Analysis of Change

Wetland Surface Elevation Table (SET) Data

for

Waquoit Bay National Estuarine Research Reserve (WQB)

Massachusetts, 2013-2018

To learn more about project, project team, and related products visit: nerrssciencecollaborative.org/project/Cressman18

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SET Rate Calculations

2020-02-26

This document was designed for use by National Estuarine Research Reserve (NERR) technical staff and may also be useful to other Surface Elevation Table (SET) data analysts. It is meant to calculate, visualize, and describe rates of elevation change at SET stations in a given area (such as an individual NERR or reserve component). These products are output from a 2018-2019 NERRS Science Collaborative Catalyst Grant project nicknamed "SETr". For information on options to customize this report, see the document "Guide to the SETr Workflow" in the main folder of SETr outputs.

Background on the data

This analysis was run on **wqbset_processed.csv** on *2020-02-26*.

In this report, the user may have chosen to exclude data associated with certain QA/QC codes. Any values that have been removed are listed in the appropriate section below.

Data and metadata setup

We start by reading in the long SET measurement dataset, converted from other formats by earlier SETr scripts. See the "Guide to the SETr Workflow" document for more detail on data formatting. In this step, pin heights were converted to mm if they were previously in cm.

This dataset spans the dates **2013-06-25** to **2018-07-05**.

If custom start and/or end dates were specified for this analysis, the dataset is subsetted here and the chosen date range will be printed below this paragraph. These options can be changed in the file `metadata/user_defined_inputs.xlsx`, `general` tab.

QA/QC codes

In the same `user_defined_inputs` spreadsheet, certain QA/QC codes may have been specified for removal in this analysis. In the `qaqc_codes` worksheet, they were labeled with “-3”, to be consistent with SWMP’s water quality/weather/nutrient “reject” flagging. If such values are present, they will be printed below, then turned into NAs so they are not used in the analysis.

Note that the R code dealing with these flags looks for an EXACT match in the `qaqc_codes` worksheet, and matches are case-sensitive (all codes should be in all caps). If “LHE” is specified for removal, only values with “LHE” will be removed. “LHE CB” and “CRM LHE” will *not* be removed if only “LHE” is specified; combinations of codes need to be specified on their own line in the input spreadsheet. If you are using a new combination of codes, you may need to create a new row in that spreadsheet See the “Guide to the SETr Workflow” document for more information.

```
## No QA/QC codes were labeled for exclusion. All data values are present.
```

File Matching checks

If any mismatches in SET stations between the data and metadata files are present, they will be noted below. The user of this report will need to make any necessary changes in the data/metadata files.

```
## Warning: The following SET IDs exist in your metadata, but not in your
## data: 1020
```

Background information

Reserve-level characteristics

- The local, long-term rate of sea level change is **2.86** +/- **0.17** mm/yr.

- This rate is reported by Woods Hole, Massachusetts, NWLON station number 8447930 based on data from *1932* to *2017*.

- A shorter-term rate of water level change based on 19 years of data from the same NWLON station, using the same methods NOAA uses to calculate long-term sea level rise (ARIMA 1,0,0), is **4.32** +/- **1.56** mm/yr. This date range is from *1998* to *2017*.

- The technical report on NOAA’s calculation of long-term SLR trends, *Technical Report NOS CO-OPS 053 - Sea Level Variations of the United States 1854-2006* can be found here (accessed 2020-02-25): https://tidesandcurrents.noaa.gov/publications/Tech_rpt_53.pdf

SET-level characteristics

Setting

SET_ID	Type	Main_Veg
1020	Deep ROD SET	Spartina alterniflora
1040	Deep ROD SET	Spartina alterniflora
1060	Deep ROD SET	Spartina alterniflora
1080	Deep ROD SET	Spartina alterniflora
2020	Deep ROD SET	Spartina alterniflora
2040	Deep ROD SET	Spartina alterniflora
2060	Deep ROD SET	Spartina alterniflora
2080	Deep ROD SET	Spartina alterniflora
3020	Deep ROD SET	Spartina alterniflora
3040	Deep ROD SET	Spartina alterniflora
3060	Deep ROD SET	Spartina alterniflora
3080	Deep ROD SET	Spartina alterniflora

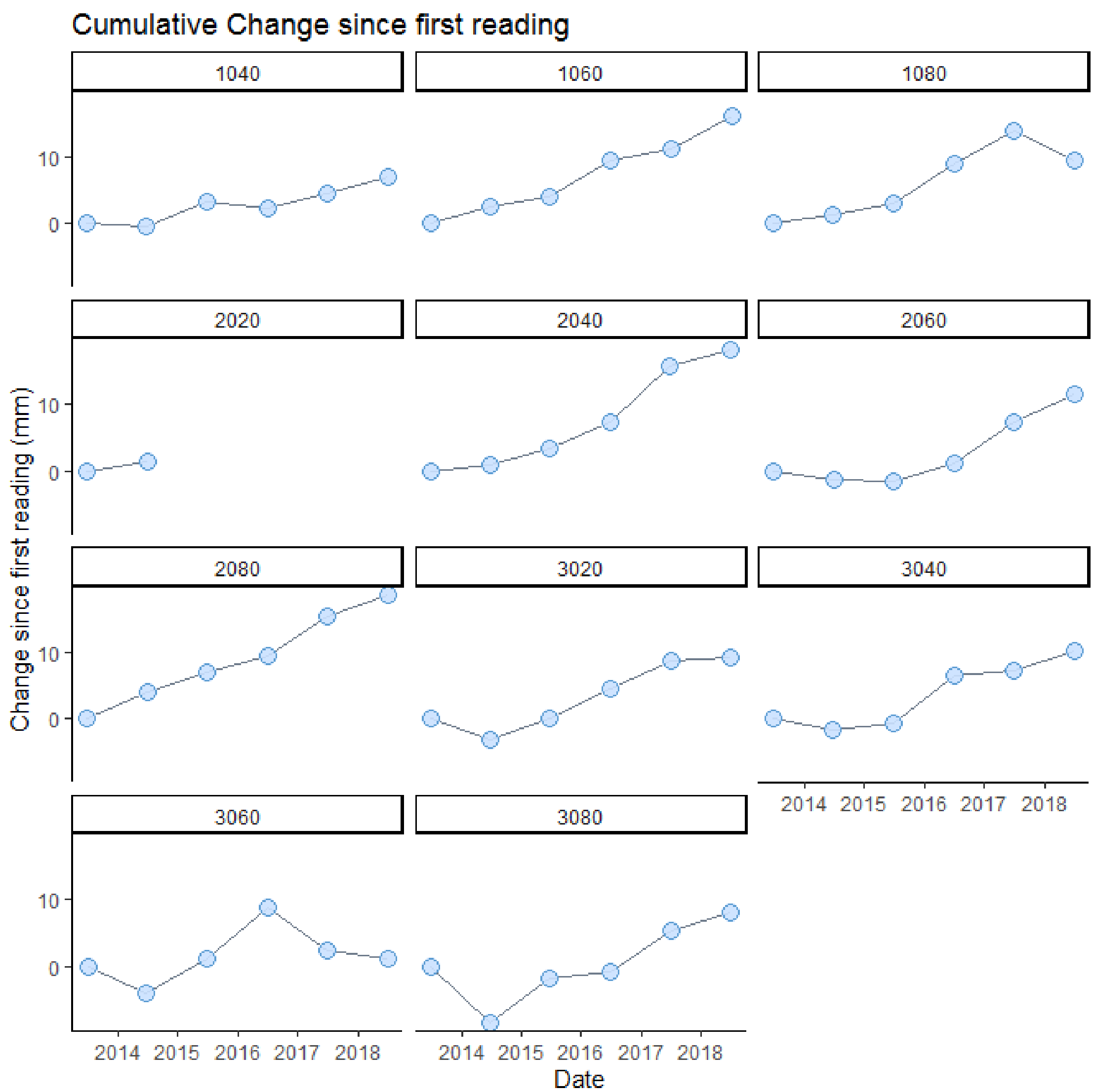
Sampling Information

set_id	first_sampled	last_sampled	years_sampled	sample_events
1040	2013-06-27	2018-07-05	5.021	6
1060	2013-06-27	2018-07-05	5.021	6
1080	2013-06-27	2018-07-05	5.021	6
2020	2013-06-25	2014-06-27	1.005	2
2040	2013-06-25	2018-07-02	5.018	6
2060	2013-06-25	2018-07-02	5.018	6
2080	2013-06-25	2018-07-02	5.018	6
3020	2013-06-26	2018-07-03	5.018	6
3040	2013-06-26	2018-07-03	5.018	6
3060	2013-07-01	2018-07-03	5.005	6
3080	2013-06-26	2018-07-03	5.018	6

Cumulative Change Snapshot

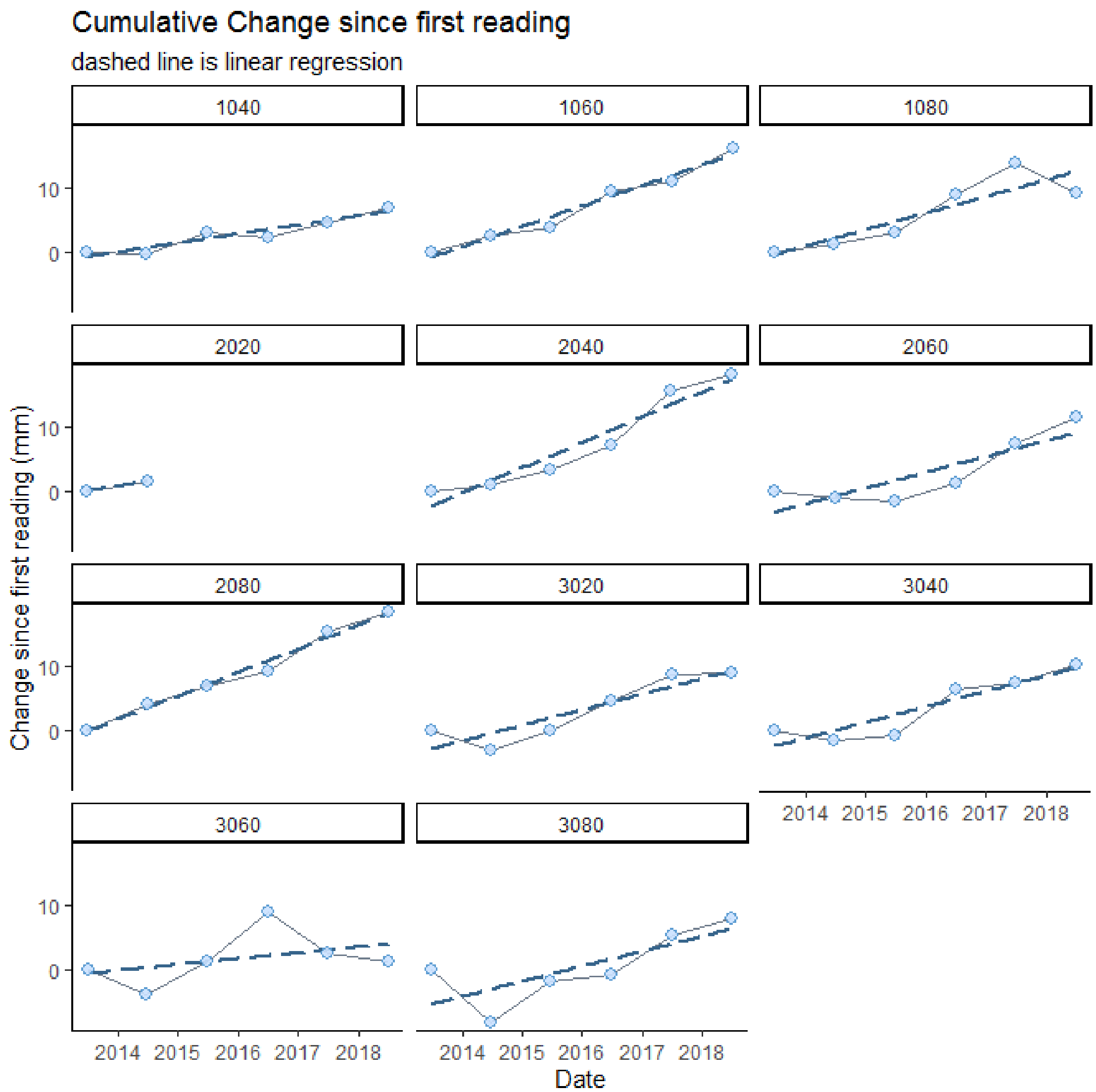
Take a look at your overall change since the first reading - make sure the change looks generally linear, and make sure there are no big breaks in the data that could influence the outputs. Output will be generated even if it is not appropriate - **it is up to you to use discretion and make sure a linear model is appropriate for the data!**

In the graphics below, the first (baseline) measurement for each pin was subtracted from every subsequent reading, to yield change-since-baseline at a pin level, for all dates. Then pins on an arm were averaged together for each date to yield change-since-baseline at the arm level. Finally, the arms for each date were averaged together to yield change-since-baseline for the SET as a whole. This is a slightly different approach than the rate calculations performed below but gives an almost identical point estimate for rate of change, and makes it easy to put change since baseline on a plot.



The above graph is saved as:
R_output/figures/cumu_change_plots/cumu_change_noLine.png

Graphs for each SET individually are not shown here but have been saved in *R_output/figures/cumu_change_plots/individual_sets*



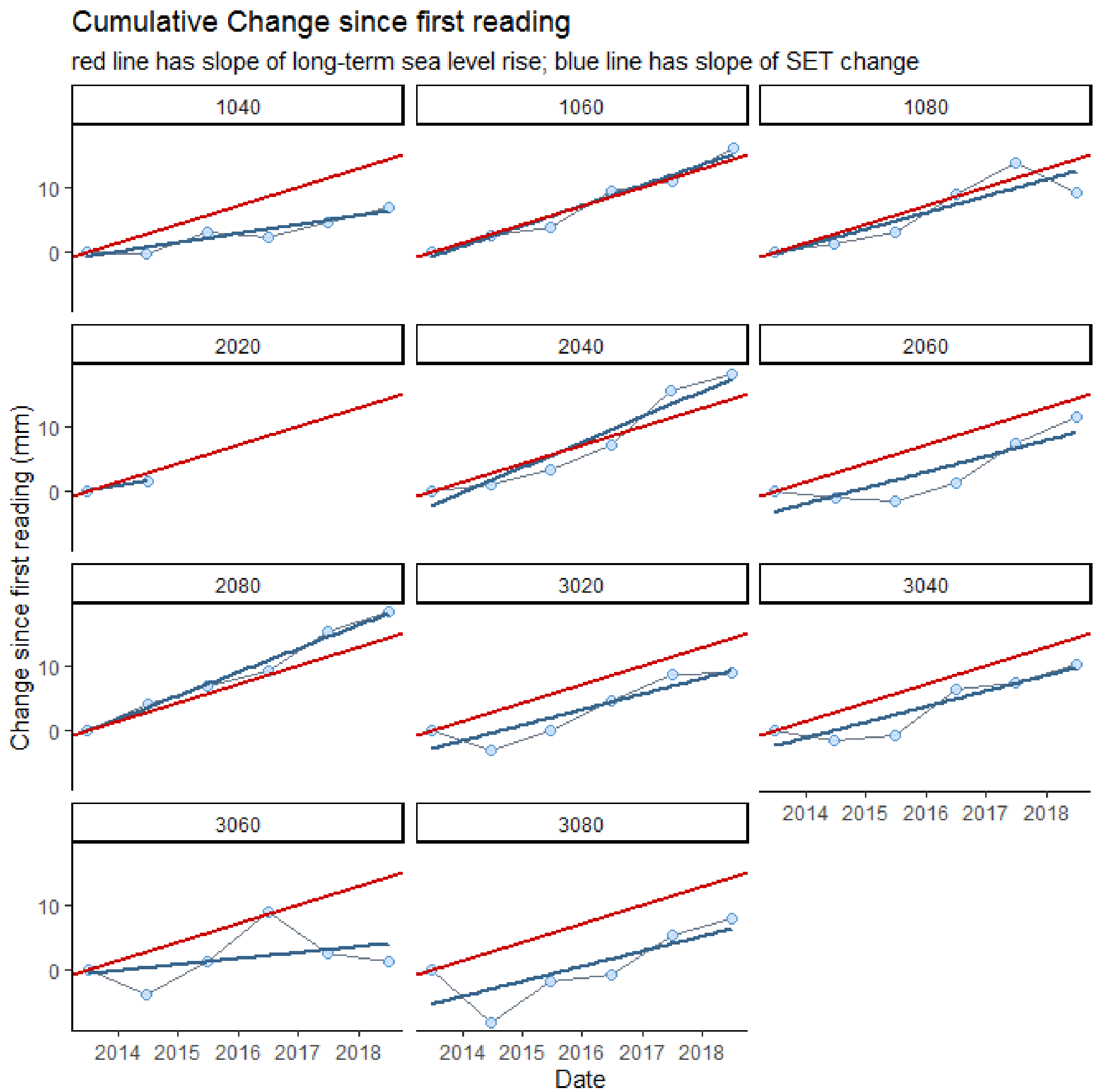
The above graph is saved as:
R_output/figures/cumu_change_plots/cumu_change_withLine.png

Graphs for each SET individually are not shown here but have been saved in *R_output/figures/cumu_change_plots/individual_sets*

Plus Sea Level Rise Line

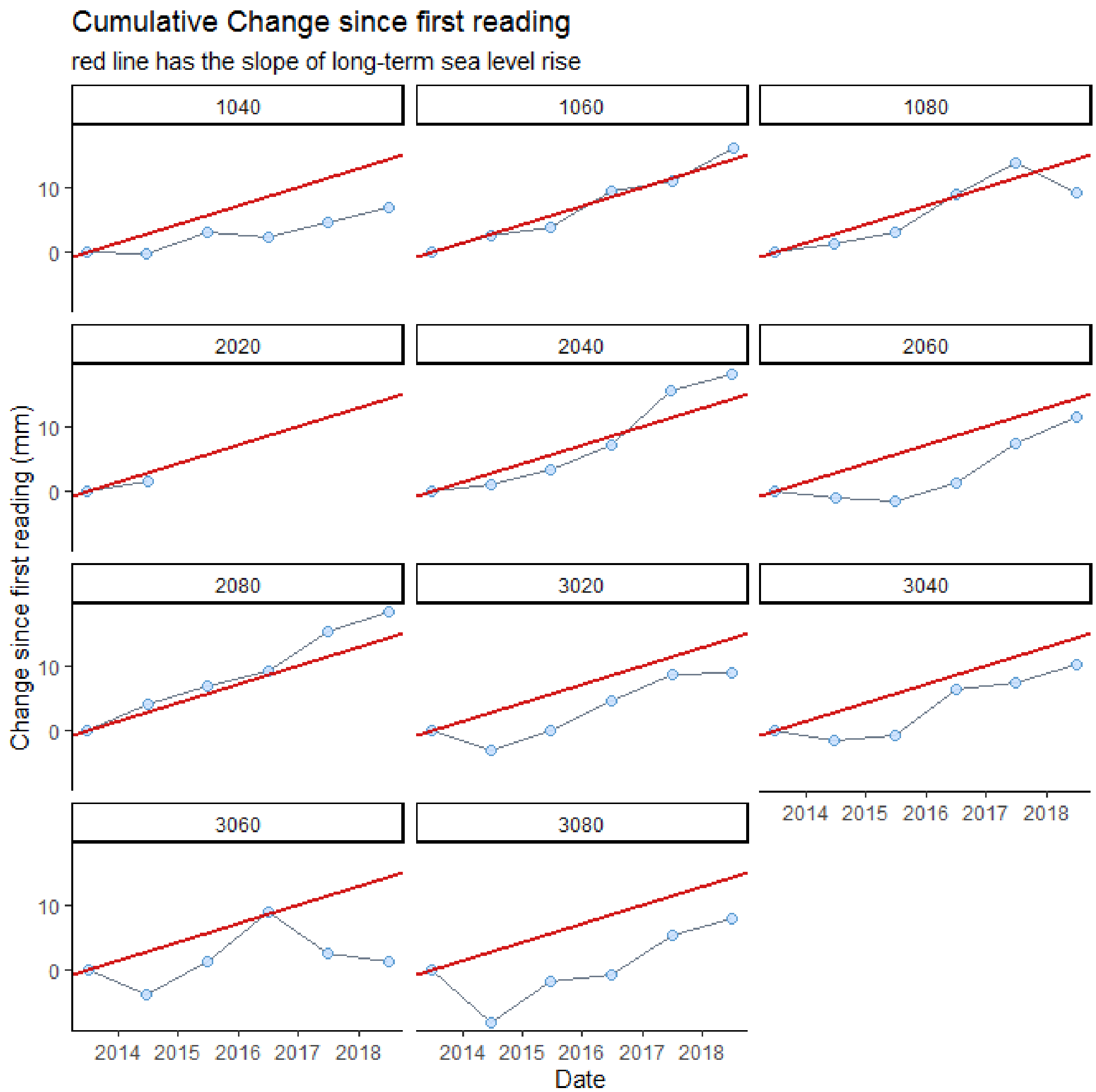
This is an oversimplification of sea level rise: the slope is that of long-term, local SLR, calculated by NOAA COOPS at the NWLON station closest to the reserve. This line does not account for accelerating sea level rise or site-specific processes, and these graphs do not include actual water level data.

These graphs are meant to illustrate and provide context for SET elevation change relative to long-term SLR.



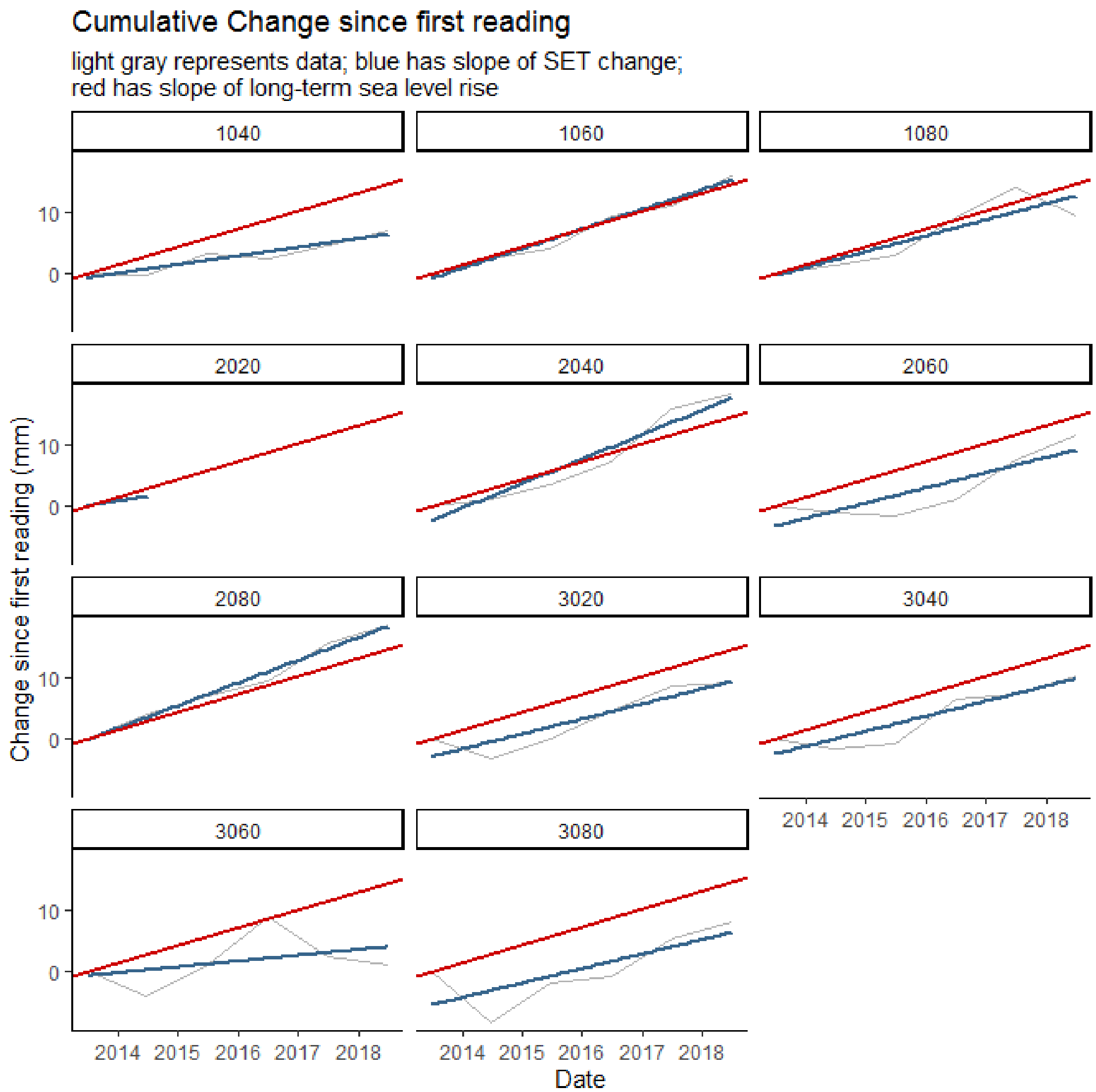
The above graph is saved as:
R_output/figures/cumu_change_plots/cumu_change_withLineAndSLR.png

Graphs for each SET individually are not shown here but have been saved in *R_output/figures/cumu_change_plots/individual_sets*



The above graph is saved as:
R_output/figures/cumu_change_plots/cumu_change_withSLR.png

Graphs for each SET individually are not shown here but have been saved in *R_output/figures/cumu_change_plots/individual_sets*



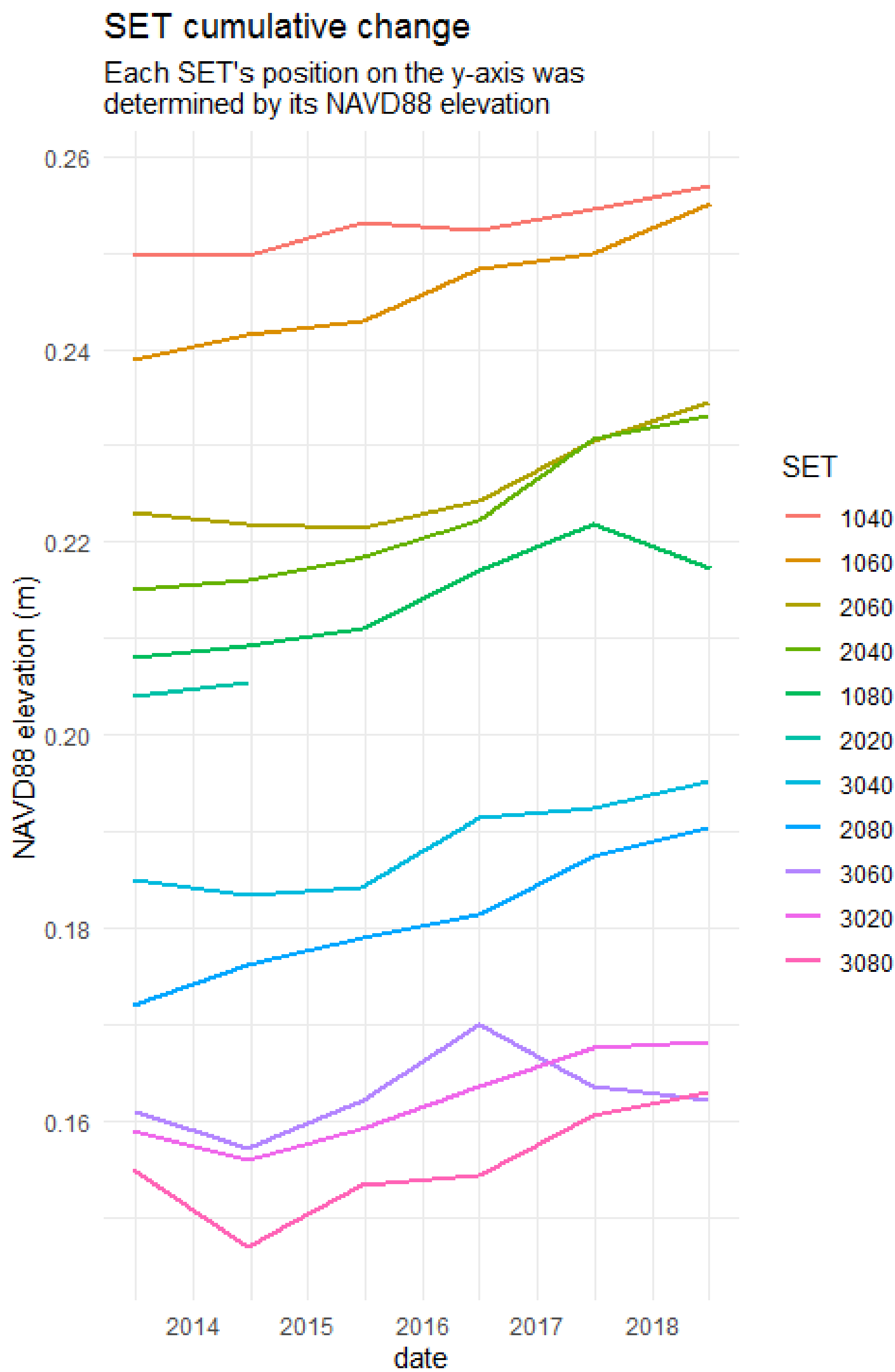
The above graph is saved as:
R_output/figures/cumu_change_plots/cumu_change_linesOnly.png

Graphs for each SET individually are not shown here but have been saved in *R_output/figures/cumu_change_plots/individual_sets*

Cumulative change along the elevation gradient

The following graph shows cumulative elevation change at all SETs in one graph panel. If NAVD88 information was present in metadata, the first reading at each SET was placed at that point on the y-axis. Otherwise, the SET cumulative change lines start at 0.

Available elevation information varied between reserves in this project; **this graph is meant to show changes along a relative elevation gradient only.** We have not overlaid water levels because we could not always be sure of the appropriate offset.



The above graph is saved as:
R_output/figures/cumu_change_plots/cumu_change_NAVD88.png

Rate Calculations

From this point on, **only SETs with 5 or more measurements over 4.5 or more years will be analyzed.** If you do not have any SETs that have been measured for this amount of time, you will NOT see analyses or graphs below.

SETs that are included in the following analyses

```
## 1040, 1060, 1080, 2040, 2060, 2080, 3020, 3040, 3060, 3080
```

SETs that are not included in analyses

```
## 2020
```

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 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.

General recommendations on analysis of SET data

- Before analysis, the analyst should carefully examine plots of the data to ensure that a linear model is appropriate. *If the points exhibit curvature or if there is some sort of a changepoint, this type of analysis may not be appropriate.* Graphs are provided in this report to help with this determination.

- The analyst should also look for highly influential observations. One way that this could occur is when there is a *large temporal gap* in the data.

- Be aware that, though we have done our best to appropriately describe uncertainty in the following rate calculations, the analyses below do not account for *temporal* *dependence* in the data. This could mean that confidence intervals are narrower than they should be and may be something the analyst wishes to address in future analyses.

- The analyst should employ a statistically valid model fitting strategy. When using Linear Mixed Models (LMMs), as we do below, this should also include addressing issues such as:
  - ensuring convergence of the numerical optimization
  - exploring sensitivity to starting values in the optimization procedure
  - determining whether a random slope model or a random slope/random intercept model is most appropriate, and
  - verifying model assumptions.

Statistical details of this analysis

For this analysis, models were fit in R, using the `lme()` function in the `nlme` package (Pinheiro et al. 2019). Confidence intervals were generated using the `intervals()` function, also in the `nlme` package.

Variable names within each SET were:

- **response variable:** pin_height
- **fixed effect:** date
- **random effects:** arm_position, pin_number (with pin_number nested in arm_position)

All calculations generated output in *mm/day* and these rates were converted to *mm/yr* by multiplying by 365.25, to account for leap years.

Calculated rates of elevation change

reserve	set_id	rate	CI_low	CI_high
WQB	1040	1.444	1.014	1.875
WQB	1060	3.169	2.721	3.617
WQB	1080	2.566	2.117	3.015
WQB	2040	3.946	3.659	4.234
WQB	2060	2.442	1.915	2.969
WQB	2080	3.646	3.384	3.907
WQB	3020	2.422	1.886	2.959
WQB	3040	2.423	2.077	2.769

reserve	set_id	rate	CI_low	CI_high
WQB	3060	0.935	0.146	1.723
WQB	3080	2.279	1.516	3.042

Additional model diagnostics

reserve	set_id	sigma	AIC	BIC	logLik
WQB	1040	5.468	1441.398	1458.205	-715.699
WQB	1060	5.720	1481.939	1498.769	-735.969
WQB	1080	5.737	1451.112	1467.942	-720.556
WQB	2040	3.664	1255.286	1272.116	-622.643
WQB	2060	6.686	1507.648	1524.454	-748.824
WQB	2080	3.339	1241.746	1258.576	-615.873
WQB	3020	6.854	1557.845	1574.675	-773.922
WQB	3040	4.423	1324.574	1341.404	-657.287
WQB	3060	10.054	1670.777	1687.607	-830.389
WQB	3080	9.723	1691.196	1708.002	-840.598

Comparisons to 0 and SLR

In the following tables and graphics, rates of elevation change at each SET are compared to rates of water level change (SLR = long-term sea level rise; 19yr = water level change over a 19 year period) by investigating whether confidence intervals overlap. 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).

For comparisons to 0, if the SET's 95% CI does not include 0, this *is* equivalent to a formal hypothesis test. For consistency, we are using the same terminology, involving overlapping CIs for all comparisons.

Overall Summary Table

In this table, the SETs are ordered by their rate of change, from lowest at the top to highest at the bottom. The rate and 95% CI (all in mm/yr) for each SET are provided. The last 6 columns show comparisons to: zero (is elevation at the SET changing?), long-term SLR, and 19-year water level change. Each comparison takes up two columns: a comparison of point estimates (is the SET rate higher or lower than what it is compared to), and whether or not the confidence intervals overlap.

SET	Rate	95% CI		Compared to 0		Compared to SLR		Compared to 19-yr change	
	mm/yr	lower	upper	point	CI overlap?	point	CI overlap?	point	CI overlap?
3060	0.935	0.146	1.723	higher	no	lower	no	lower	no
1040	1.444	1.014	1.875	higher	no	lower	no	lower	no
3080	2.279	1.516	3.042	higher	no	lower	yes	lower	yes
3020	2.422	1.886	2.959	higher	no	lower	yes	lower	yes
3040	2.423	2.077	2.769	higher	no	lower	yes	lower	yes
2060	2.442	1.915	2.969	higher	no	lower	yes	lower	yes
1080	2.566	2.117	3.015	higher	no	lower	yes	lower	yes
1060	3.169	2.721	3.617	higher	no	higher	yes	lower	yes
2080	3.646	3.384	3.907	higher	no	higher	no	lower	yes
2040	3.946	3.659	4.234	higher	no	higher	no	lower	yes

Increasing/Decreasing (Comparison to 0)

The following tables break the SETs into groups where the rate of SET elevation change is *lower than* / *higher than* / *not different from* 0. *Lower than* and *higher than* tables imply that the 95% confidence intervals for the SET's rate of elevation change do not include 0. *Not different from* means that 0 *is* included.

SET Elevation Change < 0 mm/yr

reserve	set_id	rate	CI_low	CI_high

SET Elevation Change > 0 mm/yr

reserve	set_id	rate	CI_low	CI_high
WQB	1040	1.444	1.014	1.875
WQB	1060	3.169	2.721	3.617

reserve	set_id	rate	CI_low	CI_high
WQB	1080	2.566	2.117	3.015
WQB	2040	3.946	3.659	4.234
WQB	2060	2.442	1.915	2.969
WQB	2080	3.646	3.384	3.907
WQB	3020	2.422	1.886	2.959
WQB	3040	2.423	2.077	2.769
WQB	3060	0.935	0.146	1.723
WQB	3080	2.279	1.516	3.042

SET Elevation Change 95% CI Includes 0 mm/yr

reserve	set_id	rate	CI_low	CI_high

Sea Level Rise Comparisons

Period of Record (long-term SLR)

The long-term local rate of sea level rise is **2.86 +/- 0.17 mm/yr** .

This rate is reported by Woods Hole, Massachusetts, NWLON station number 8447930 based on data from *1932* to *2017*.

The following tables break the SETs into groups where the rate of SET elevation change is *lower than* / *higher than* / *not different from* this SLR rate. *Lower than* and *higher than* tables imply that 95% confidence intervals do not overlap between the SET and SLR. *Not different from* means that confidence intervals *do* overlap.

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).

SET Elevation Change < SLR; CIs don't overlap

reserve	set_id	rate	CI_low	CI_high
WQB	1040	1.444	1.014	1.875
WQB	3060	0.935	0.146	1.723

SET Elevation Change > SLR; CIs don't overlap

reserve	set_id	rate	CI_low	CI_high
WQB	2040	3.946	3.659	4.234
WQB	2080	3.646	3.384	3.907

SET Elevation Change and SLR CIs overlap

reserve	set_id	rate	CI_low	CI_high
WQB	1060	3.169	2.721	3.617
WQB	1080	2.566	2.117	3.015
WQB	2060	2.442	1.915	2.969
WQB	3020	2.422	1.886	2.959
WQB	3040	2.423	2.077	2.769
WQB	3080	2.279	1.516	3.042

19-year water level change

The local, 19-year rate of water level change is **4.32 +/- 1.56 mm/yr** .

This rate uses data reported by Woods Hole, Massachusetts, NWLON station number 8447930 based on data from *1998* to *2017*.

The following tables break the SETs into groups where the rate of SET elevation change is *lower than* / *higher than* / *not different from* this 19-year rate. *Lower than* and *higher than* tables imply that 95% confidence intervals do not overlap between the SET and water level change. *Not different from* means that confidence intervals *do* overlap.

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).

SET Elevation Change < 19-year water level change; CIs don't overlap

reserve	set_id	rate	CI_low	CI_high
WQB	1040	1.444	1.014	1.875
WQB	3060	0.935	0.146	1.723

SET Elevation Change > 19-year water level change; CIs don't overlap

reserve	set_id	rate	CI_low	CI_high

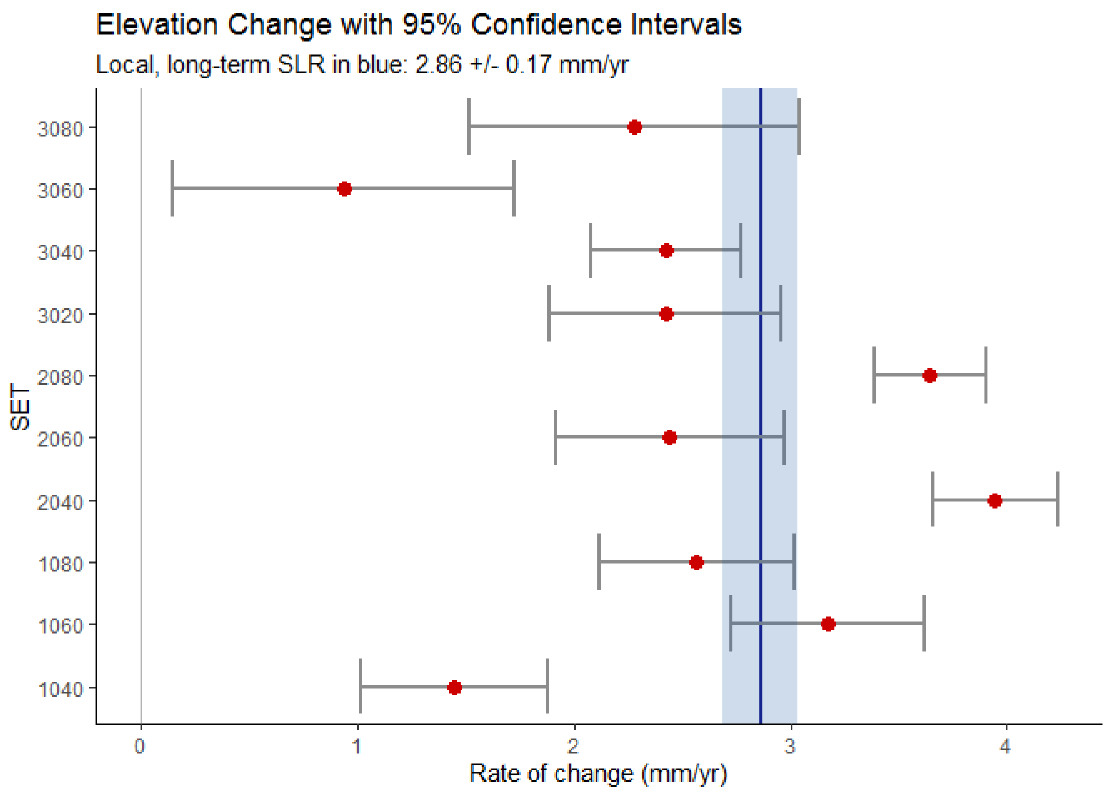
SET Elevation Change and 19-year water level change CIs overlap

reserve	set_id	rate	CI_low	CI_high
WQB	1060	3.169	2.721	3.617
WQB	1080	2.566	2.117	3.015
WQB	2040	3.946	3.659	4.234
WQB	2060	2.442	1.915	2.969
WQB	2080	3.646	3.384	3.907
WQB	3020	2.422	1.886	2.959
WQB	3040	2.423	2.077	2.769
WQB	3080	2.279	1.516	3.042

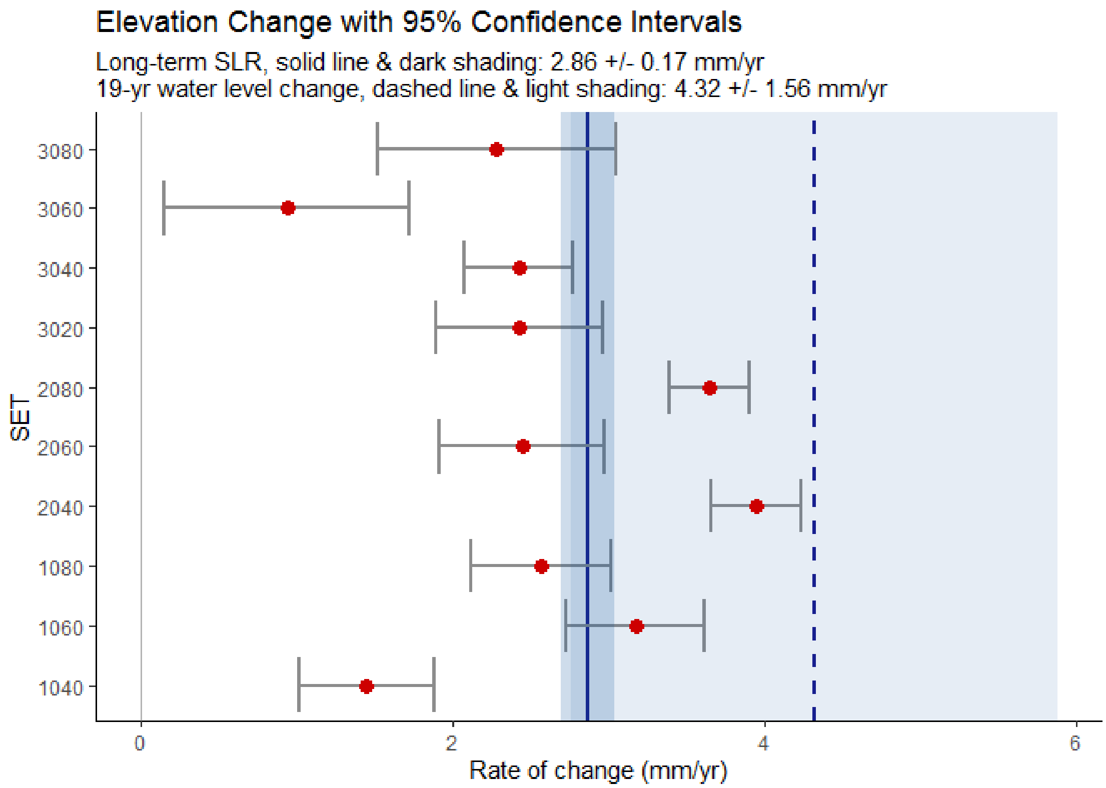
Graphical Comparisons to Sea Level Rise and 0

If dominant vegetation was provided in the metadata document, the following graphs will be provided both with and without points colored by vegetation type. If any vegetation entries were missing, the vegetation point-coloration will NOT be provided. You can generate them by adding vegetation to the "CoDominant Species 1" column of the `---set_metadata.xlsx` document.

Sites in alphabetical order, R's default



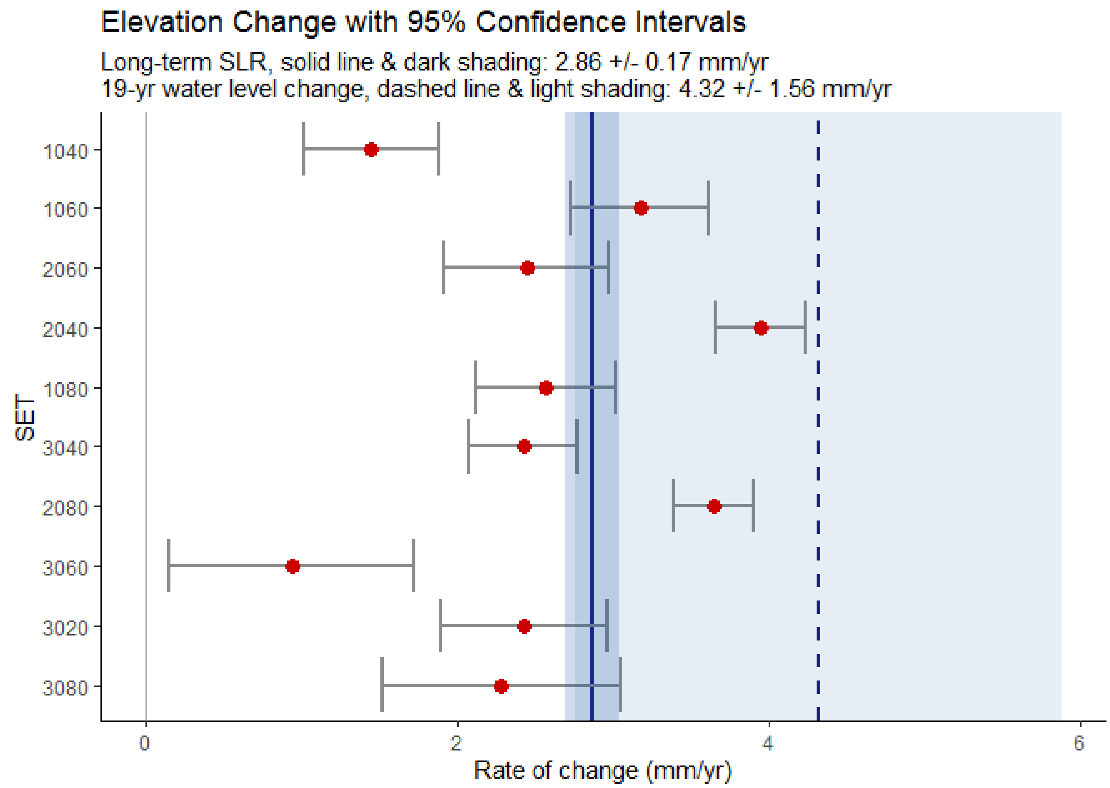

```
## The above graph is saved as:  R_output/figures/summary_plots/summary_plot.png

## The above graph is saved as:  R_output/figures/summary_plots/summary_plot_veg.png
```



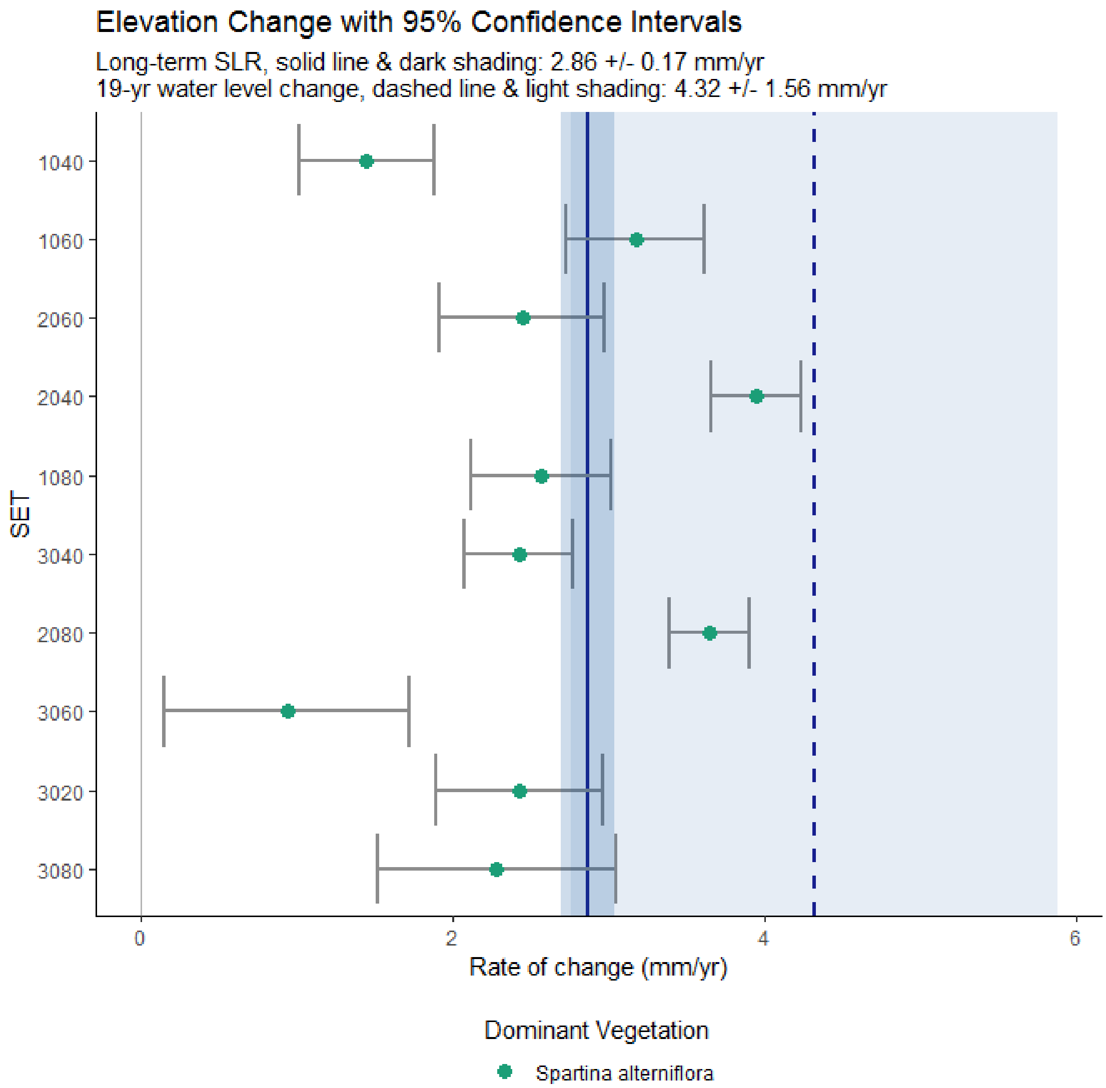

```
## The above graph is saved as:  R_output/figures/summary_plots/summary_plot_bothSLRs.png

## The above graph is saved as:  R_output/figures/summary_plots/summary_plot_veg_19yr.png
```

Ordered (categorically) by NAVD88 elevation

If NAVD88 elevations were provided in the metadata, two more versions of the graph above are produced below. The SETs are ordered along the y-axis from highest to lowest elevation.




```
## The above graph is saved as:  R_output/figures/summary_plots/summary_plot_bothSLRs_navd88ordering.png
```




```
## The above graph is saved as:  R_output/figures/summary_plots/summary_plot_bothSLRs_navd88ordering_veg.png
```

Sites by a user-specified order

If the `numerical_order` column of the metadata was filled out, the order of SETs in the graphics below will be in that order, as well as labeled with user-friendly names. Note that no plot will be produced if there are any NAs (missing values) in the metadata fields `numerical_order` or `user_friendly_set_name`.

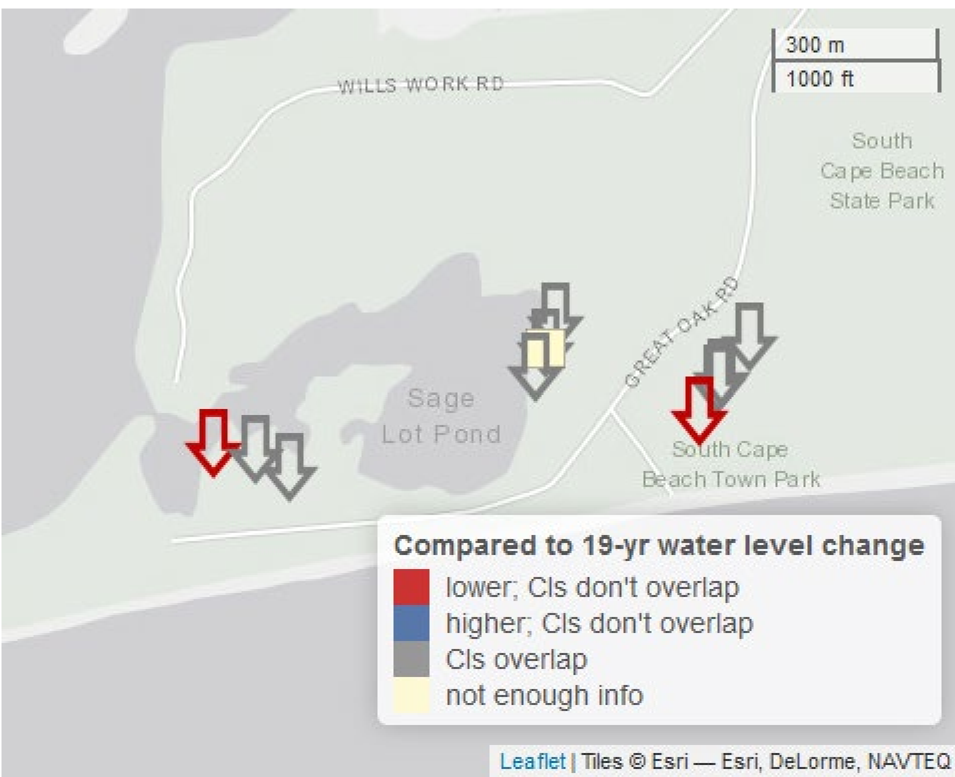
MAPS

The way the maps are rendered below (and even *if* they are rendered) depends on several things specific to your computer. The script `R_scripts/04_interact_maps.R` will let you interact with the maps, and you can either take a screenshot or use the `Export` command from RStudio's Viewer pane to save a version that looks better. Even if no output was generated in this Word document, you should still be able to use the interactive script to generate maps.

Comparisons to 0

Comparisons to long-term SLR

Comparisons to 19-yr water level change



References

Cahoon, D.R., J.C. Lynch, C.T. Roman, J.P. Schmit, and D.E. Skidds. 2019. Evaluating the Relationship Among Wetland Vertical Development, Elevation Capital, Sea-Level Rise, and Tidal Marsh Sustainability. Estuaries and Coasts 42:1-15. https://doi.org/10.1007/s12237-018-0448-x

Pinheiro J, Bates D, DebRoy S, Sarkar D, R Core Team. 2019. *nlme: Linear and Nonlinear Mixed Effects Models*. R package version 3.1-140, https://CRAN.R-project.org/package=nlme

Schenker, N. and J.F. Gentleman. 2001. On Judging the Significance of Differences by Examining the Overlap Between Confidence Intervals. The American Statistician 55(3):182-186. https://doi.org/10.1198/000313001317097960

Zuur, A.F., E.N. Ieno, N.J. Walker, A.A. Saveliev, and G.M. Smith. 2009. Mixed effects models and extensions in ecology with R. New York: Springer.