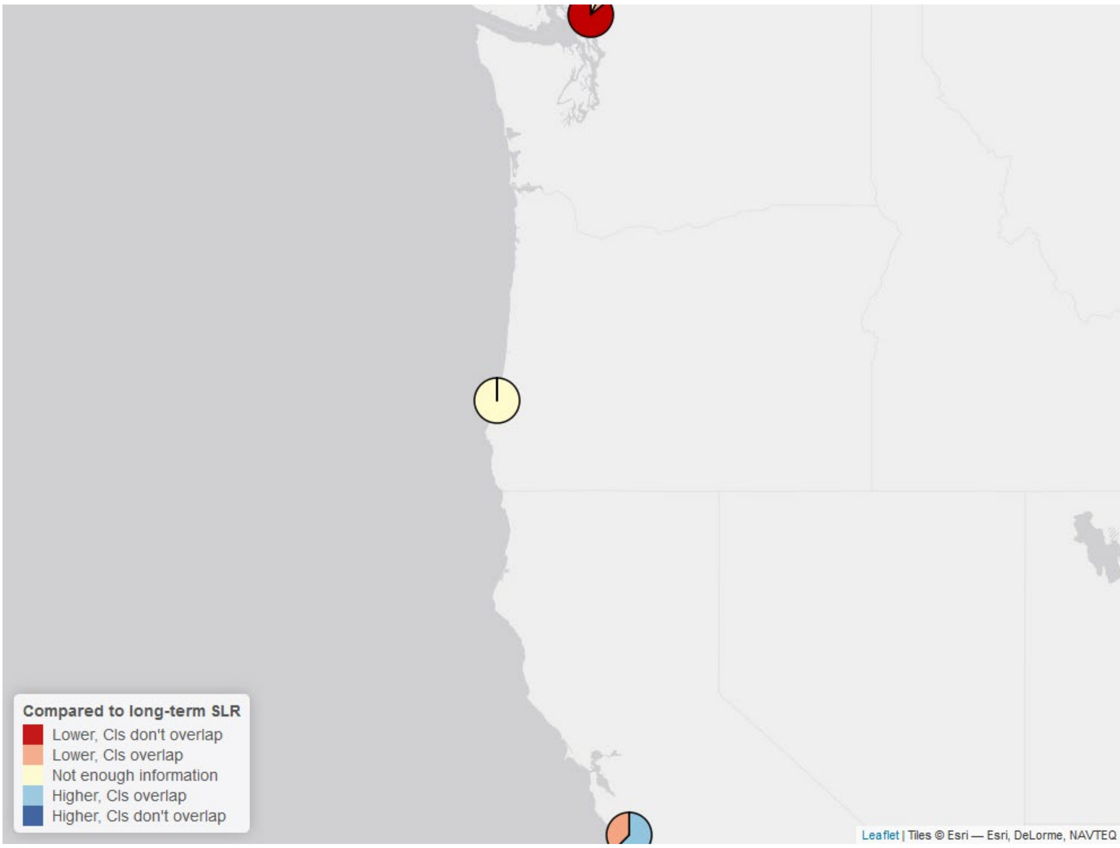

Figure 6. West Coast region compared to long-term SLR.

Region-level maps, 19-year water level change

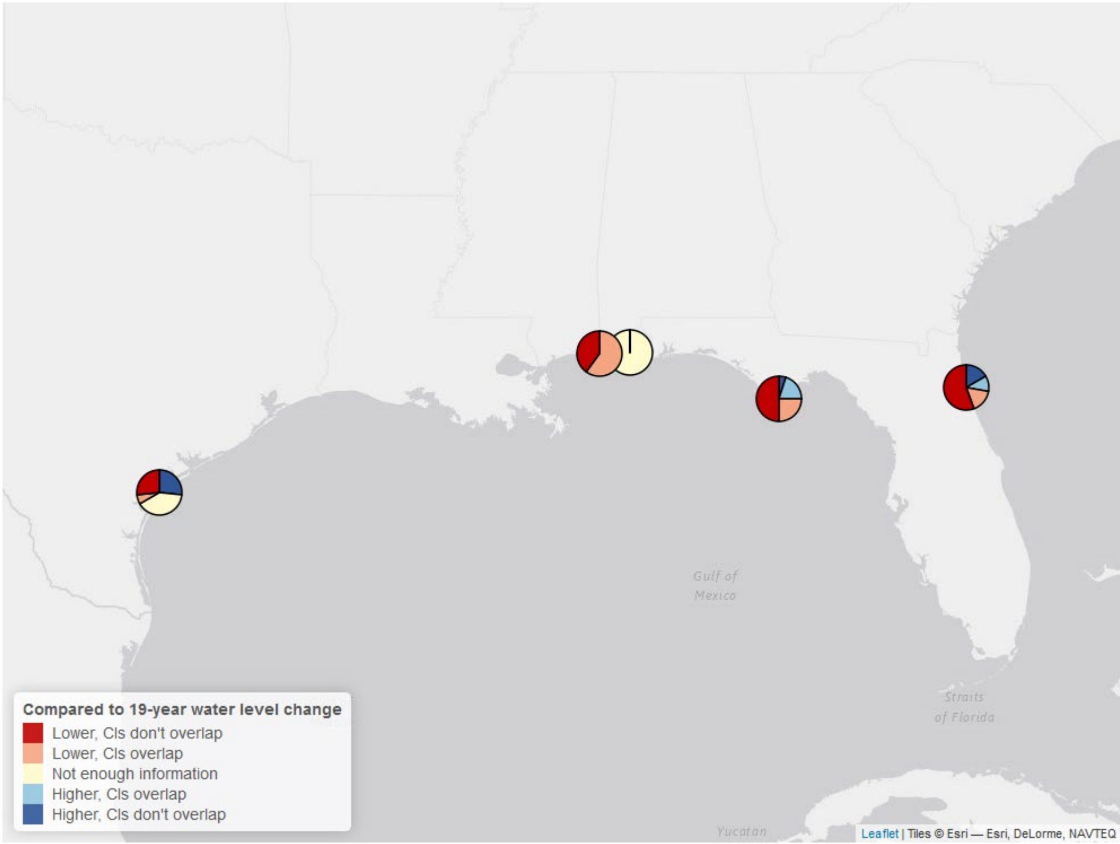

Figure 7. Gulf and Southeast region compared to 19-year water level change.

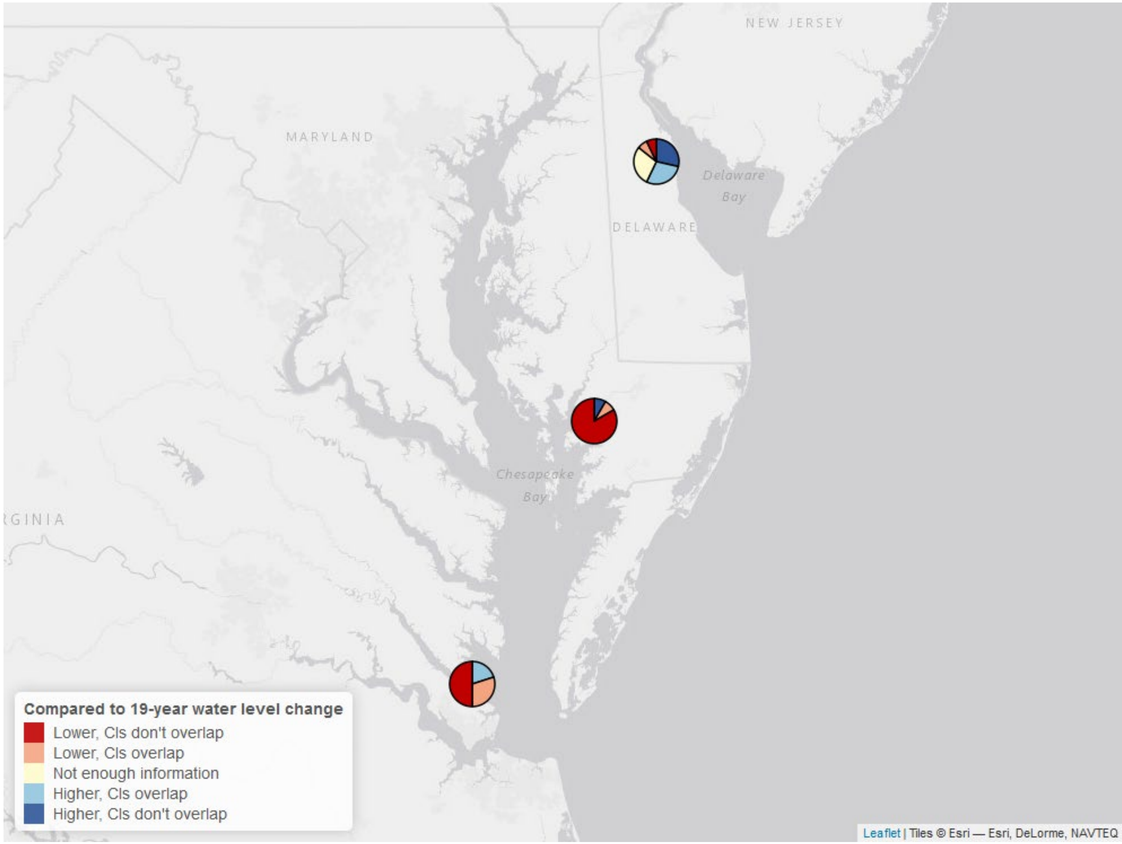

Figure 8. Mid-Atlantic region compared to 19-year water level change.

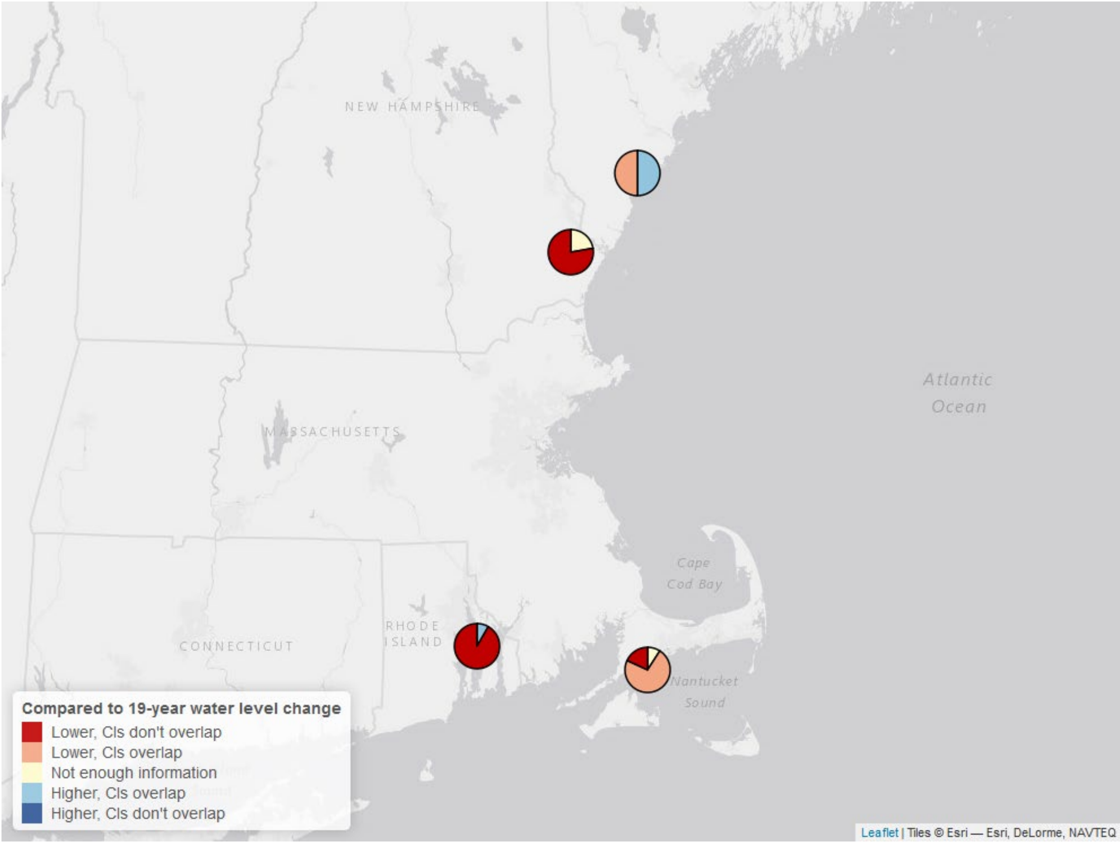

Figure 9. Northeast region compared to 19-year water level change.

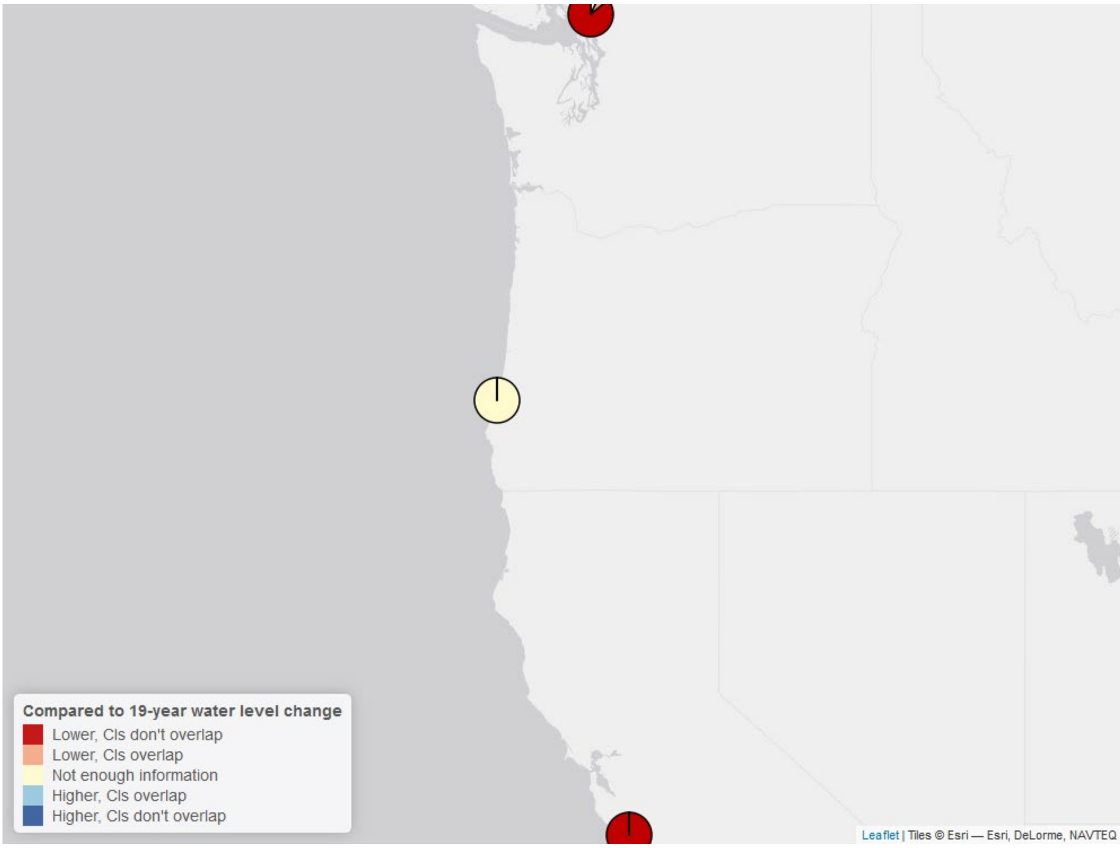

Figure 10. West Coast region compared to 19-year water level change.

Region-level maps, 19-year water level change, with details for each NERR's SETs

One of the key graphics produced in each Reserve's technical report is a visual summary of how each SET at the reserve compares to the rates of long-term SLR and 19-year water level change. The x-axis represents rate of change, lower on the left to higher on the right. SETs are categorically arranged along the y-axis. A light gray vertical line on the graph marks 0 along the x-axis. The solid blue line is the point estimate for long-term SLR, with the dark shading around it representing the 95% CI. The dashed line represents the 19-year rate of water level change, and the light blue shading is the associated 95% CI. Point estimates of each SET's rate of elevation change are in red, with whiskers for the associated 95% CIs.

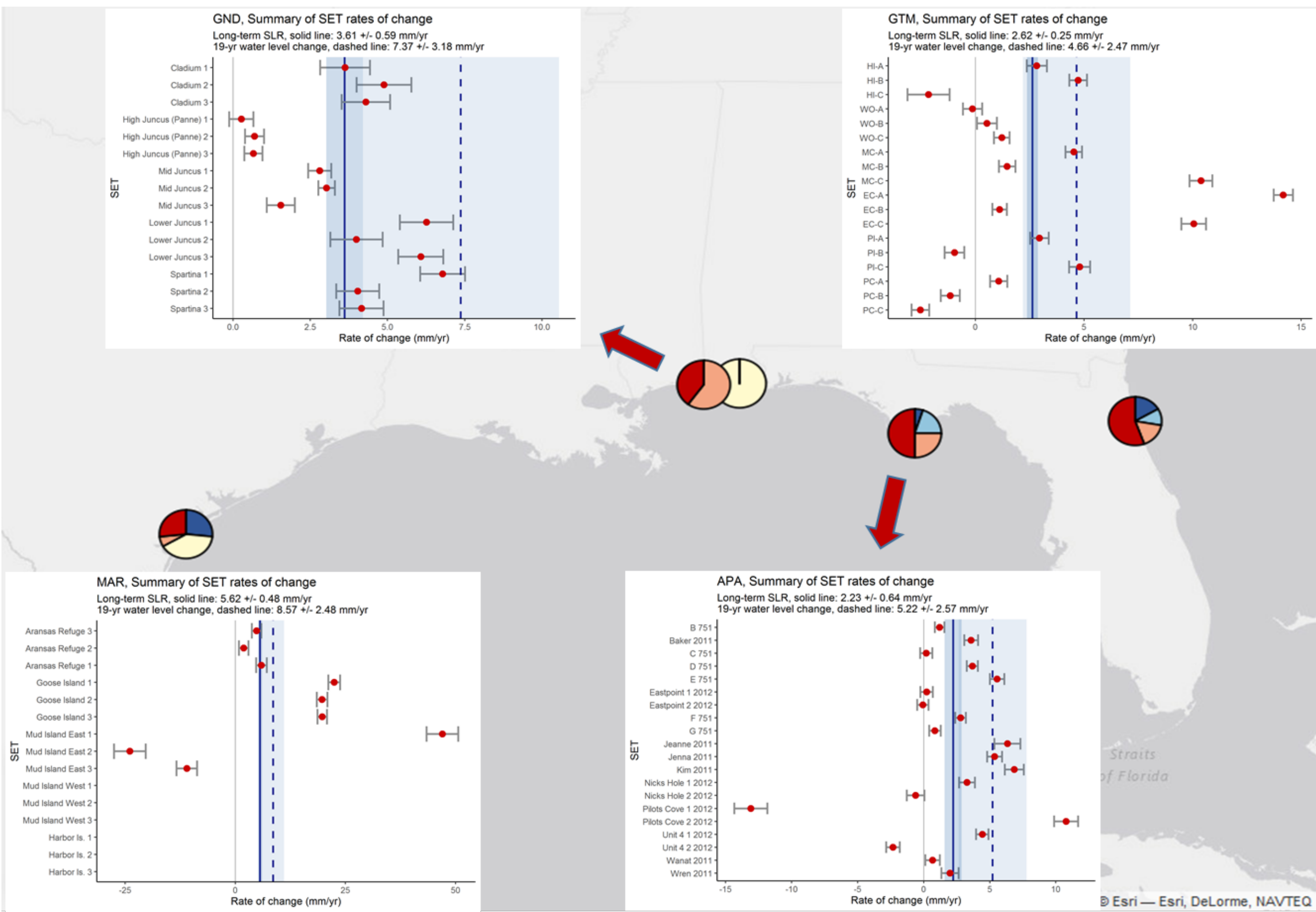

Figure 11. Gulf and Southeast region compared to 19-year water level change, with summary rate graphics for each Reserve.

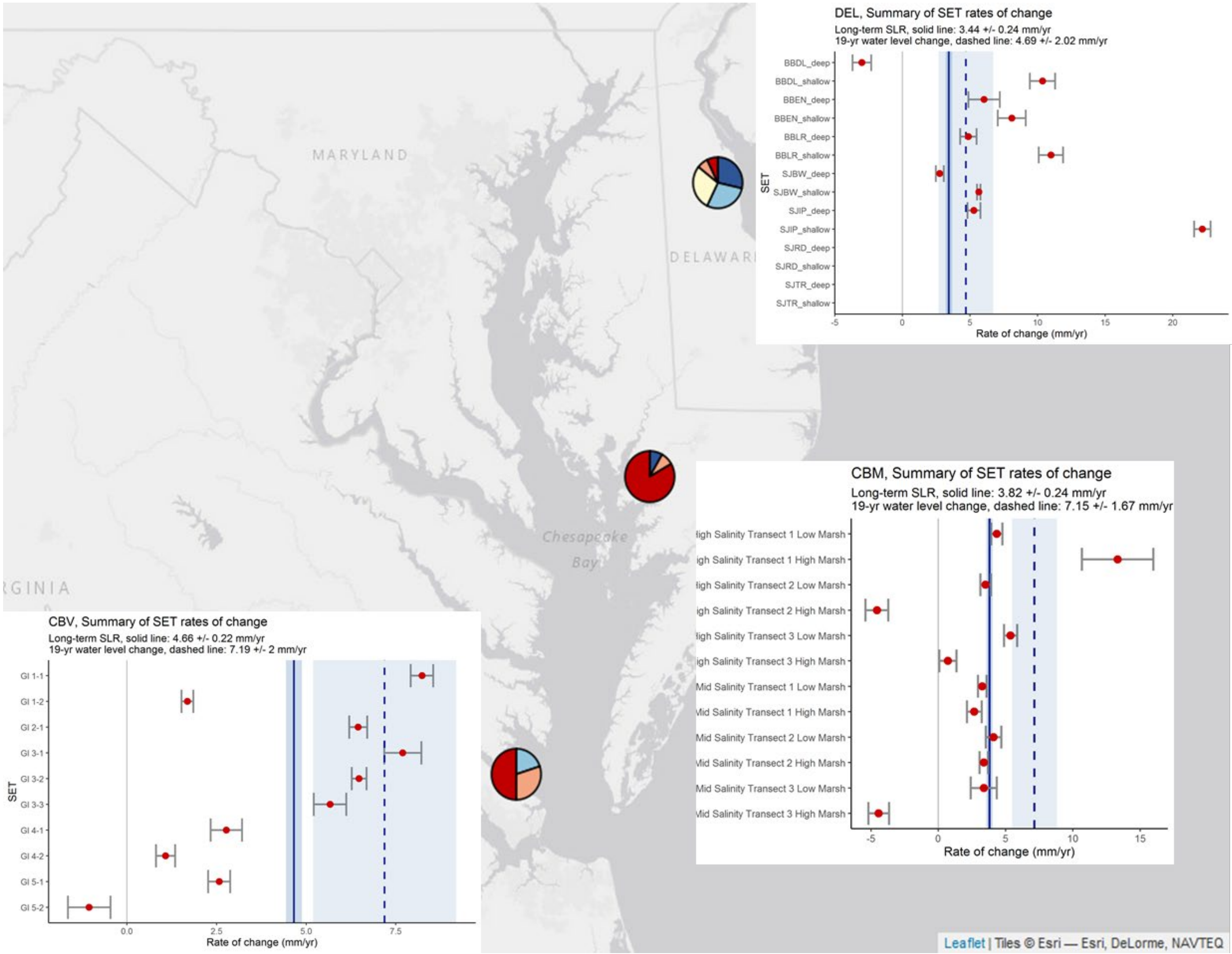

Figure 12. Mid-Atlantic region compared to 19-year water level change, with summary rate graphics for each Reserve.

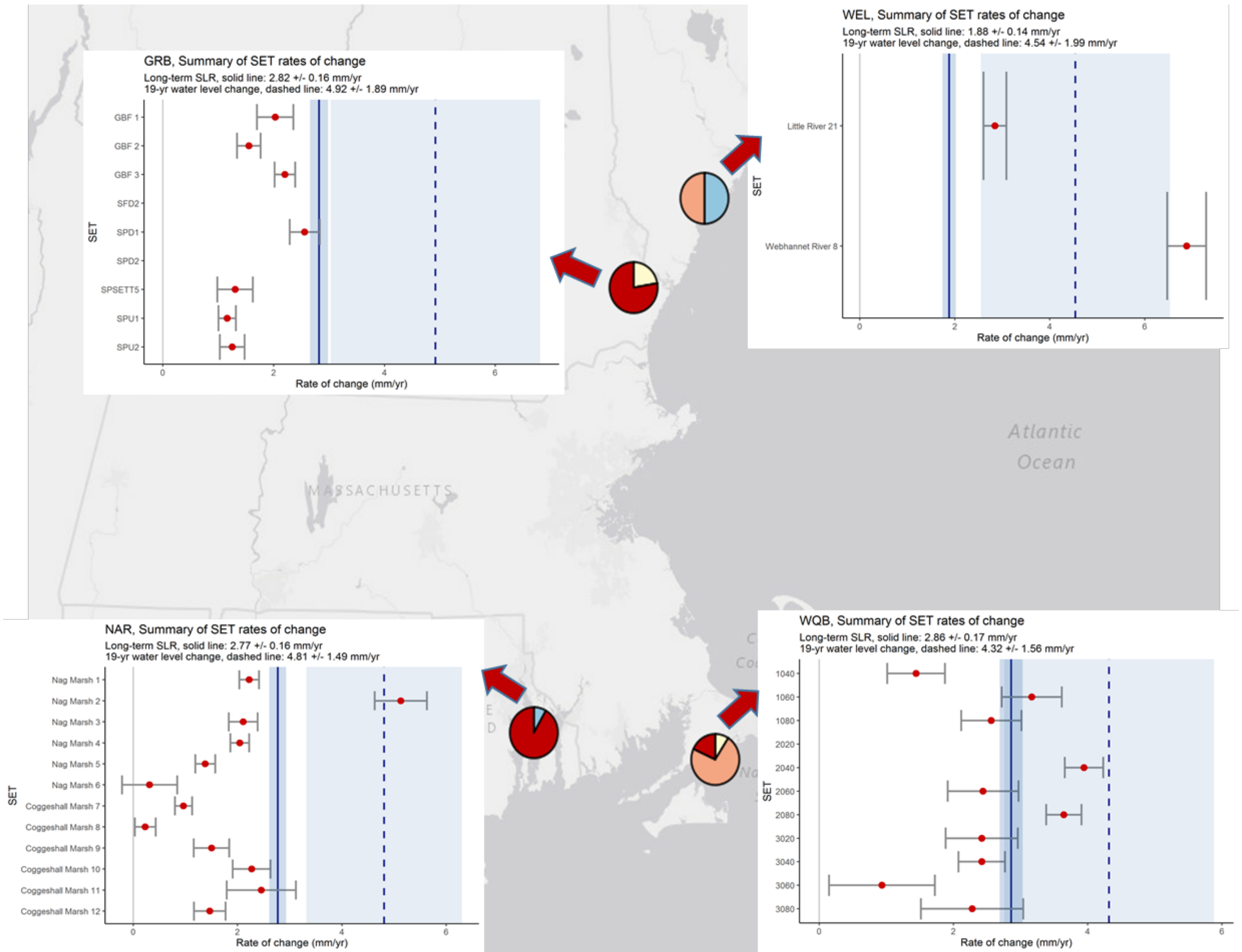

Figure 13. Northeast region compared to 19-year water level change, with summary rate graphics for each Reserve.

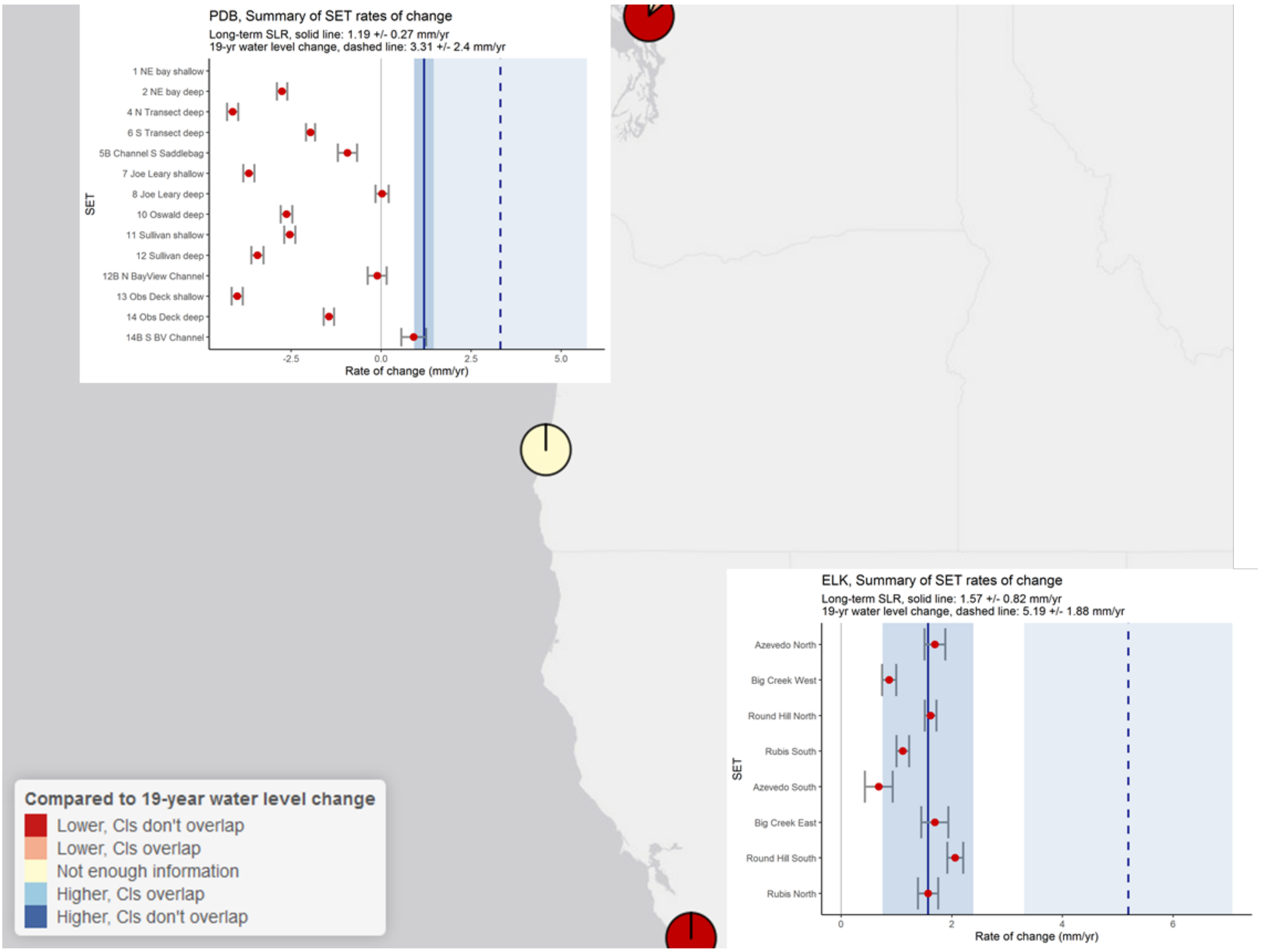

Figure 14. West Coast region compared to 19-year water level change, with summary rate graphics for each Reserve.

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