Incorporating Sea Level Change Scenarios into Norfolk Harbor Channels Deepening and Elizabeth River Southern Branch Navigation Improvements Study

Final Report on the “hydrodynamic modeling”

to

Virginia Port Authority
101 W Main Street, Suite 600
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by

Zhuo Liu, Harry Wang, Joseph Zhang, and Fei Ye

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Virginia Institute of Marine Science
Department of Physical Sciences
Gloucester Point, Virginia 23062

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Table of Contents

List of Tables

List of Figures

Executive Summary

As described in Zhang et al. (2017), the Virginia Institute of Marine Science (VIMS) team has applied a 3D unstructured-grid hydrodynamic model SCHISM in the study of the impact of channel dredging on hydrodynamics in the lower Chesapeake Bay project area. This report is a companion report to that of Zhang et al. (2017) and focuses on the impact of channel dredging specifically under the projected future sea-level change (SLC) of 1 meter rise by 2100. This is an average of the high end of semi-empirical, global sea-level rise (SLR) projections adopted by the Virginia Port Authority (VPA) and the Army Corps of Engineers, Norfolk District, for the evaluation. From a tidal dynamics point of view, the 1-meter mean SLR increases the water depth in the channel and also increases the horizontal extent of the Bay water coverage. Essentially, tide is propagating in a deeper and wider channel under the SLR condition. As a result, the tidal amplitudes (and thus tidal range) are slightly decreased over most of the existing tidal region presumably due to the increased dissipation over the shallow water and newly inundated areas that compensate for the reduced dissipation in deep water. The tidal phase slightly leads the case without SLR because the propagation speed of the tide is slightly increased (due to the larger depth). The largest change of amplitude in M_2 component is about 0.1% of the post-dredged channel depth, and the largest change of the phase is about 0.78% for the N_2 tidal component. For the effect of SLR on the salinity, it is apparent that the salinity intrusion limit increases, and the surface and bottom salinities in all dredging conditions increase under SLR. The SLR has the largest impact in James River where the increases of surface and bottom salinity reach 2 and 2.5 PSU, respectively. The smallest changes near the project area are in the main stem of the lower Chesapeake Bay with ~ 0.6 PSU changes at both surface and bottom. The changes in the Elizabeth River are intermediate at 1.75 – 1.85 PSU for surface salinity and 1.85 – 2 PSU for bottom salinity. The inter-comparison of the net impacts on salinity strictly due to each individual dredging scenario (3-2S, 4-2S, and 5-2S) under SLR condition is also assessed by excluding the influence of base-2S. The results show that the impact is the largest under the combination of Norfolk Harbor and Elizabeth River dredging, followed by the dredging in Norfolk Harbor. The dredging in the Southern Branch alone has the least impact on the salinity, which is consistent with the results under the "without" SLC condition (Zhang et al., 2017).

1. Background

Based on long-term tidal records available from stations in Baltimore (Maryland), Washington DC, and Sewells Point (Virginia), the relative sea-level change (SLC) in the Chesapeake Bay is evident (Boon et al., 2008). The global sea-level rise (SLR) has been a persistent trend for decades, and is expected to continue beyond the end of this century, which will cause significant impact in the United States (US). A wide range of estimates for future global mean SLR is scattered throughout the scientific literature and other high profile assessments, such as the Intergovernmental Panel on Climate Change (IPCC). Scenarios do not predict future changes but describe future potential conditions in a manner that supports decision-making under conditions of uncertainty. Scenarios are used to develop and test decisions under a variety of plausible futures. This approach strengthens an organization's ability to recognize, adapt to, and take advantage of changes over time. In recent decades, the dominant contributors to global sea-level rise have been ocean warming (i.e. thermal expansion) and ice sheet loss. The relative magnitude of each of these factors in the future remains highly uncertain. Many previous studies, including that of the IPCC, assume thermal expansion to be the dominant contributor. However, the National Research recently reports that advances in satellite measurements indicate ice sheet loss as a greater contribution to global SLR than thermal expansion over the period of 1993 to 2008. There are four estimates of global SLR by 2100 that reflect different degrees of ocean warming and ice sheet loss (NOAA, 2012). In this study, the medium high scenario of 1 m SLR by 2100 is adopted as an average of the high end of semi-empirical, global SLR projections. Semi-empirical projections utilize statistical relationships between observed global sea level change, including recent ice sheet loss, and air temperature. This is consistent with SLC used by other studies (Hong and Shen, 2012; Yang and Wang, 2015). Section 2 describes the SCHISM model set-up for sea-level rise and observation data used for the baseline case. Section 3 details the scenarios development under different dredging conditions in Norfolk Harbor and the effects of SLC on water level and salinity changes. Section 4 provides the summary for the report.

2. SCHISM model set-up for sea level rise and observation data

In order to conduct a sea-level rise scenario, the model will need to be calibrated and validated first with the existing condition. The model is forced by USGS-measured flows from the 7 major tributaries of the Bay (Susquehanna, Patuxent, Potomac, Rappahannock, York, James, and Choptank Rivers). At the air-water interface, the model is forced by the wind, atmospheric pressure, and heat fluxes predicted by NARR (https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/north-american-regional-reanalysis-narr). At the outer ocean boundary, the elevation boundary condition (B.C.) is obtained from inverse-distance interpolated values from two tide gauges at Duck, NC and Lewes, DE. The salinity and temperature B.C.s are interpolated from HYCOM (hycom.org) and, in addition, a 20-km nudging zone near the ocean boundary is used where the salinity and temperature are relaxed to corresponding HYCOM values in order to prevent long-term drift, with a maximum relaxation period of 1 day. For model validation, we use NOAA tide and current data for the lower Bay (http://tidesandcurrents.noaa.gov), and salinity and temperature observations from the surveys conducted by EPA's Bay Program (http://www.chesapeakebay.net/data/downloads/cbp_water_quality_database_1984_present). Years 2010-2013 were chosen by the project team due to better availability of observational data. The stations used in model and data comparisons are shown in Figure 2 and Table 6.

From a numerical model point of view, the sea-level change (SLC) scenario can be executed either by increasing the given sea-level rise at the open boundary in the ocean or by increasing the existing bathymetric depth by the same amount across the model domain. The two approaches aforementioned are equivalent and should provide the same results when both of them reach the equilibrium state. However, for a large domain such as Chesapeake Bay and its continental shelf, the former approach will take some time to reach an equilibrium state of cyclo-stationary. On the other hand, the latter approach will reach an equilibrium state much faster and thus was adopted by this project. Based on the sea-level rise amount prescribed by VPA, the amount of sea-level rise is applied by adding 3.3 feet (1 m) in depth uniformly across the whole domain.

3. Sea level rise scenarios development and the results

3.1. Sea level rise scenario developments

Given that the Norfolk region has had a persistent sea level rise trend for decades (Boon et al., 2008), it is essential for the Harbor dredging environmental impact to address 'what if' under SLC conditions going into the future. Without SLC, the scenarios fall under 3-2 (future condition with deepened Norfolk Harbor Channel), 4-2 (future condition with deepened Southern Branch), and 5-2 (future condition with deepened Norfolk Harbor and Southern Branch). The 'Base 2S', '3-2S', '4-2S', and '5-2S' correspond to 3.3-feet SLC applied to 'Base 2', '3-2', '4-2', and '5-2', respectively. Scenarios '3-2','4-2' and '5-2' are based on Base 2 with the dredging located in different stretches of the ship channel. With SLC, the baseline condition will be base-2S, and the scenarios are: 3-2S, 4-2S, 5-2S. Table 1 describes all scenarios considered in this project. Of note, the scenario '5-2S' is essentially the combination of '3-2S' and '4-2S'.

Table 1: Description of simulation scenarios.

Runs	Scenarios	Description of Physical Scenarios	SLC Applied (feet)	NH Deepened	SB Deepened
9	Base 2S	Future without-project	3.3	No	No
10	3-2S	Future Conditions with deepened NH channel	3.3	Yes	No
11	4-2S	Future Conditions with deepened SB Channel	3.3	No	Yes
12	5-2S	Future Conditions with deepened NH & SB Channel	3.3	Yes	Yes

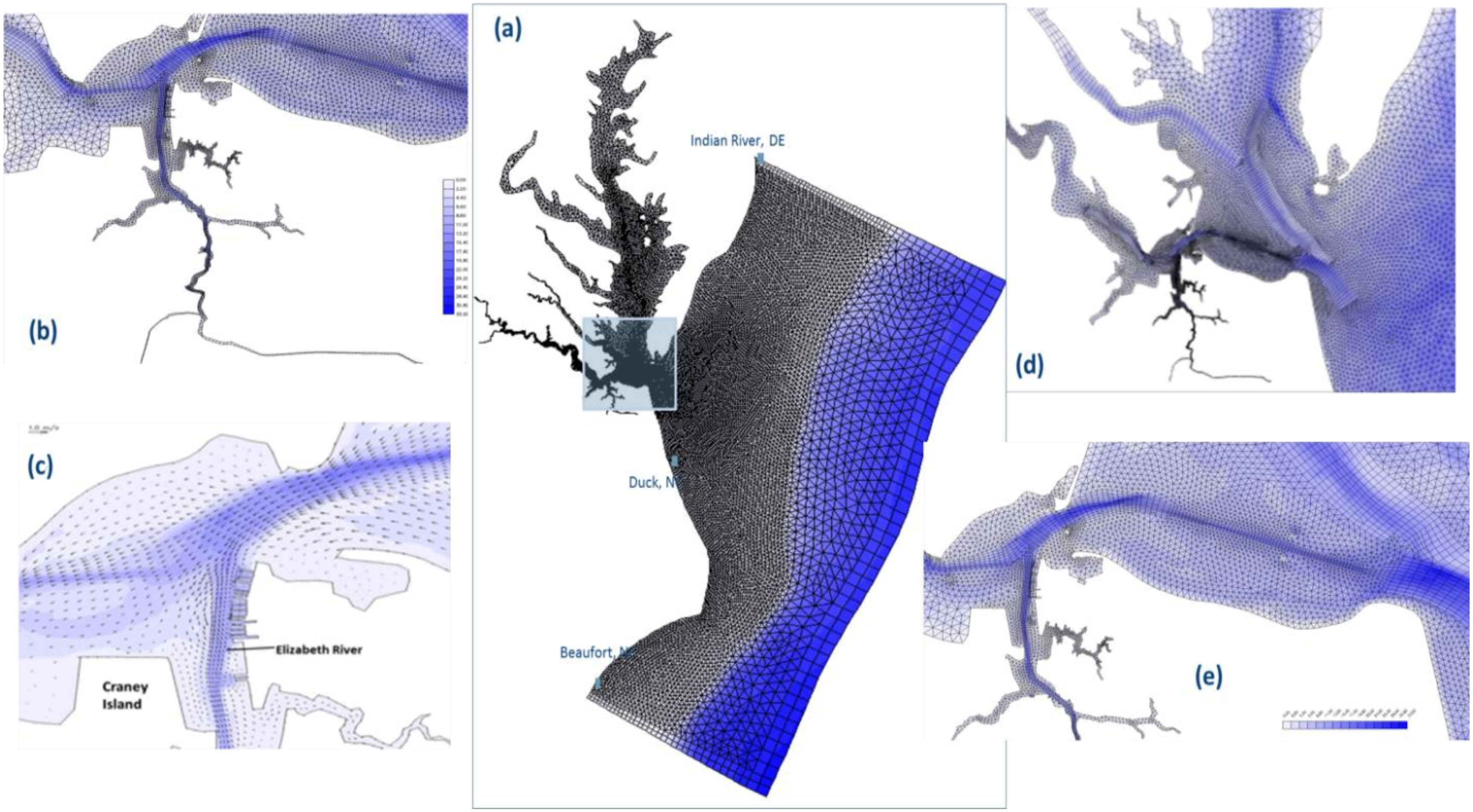


Figure 1: SCHISM grid for Chesapeake Bay and its adjacent shelf. (b-e) show zoom-in near Elizabeth River, mouth of Elizabeth River, lower Bay and James-Elizabeth Rivers, and Thimble Shoal respectively.

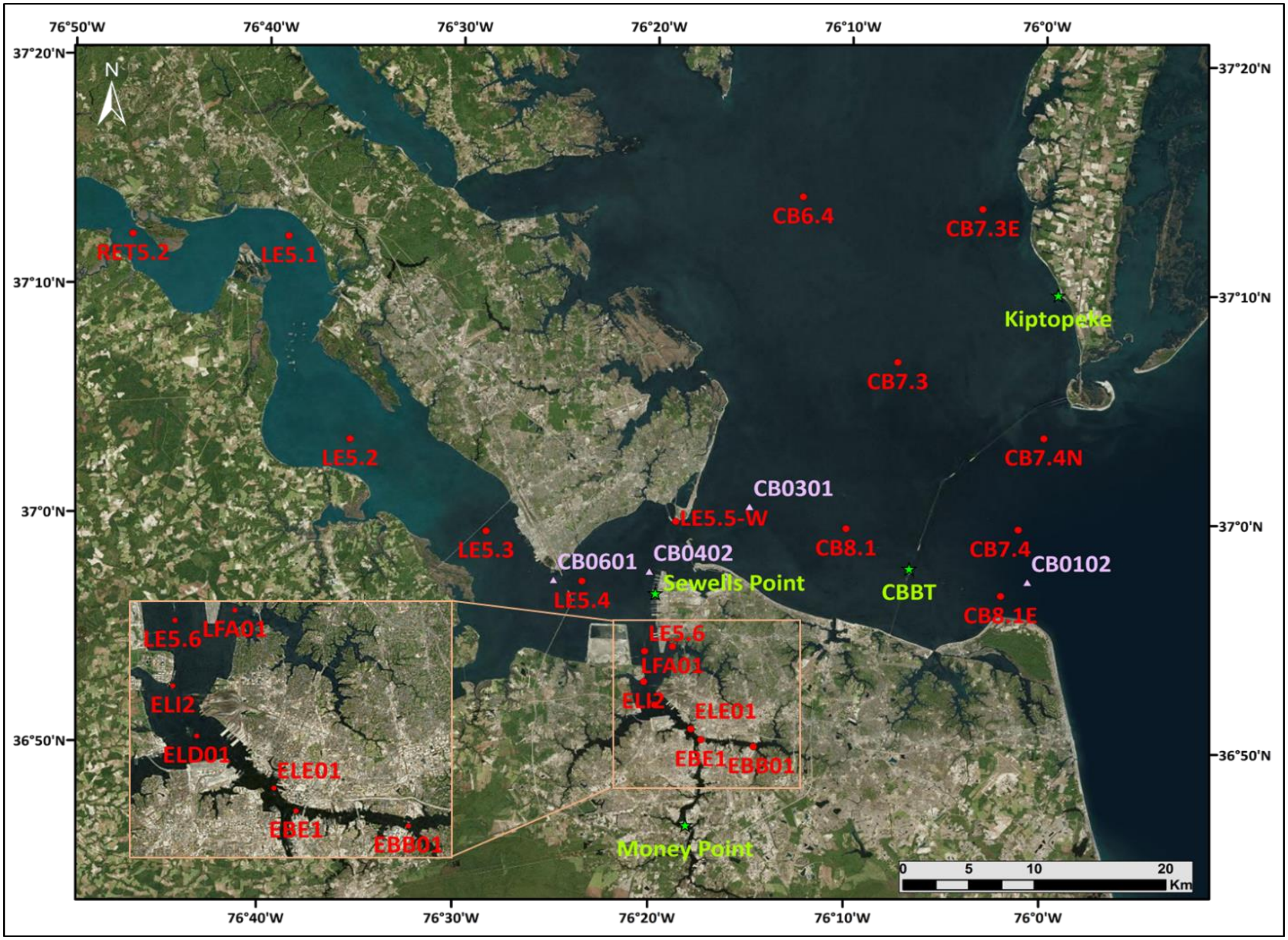


Figure 2: Observation stations used in this study. Red dots: salinity and temperature stations; Green stars: NOAA tidal gauges; Purple triangles: ADCP velocity profile measurement locations.

3.2. The results

3.2.1. Effect of SLC on tidal dynamics

SLC refers to the change of the mean water level. When the mean water level is increased, the question is whether the tidal amplitude and phase will be affected. The comparisons of total water elevations at 4 stations between ‘scenarios w/ SLC’ (Base 2S, 3-2S, 4-2S, 5-2S) vs. ‘scenarios w/o SLC’ (‘Base 2’, ‘3-2’, ‘4-2’, ‘5-2’), respectively, are shown below in Fig. 3 – Fig. 6. The increase on total elevation at each station is as expected at 1m in all scenarios w/ SLC. Additional analysis of three major tidal harmonic constituents (M_2, N_2, and O_1) was also conducted. The differences in amplitude and phase between ‘scenarios w/ SLC’ and ‘scenarios w/o SLC’ are shown in Table 2 – Table 5. The SLC essentially makes the tide propagate in a deeper and wider channel and the increased dissipation over the shallow water and newly inundated areas that compensates for the reduced dissipation in deep water. As a result, the tidal amplitudes (and thus tidal range) are slightly decreased in most of the existing tidal region. In these tables, it can be seen across the board that the amplitude is reduced and the phase angle leads because of the faster propagation speed of the tide. This demonstrates that the numerical model catches the essences of the tidal change and the trends have the correct tendency. The difference, however, is small; for example, the change in the M_2 tide amplitude is on the order of 0.01 m, and the phase difference is usually less than 2.5 degrees. If one examines across different dredging conditions, the changes can be seen to be slightly larger when the channel is deeper. Examining Tables 2-5, it appears the worst condition for the amplitude change is 0.015 m, which is less than 0.1% of the deepest proposed channel depth. The worst phase change is 2.83 degrees (0.78%), which occurred in the N_2 component at Money Point inside the Southern Branch.

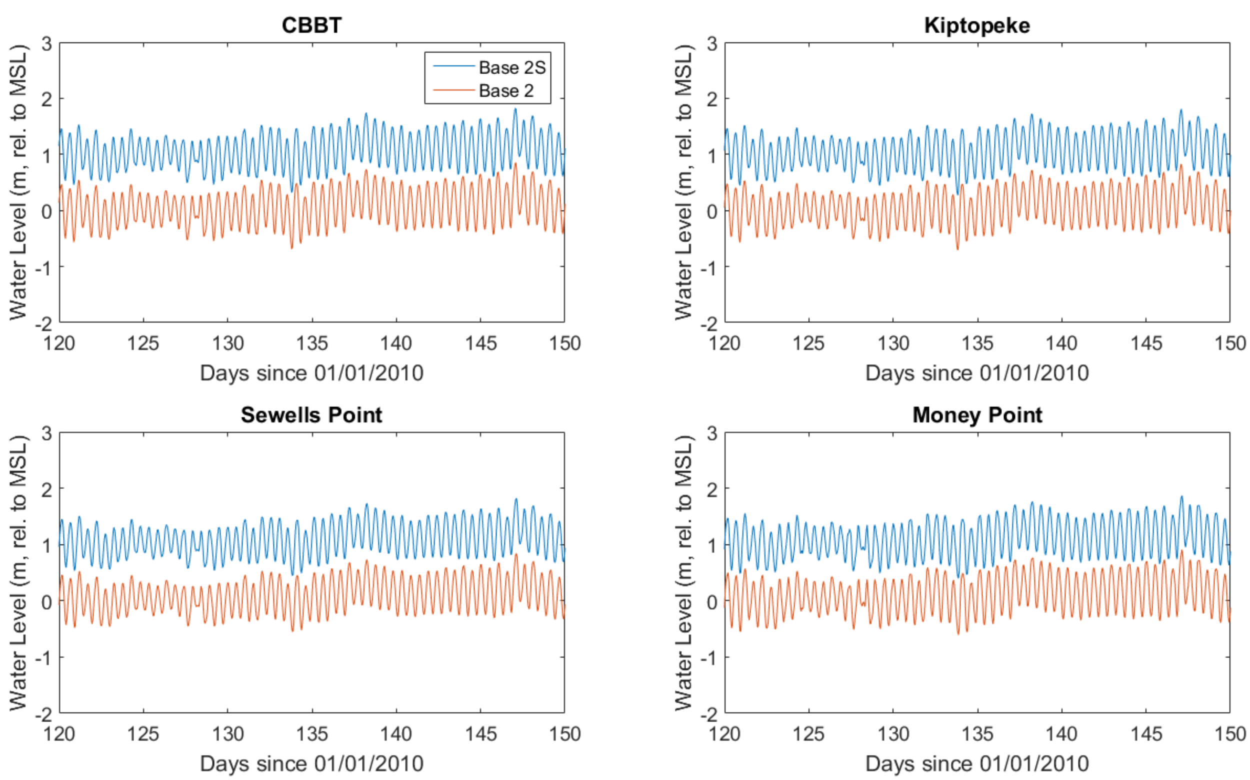


Figure 3: Comparisons of total elevations at 4 stations between 'Base 2S' and 'Base 2'.

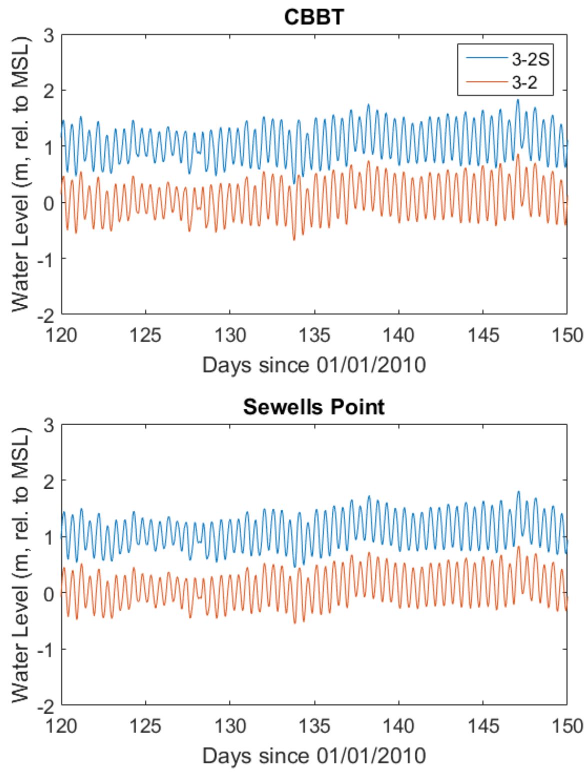


Figure 4: Comparisons of total elevations at 4 stations between '3-2S' and '3-2'.

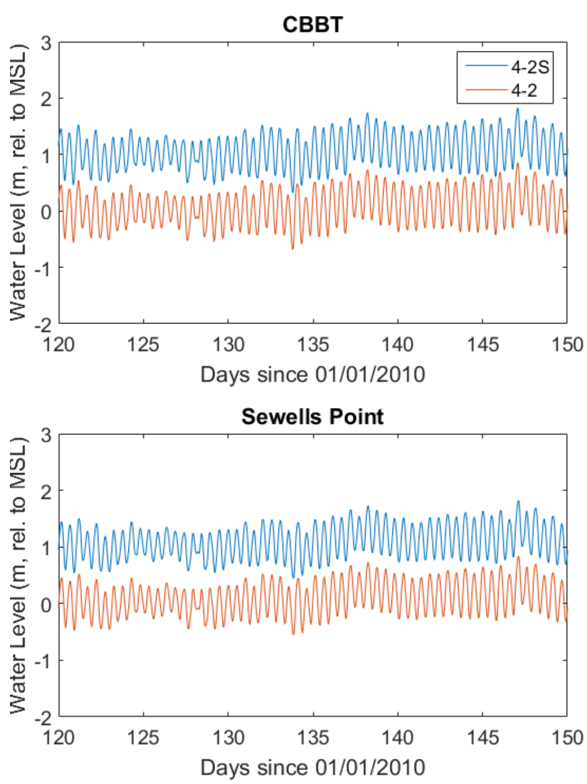


Figure 5: Comparisons of total elevations at 4 stations between '4-2S' and '4-2'.

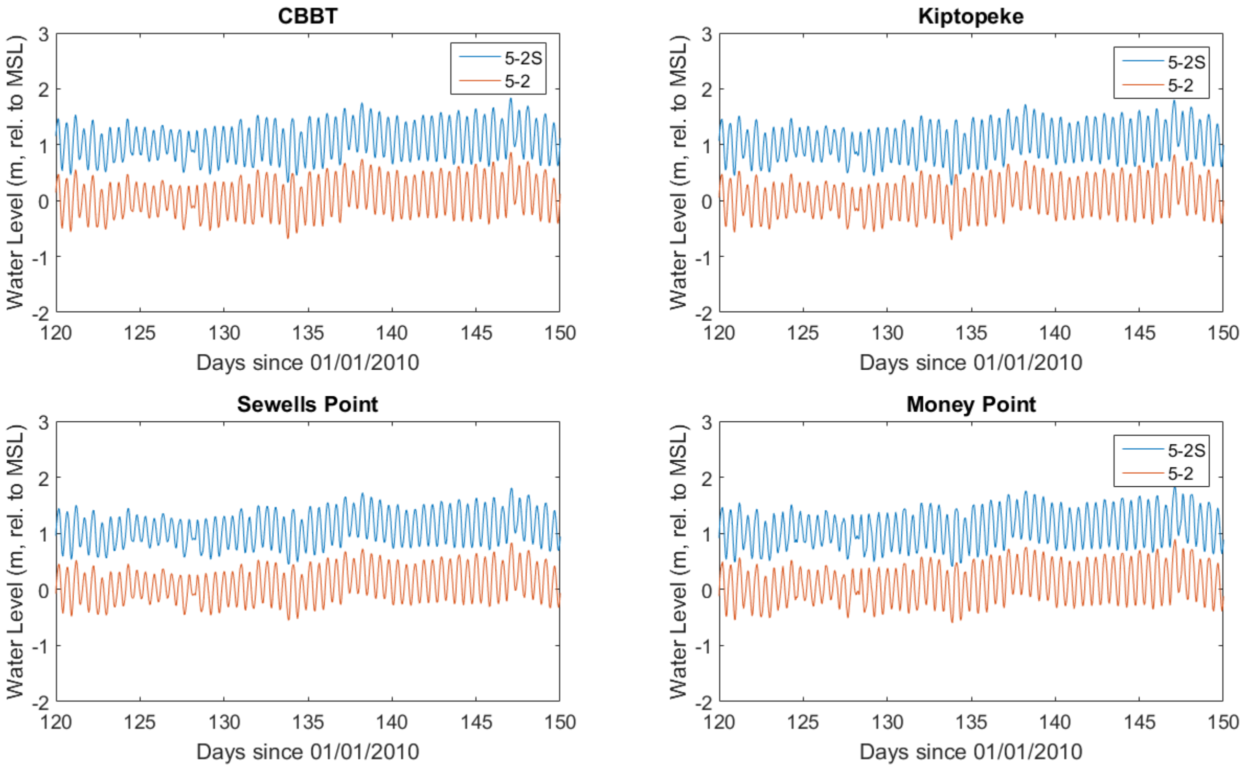


Figure 6: Comparisons of total elevations at 4 stations between '5-2S' and '5-2'.

Table 2: Differences in tidal harmonic constituents between 'Base2S' and 'Base2'

Differences in tidal harmonics: 'Base 2S' – 'Base 2'						
	M2		N2		O1	
	Amplitude (m)	Phase (degree)	Amplitude (m)	Phase (degree)	Amplitude (m)	Phase (degree)
CBBT	-0.014	-1.42	-0.003	-1.40	-0.001	-0.32
Kiptopeke	-0.009	-1.36	-0.001	-1.47	0.001	0.57
Sewells Pt	-0.007	-2.40	-0.001	-2.34	0.001	-1.78
Money Pt	-0.015	-2.69	-0.002	-2.83	-0.001	-2.06

Table 3: Differences in tidal harmonic constituents between '3-2S' and '3-2'

Differences in tidal harmonics: '3-2S' – '3-2'						
	M2		N2		O1	
	Amplitude (m)	Phase (degree)	Amplitude (m)	Phase (degree)	Amplitude (m)	Phase (degree)
CBBT	-0.014	-1.42	-0.002	-1.39	-0.001	-0.30
Kiptopeke	-0.009	-1.37	-0.001	-1.52	0.001	0.52
Sewells Pt	-0.006	-2.41	-0.001	-2.27	0.001	-1.82
Money Pt	-0.015	-2.75	-0.002	-2.82	-0.001	-2.16

Table 4: Differences in tidal harmonic constituents between '4-2S' and '4-2'

Differences in tidal harmonics: '4-2S' – '4-2'						
	M2		N2		O1	
	Amplitude (m)	Phase (degree)	Amplitude (m)	Phase (degree)	Amplitude (m)	Phase (degree)
CBBT	-0.014	-1.42	-0.002	-1.39	-0.001	-0.32
Kiptopeke	-0.009	-1.37	-0.001	-1.48	0.001	0.57
Sewells Pt	-0.007	-2.40	-0.001	-2.34	0.001	-1.75
Money Pt	-0.015	-2.66	-0.002	-2.80	-0.001	-2.00

Table 5: Differences in tidal harmonic constituents between '5-2S' and '5-2'

Differences in tidal harmonics: '5-2S' – '5-2'						
	M2		N2		O1	
	Amplitude (m)	Phase (degree)	Amplitude (m)	Phase (degree)	Amplitude (m)	Phase (degree)
CBBT	-0.014	-1.42	-0.003	-1.38	-0.001	-0.28
Kiptopeke	-0.009	-1.38	-0.001	-1.50	0.001	0.53
Sewells Pt	-0.007	-2.41	-0.001	-2.27	0.001	-1.82
Money Pt	-0.015	-2.72	-0.002	-2.79	-0.001	-2.06

3.2.2 Effect of SLC on salinity

Salinity is a tracer of the seawater that is important for mixing and the dynamic pattern of the estuarine circulation via its influence on the density of brackish water. Concerns of salinity change due to SLC include salinity intrusion that affects drinking water supplies and freshwater habitat, alteration of the mixing and the transport processes that affect the bottom DO, and changes in the aquatic community composition and the pattern of the primary production in the ecosystem. As a general principle, due to SLR, more sea water will be available inside the Chesapeake Bay and, overall, the salinity will increase. The question is how the increase of salinity will be distributed in the Bay and along the tributaries.

The modeled simulated salinity was verified with the observation (see Zhang et al., 2017). Once calibrated and validated, the model is then used for scenarios with SLC and without SLC. To analyze the results in three dimensions, the averaged differences for bottom and surface salinity, both in plain view and also along channel transects are presented. We compare 'scenarios with SLC' (Base 2S, 3-2S, 4-2S, 5-2S) vs. 'scenarios without SLC' ('Base 2', '3-2', '4-2', '5-2') respectively, and the time average is performed from 2010-2013. Based on the results, it is apparent that salinity intrusion limit increased and both surface and bottom salinity in all scenarios increased when compared to the base without SLC. Most of larger salinity differences (2-3 PSU) occur near upstream of the estuary at the limit of salinity intrusion. The differences are smaller elsewhere (~ 1.5 PSU or less). In all scenarios, the bottom salinity exhibits more increase than does the surface salinity in moving upstream. For example, near the entrance of the Elizabeth River, the bottom salinity increases 1 PSU more than that of the surface salinity.

However, in most parts of the lower James River, the surface salinity increases as much as does the bottom salinity.

From comparisons in Fig. 7 – Fig. 10, we note that the salinity increases (either surface or bottom) under the SLC condition are mostly similar under each scenarios to those under scenarios without SLC. In the vicinity of the project area, ‘Base 2S’ and ‘4-2S’ generally have larger increases of salinity than do ‘3-2S’ and ‘5-2S’, but the average difference is only on the order of 0.1 PSU. So, the projected changes in ‘3-2S’ and ‘5-2S’ have minor “counter effects” against SLC condition. The salinity increases along 2 along-channel transects in the James and Elizabeth Rivers reveal that the gravitational circulation is generally enhanced with Sea Level Rise (Figs. 11-18). The impacts from SLC tend to be larger towards the upstream, as shown in the spatial patterns. Since the strength of the gravitational circulation is a function of freshwater inflow, seasonal variability is seen in all transects; this is especially obvious in Elizabeth River, where the largest increases of 2 PSU are found during freshets, which may have significant impact for water quality. The overall statistics of salinity changes in the 3 regions (Lower Bay, James River, and Elizabeth River) (Table 6) are presented by calculating the mean absolute difference of surface and bottom salinity under “with” and “without” SLC (Table 7). In general, SLC has the largest impacts in James River with increases in the surface and bottom salinity of 2 and 2.5 PSU, respectively. The lower Bay region experiences the smallest change of ~0.6 PSU at both surface and bottom. The changes in Elizabeth River are 1.75– 1.85 PSU for surface salinity and 1.85 – 2 PSU for bottom salinity. The impacts strictly due to each individual dredging scenario (3-2S, 4-2S, and 5-2S) under the SLC condition, with the influence of base-2S being excluded, are presented in Table 8. The results show that the impacts are the largest under the combination of Norfolk Harbor and Elizabeth dredging (‘5’), followed by the dredging in Norfolk Harbor. The dredging in the southern branch alone (‘4’) has the least impact on the salinity. This is consistent with the results under the “without” SLC condition (Zhang et al., 2017).

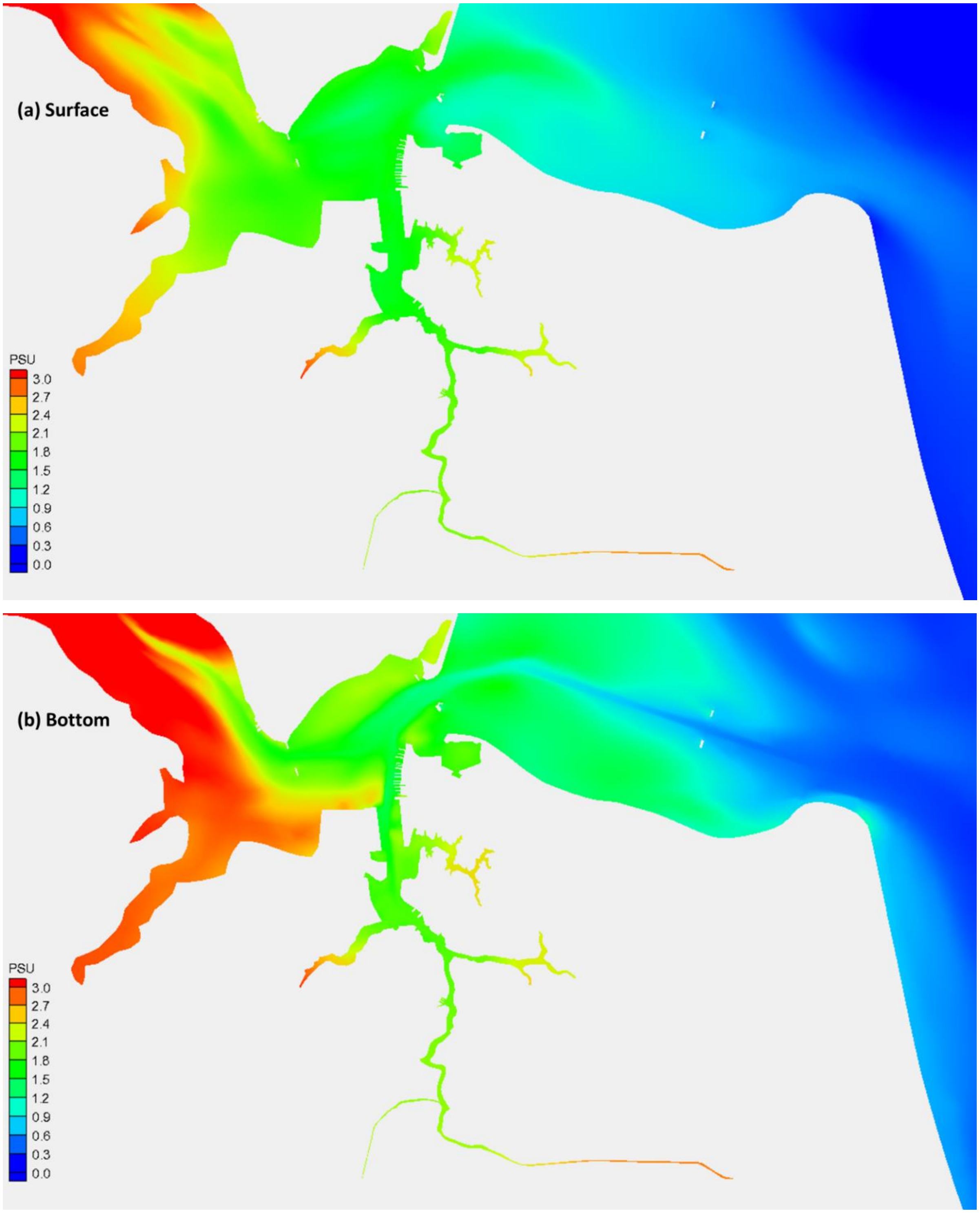


Figure 7: Time-averaged salinity differences (from 2010-2013) between Base 2S and Base 2 ('Base 2S' – 'Base 2') at (a) surface and (b) bottom.

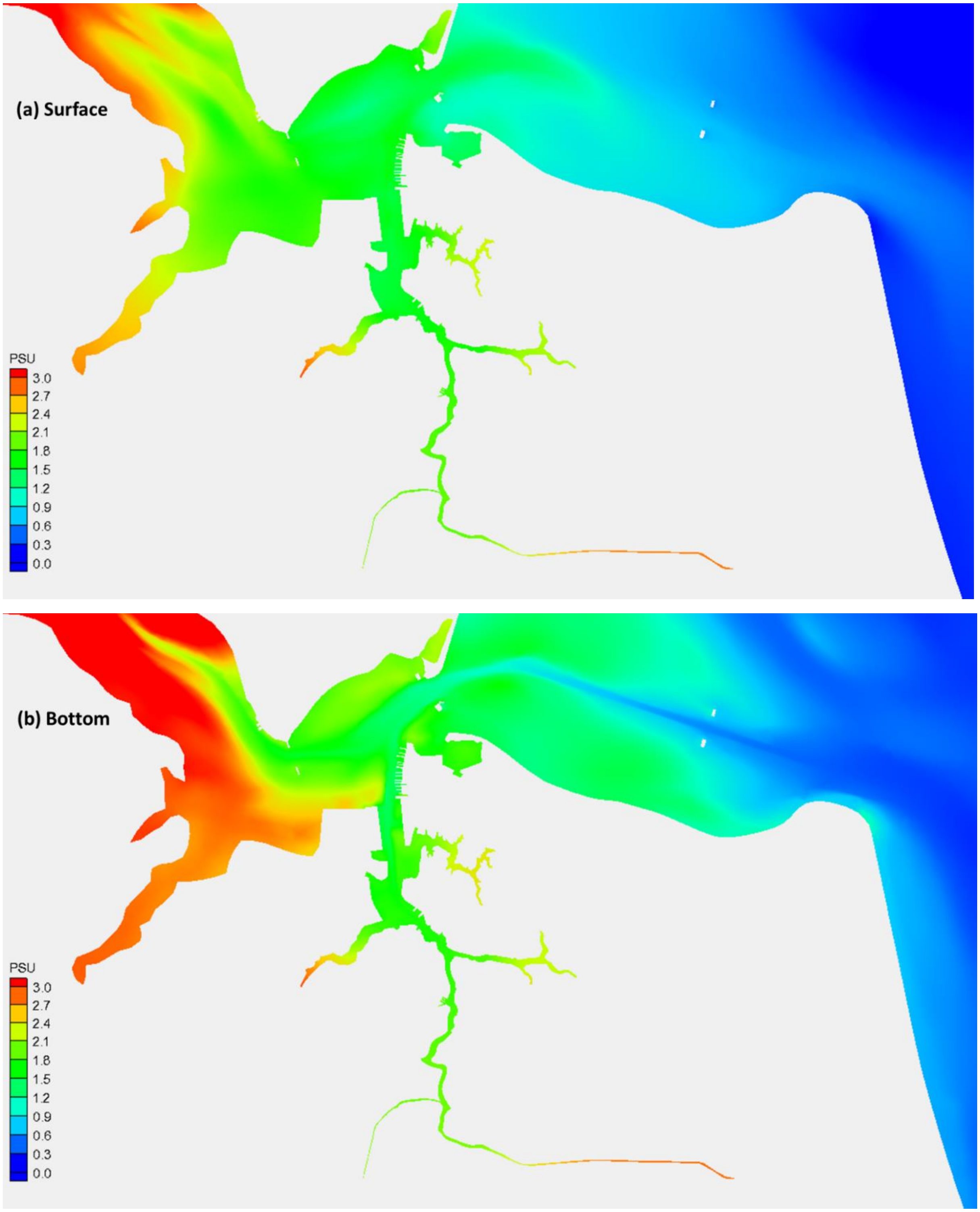


Figure 8: Time-averaged salinity differences (from 2010-2013) between 3-2S and 3-2 ('3-2S' – '3-2') at (a) surface and (b) bottom.

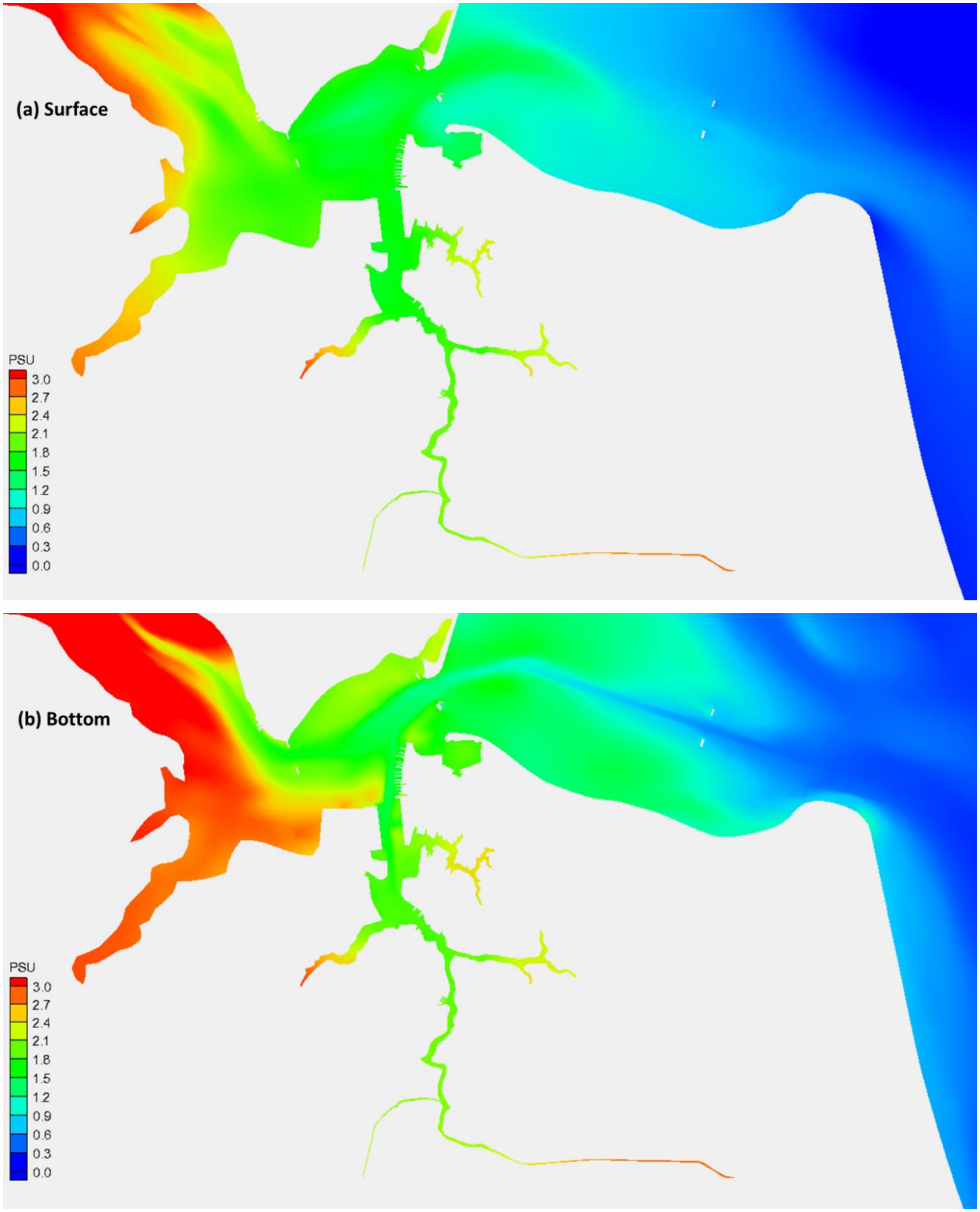


Figure 9: Time-averaged salinity differences (from 2010-2013) between 4-2S and 4-2 ('4-2S' – '4-2') at (a) surface and (b) bottom.

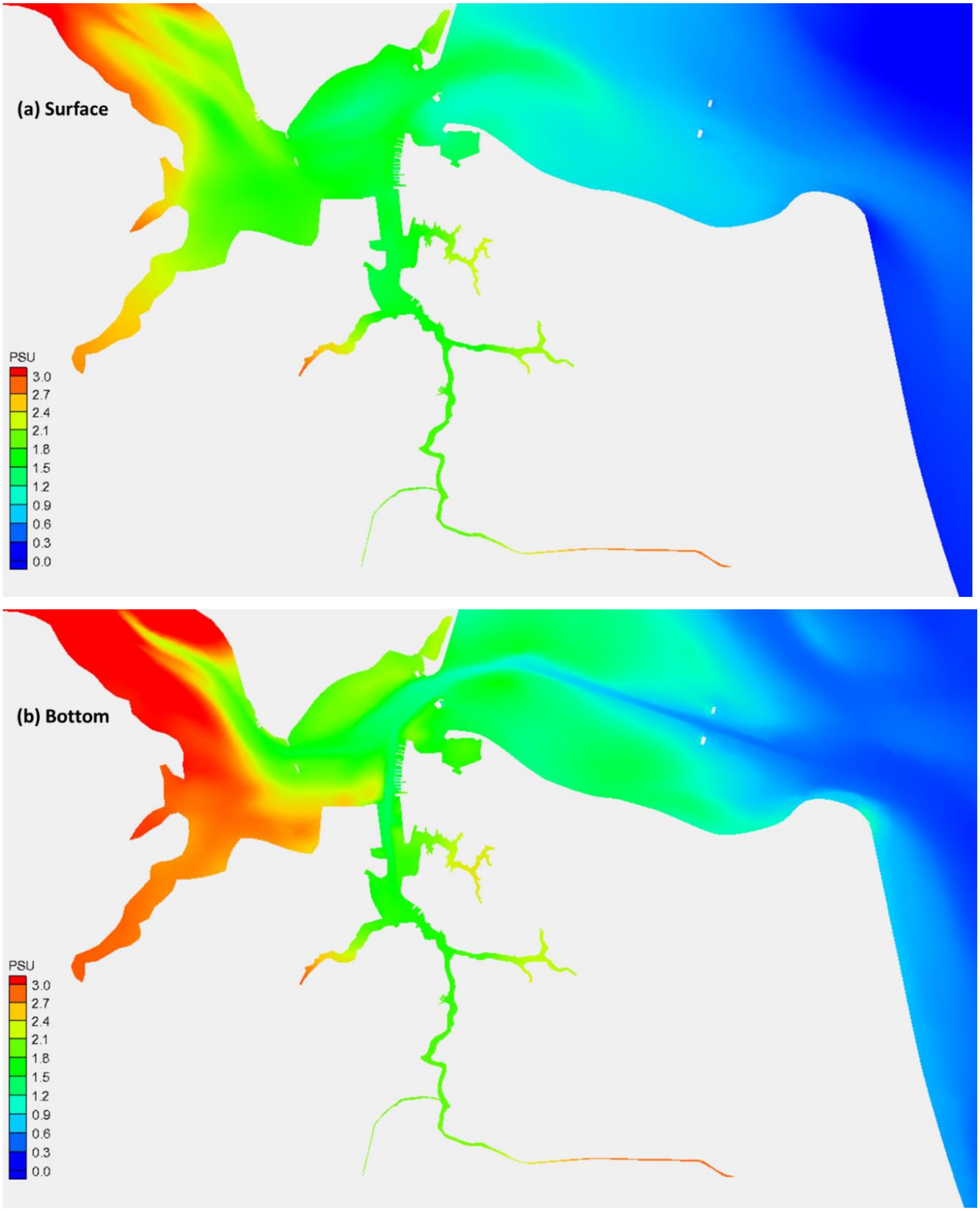
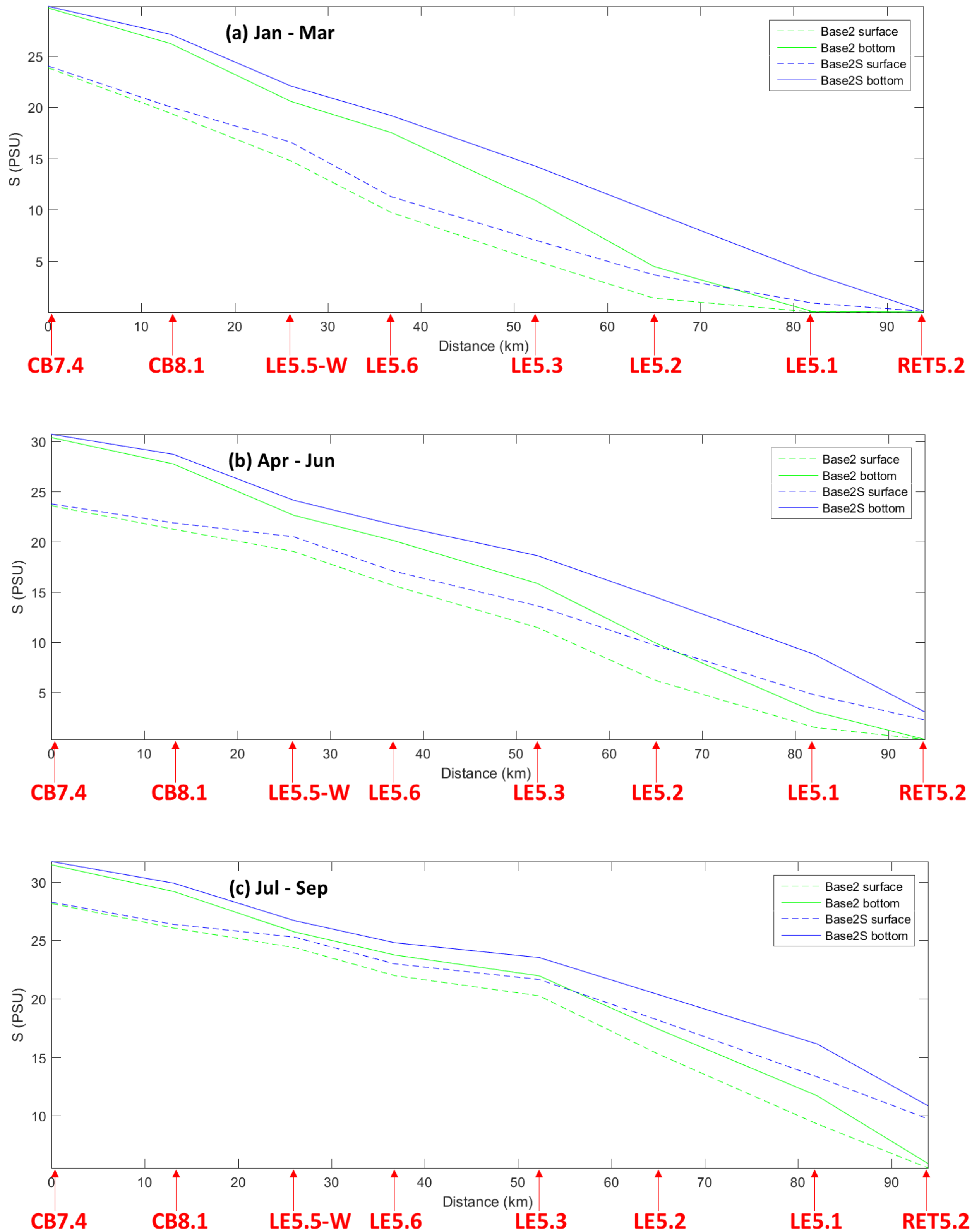


Figure 10: Time-averaged salinity differences (from 2010-2013) between 5-2S and 5-2 ('5-2S' – '5-2') at (a) surface and (b) bottom.


(a) Jan - Mar
(b) Apr - Jun
(c) Jul - Sep
Base2 surface
Base2 bottom
Base2S surface
Base2S bottom
S (PSU)
Distance (km)
CB7.4
CB8.1
LE5.5-W
LE5.6
LE5.3
LE5.2
LE5.1
RET5.2

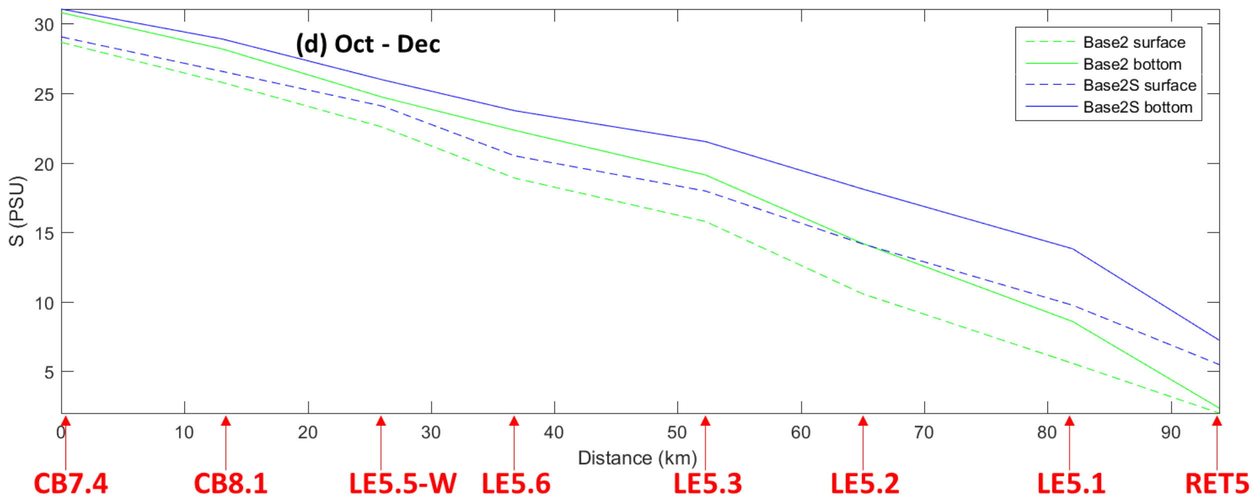
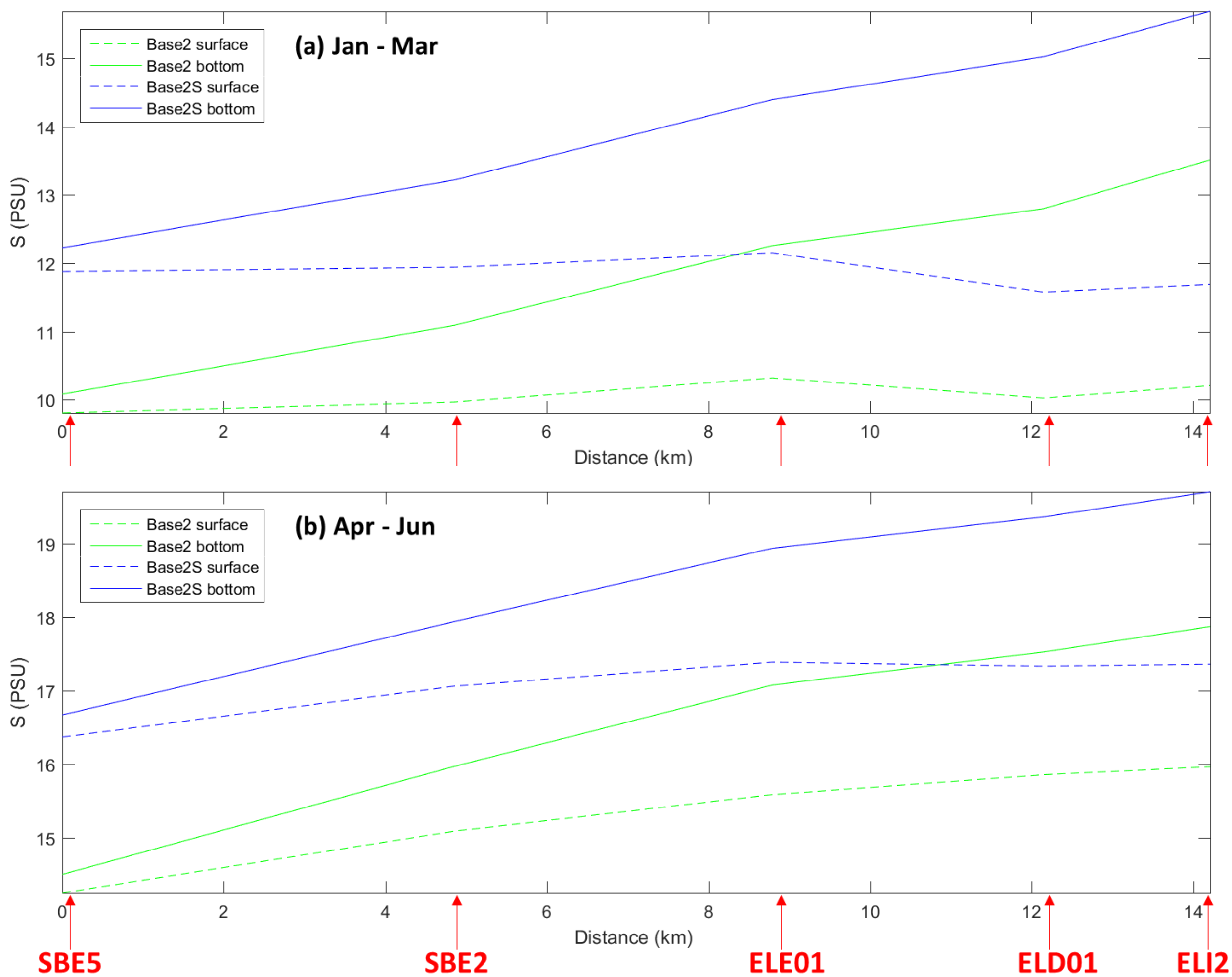


Figure 11: Averaged salinity differences (at surface and bottom) between ‘Base 2S’ and ‘Base 2’ along a transect from lower Bay into James River. See Fig. 2 for the corresponding observation stations. Differences are shown every 3 months: (a) Jan – Mar; (b) Apr – Jun; (c) Jul – Sep; (d) Oct – Dec. The averaging is over 2010-2013.



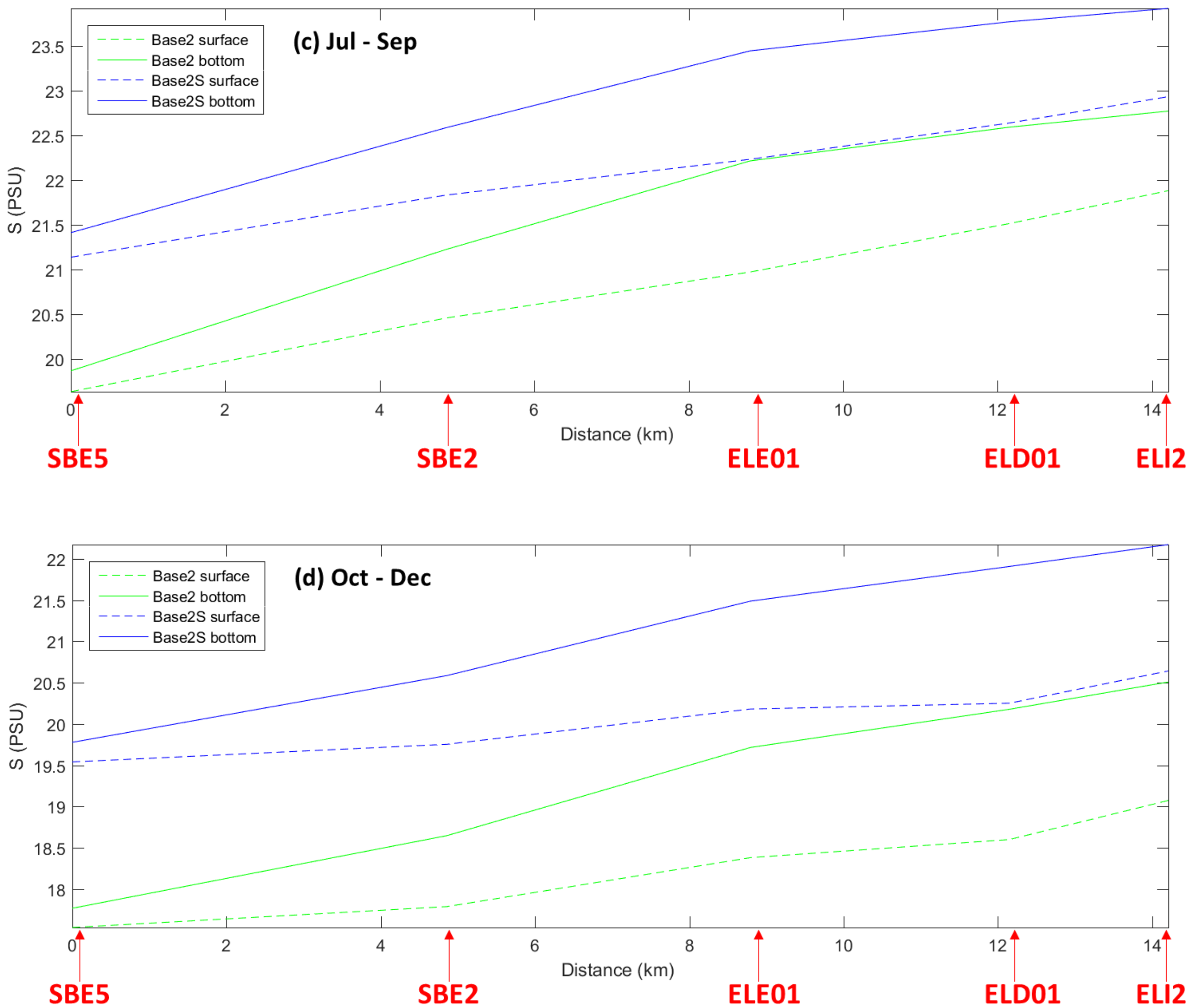
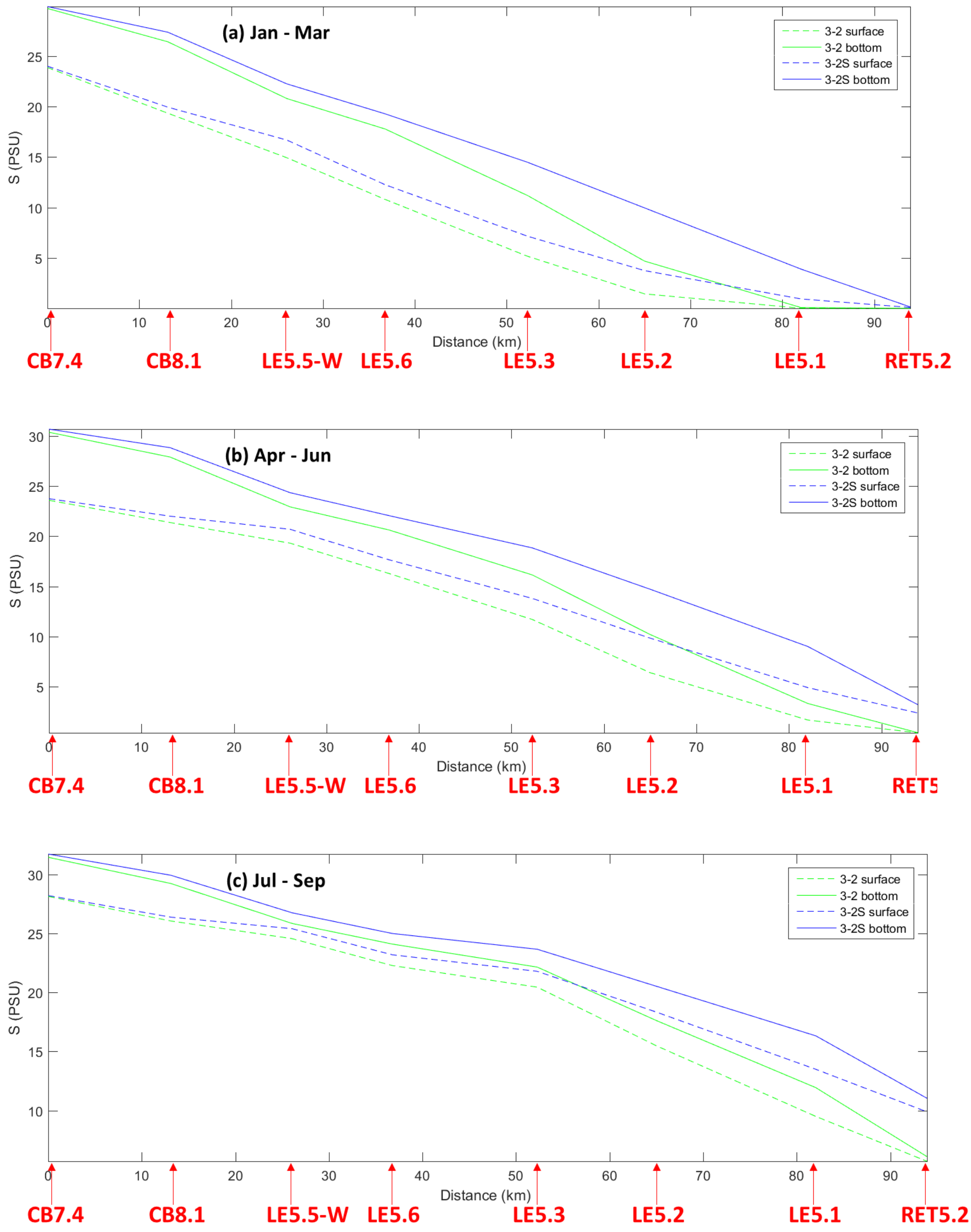


Figure 12: Averaged salinity differences (at surface and bottom) between 'Base 2S' and 'Base 2' along a transect from Elizabeth River into James River. See Fig. 2 for the corresponding observation stations. Differences are shown every 3 months: (a) Jan – Mar; (b) Apr – Jun; (c) Jul – Sep; (d) Oct – Dec. The averaging is over 2010-2013.


(a) Jan - Mar
(b) Apr - Jun
(c) Jul - Sep
3-2 surface
3-2 bottom
3-2S surface
3-2S bottom
S (PSU)
Distance (km)
CB7.4
CB8.1
LE5.5-W
LE5.6
LE5.3
LE5.2
LE5.1
RET5.2

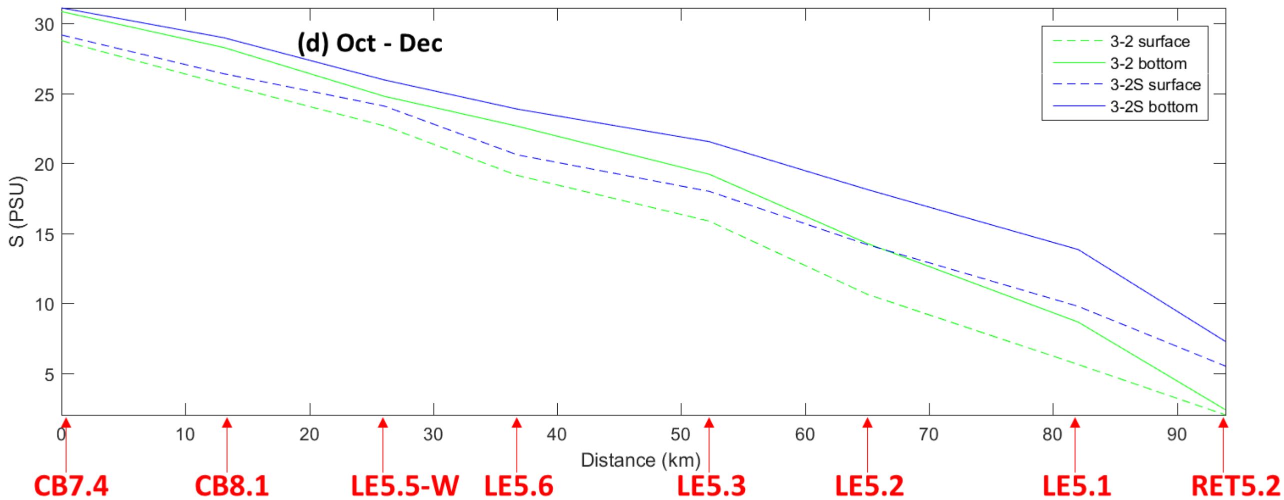
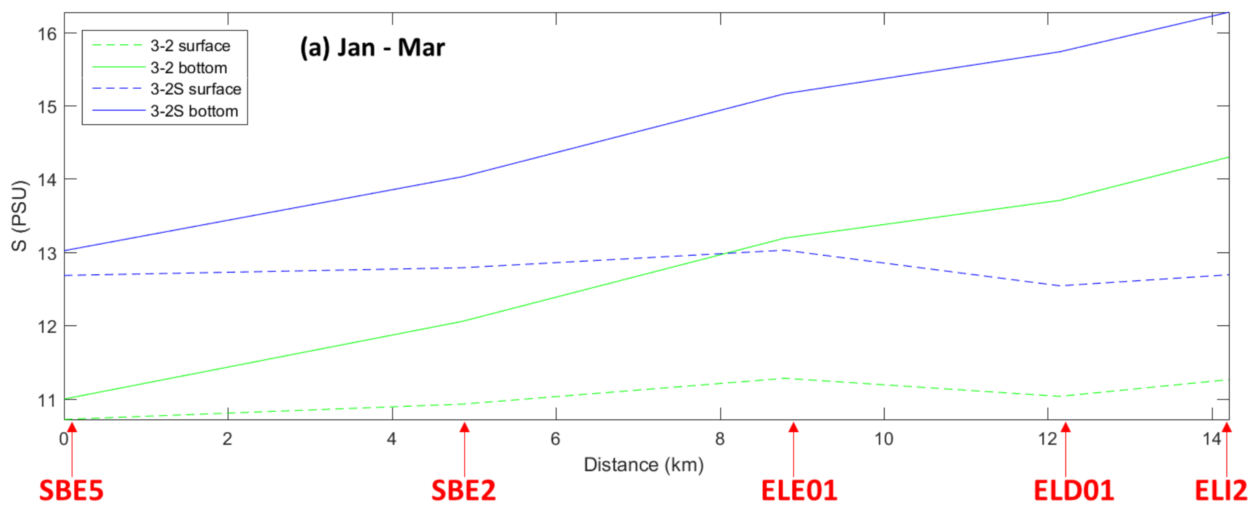
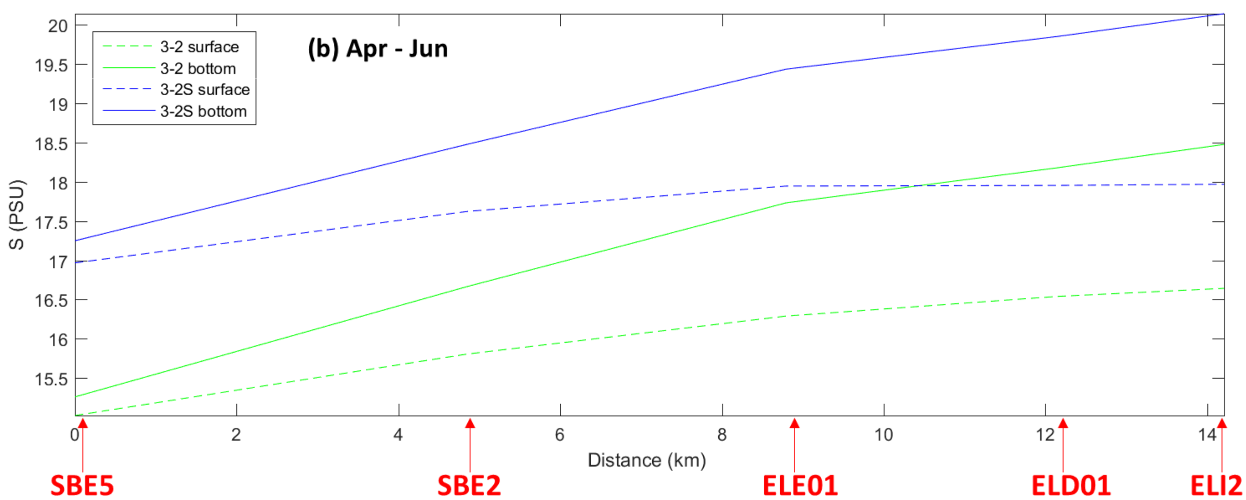
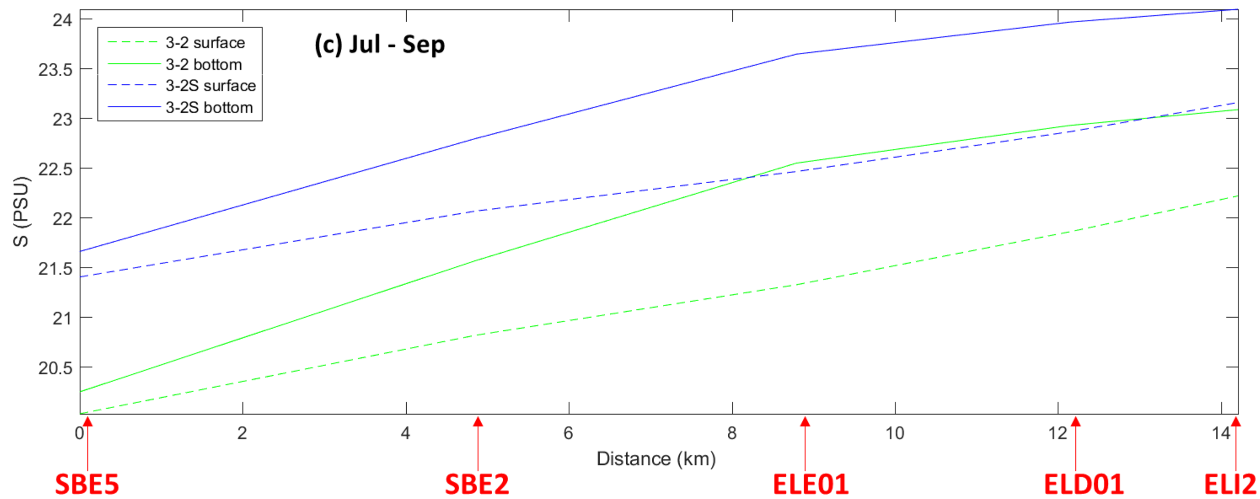


Figure 13: Averaged salinity differences (at surface and bottom) between ‘3-2S’ and ‘3-2’ along a transect from lower Bay into James River. See Fig. 2 for the corresponding observation stations. Differences are shown every 3 months: (a) Jan – Mar; (b) Apr – Jun; (c) Jul – Sep; (d) Oct – Dec. The averaging is over 2010-2013.







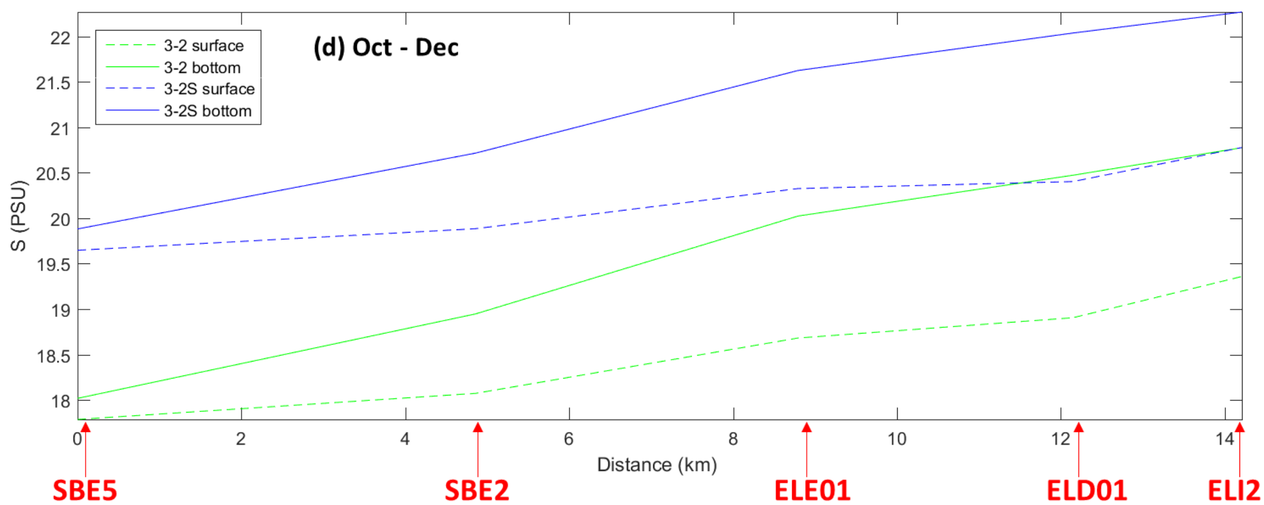
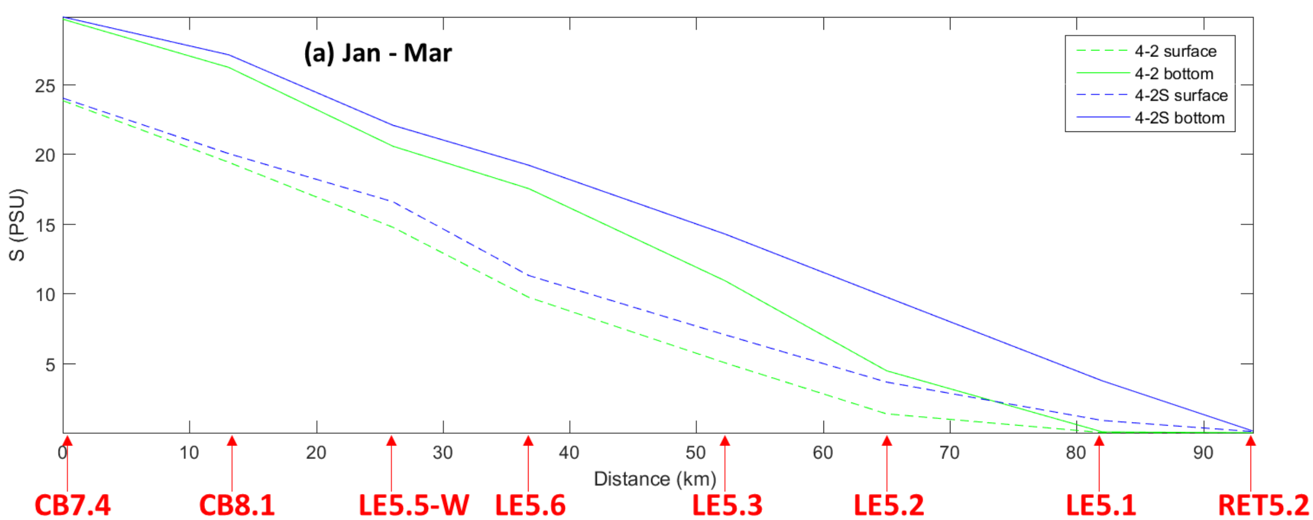


Figure 14: Averaged salinity differences (at surface and bottom) between '3-2S' and '3-2' along a transect from Elizabeth River into James River. See Fig. 2 for the corresponding observation stations. Differences are shown every 3 months: (a) Jan – Mar; (b) Apr – Jun; (c) Jul – Sep; (d) Oct – Dec. The averaging is over 2010-2013.



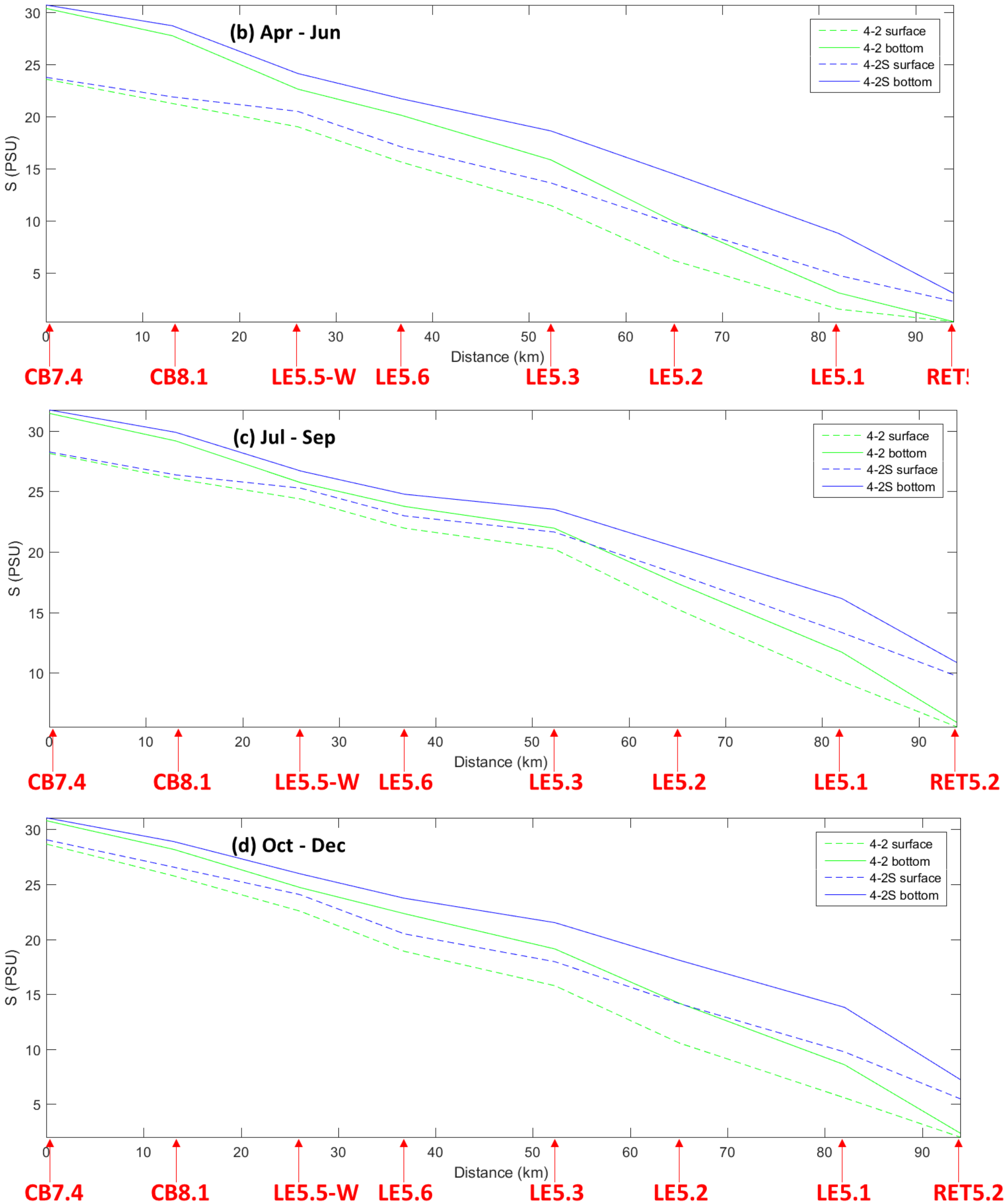
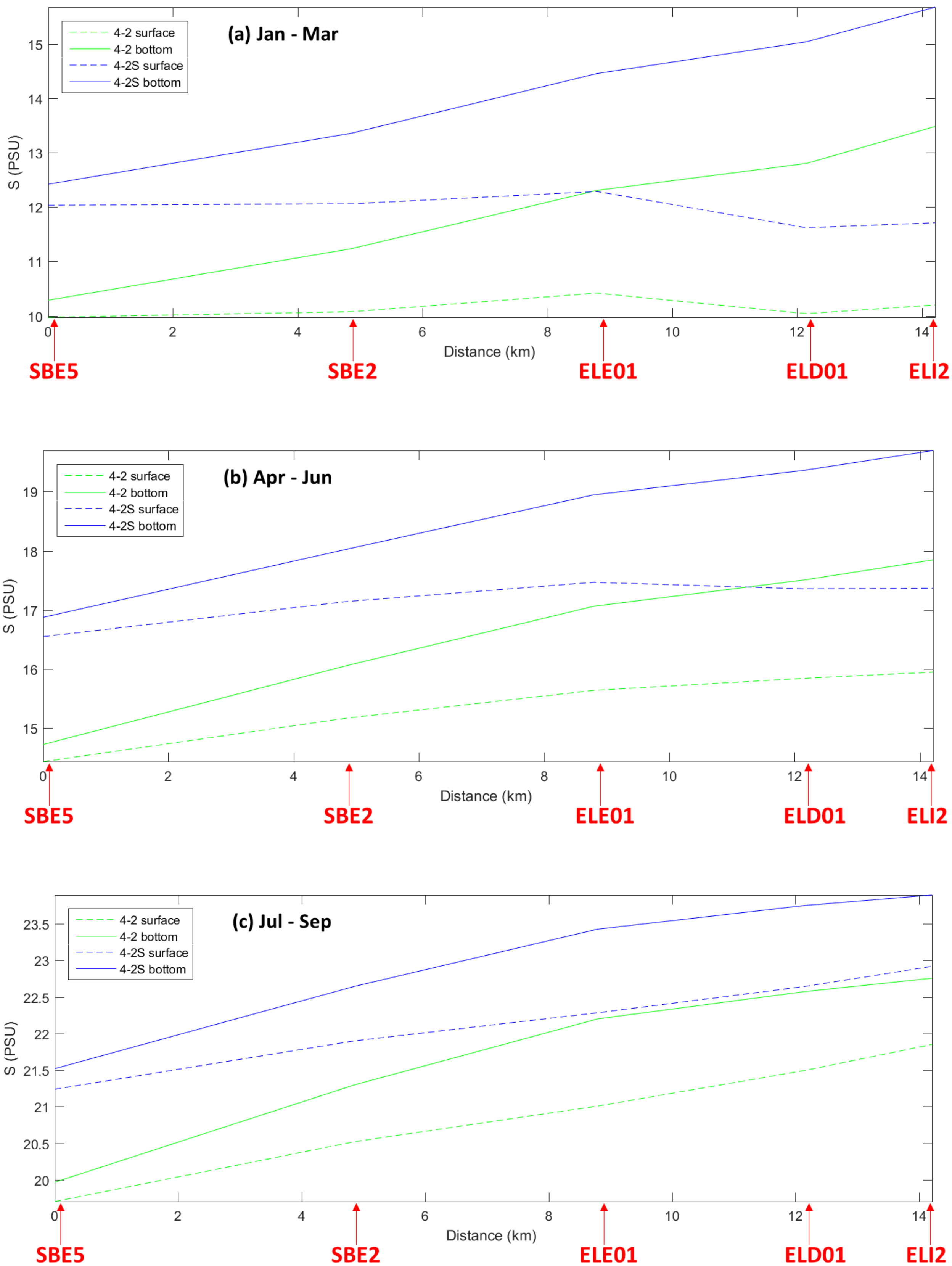


Figure 15: Averaged salinity differences (at surface and bottom) between '4-2S' and '4-2' along a transect from lower Bay into James River. See Fig. 2 for the corresponding observation stations. Differences are shown every 3 months: (a) Jan – Mar; (b) Apr – Jun; (c) Jul – Sep; (d) Oct – Dec. The averaging over 2010-2013.


(a) Jan - Mar
(b) Apr - Jun
(c) Jul - Sep
4-2 surface
4-2 bottom
4-2S surface
4-2S bottom
S (PSU)
Distance (km)
SBE5
SBE2
ELE01
ELD01
ELI2

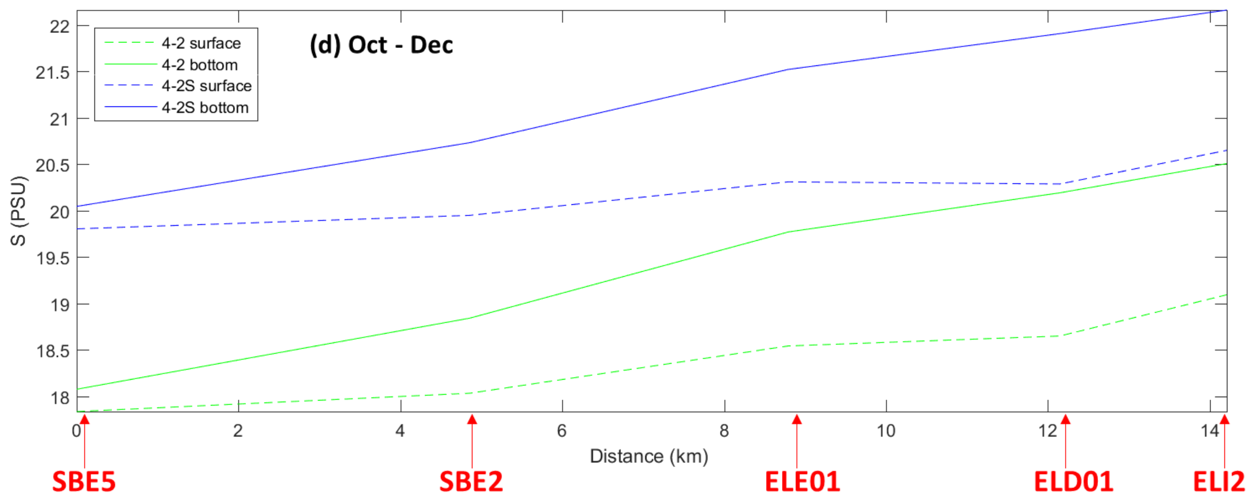
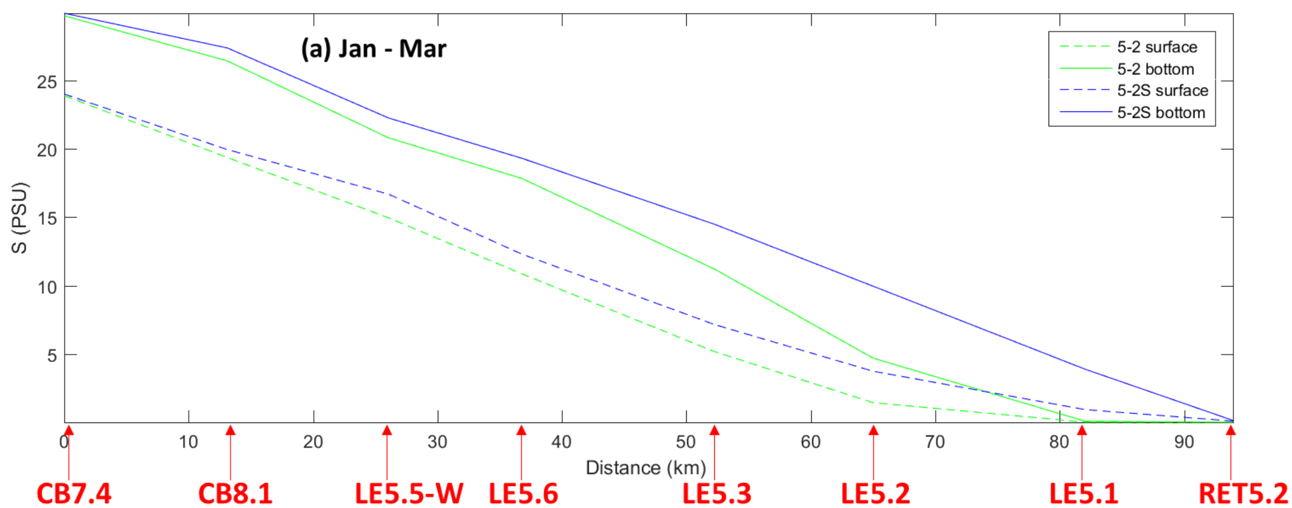
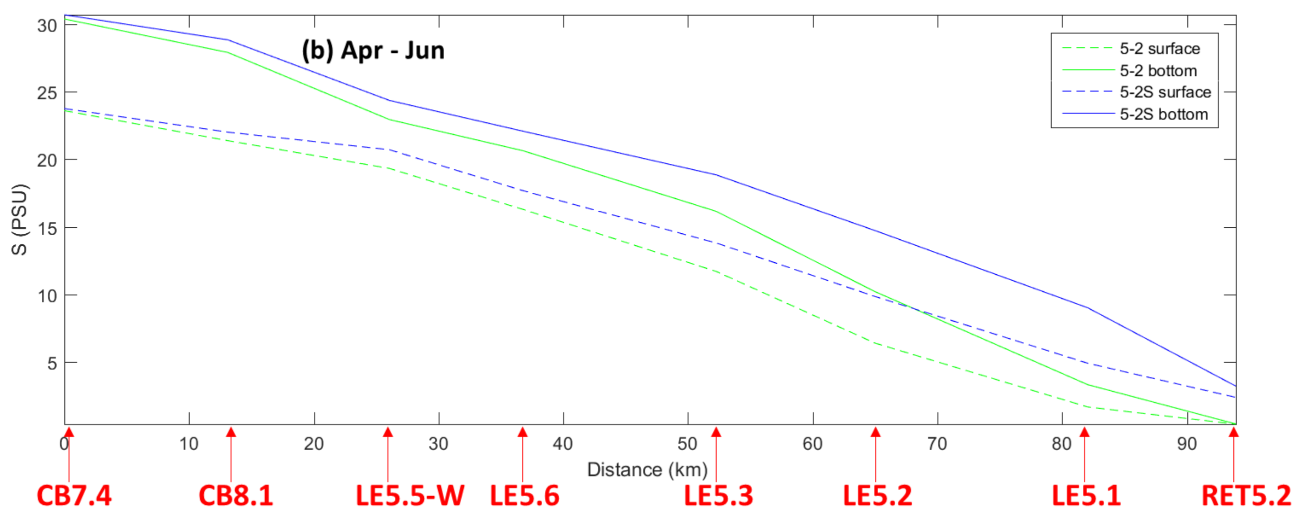
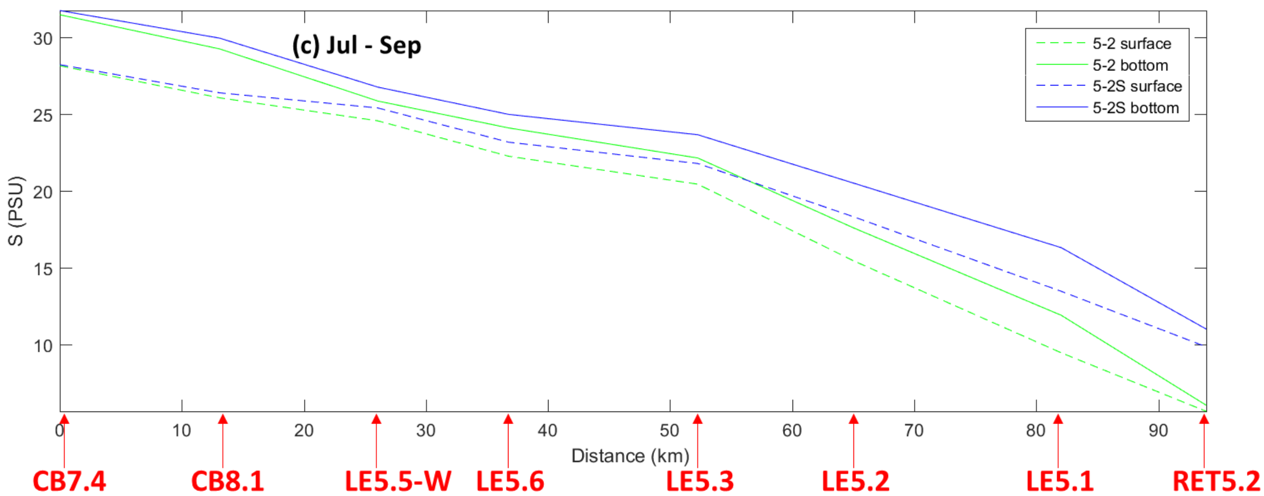


Figure 16: Averaged salinity differences (at surface and bottom) between ‘4-2S’ and ‘4-2’ along a transect from Elizabeth River into James River. See Fig. 2 for the corresponding observation stations. Differences are shown every 3 months: (a) Jan – Mar; (b) Apr – Jun; (c) Jul – Sep; (d) Oct – Dec. The averaging is over 2010-2013.







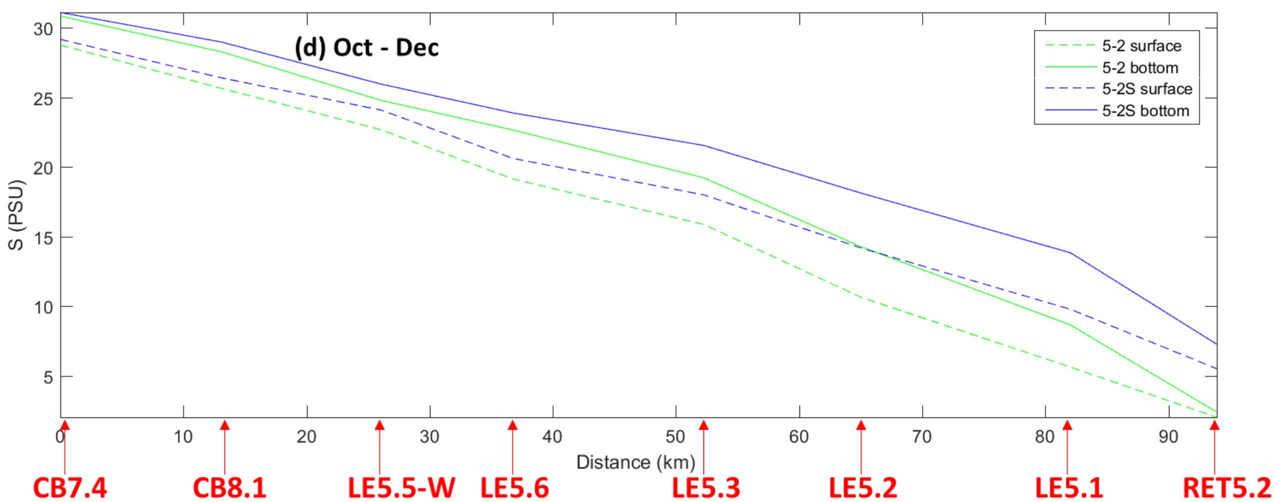
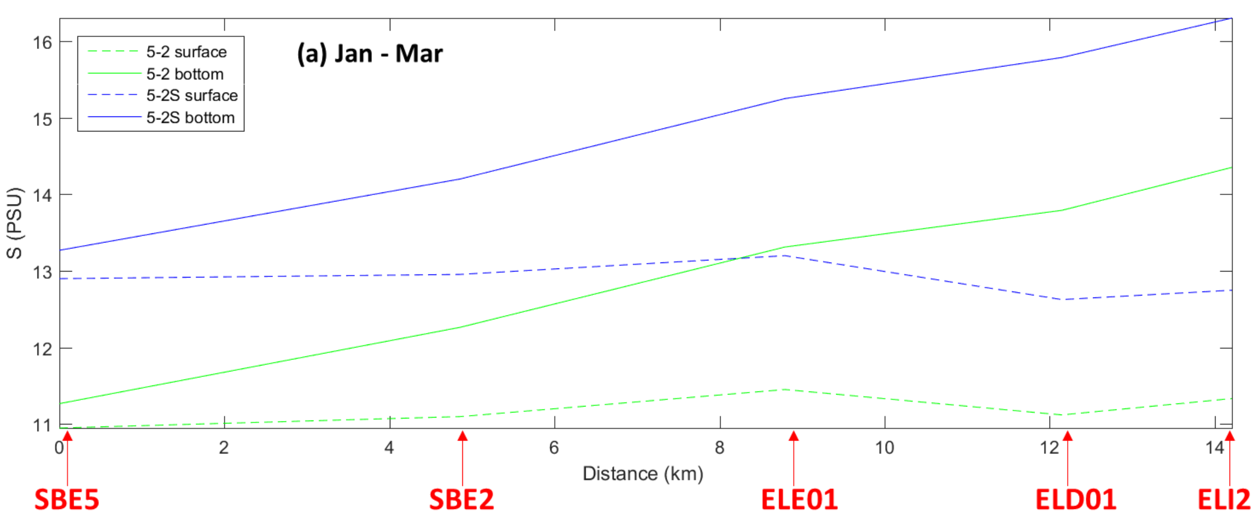


Figure 17: Averaged salinity differences (at surface and bottom) between '5-2S' and '5-2' along a transect from lower Bay into James River. See Fig. 2 for the corresponding observation stations. Differences are shown every 3 months: (a) Jan – Mar; (b) Apr – Jun; (c) Jul – Sep; (d) Oct – Dec. The averaging is over 2010-2013.



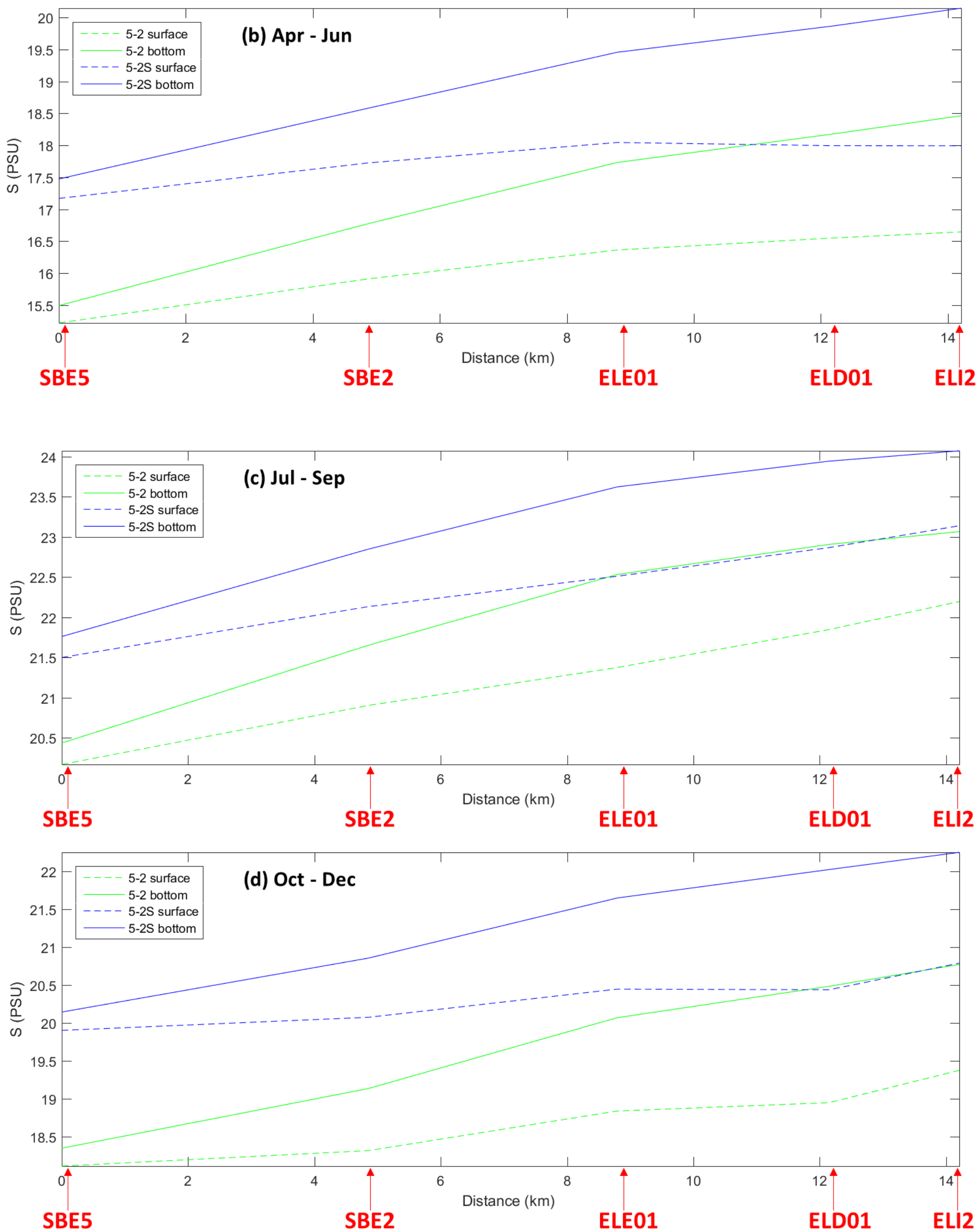


Figure 18: Averaged salinity differences (at surface and bottom) between '5-2S' and '5-2' along a transect from Elizabeth River into James River. See Fig. 2 for the corresponding observation stations. Differences are shown every 3 months: (a) Jan – Mar; (b) Apr – Jun; (c) Jul – Sep; (d) Oct – Dec. The averaging is over 2010-2013.

Table 6: Stations used in each region for statistical analysis.

Region	Stations
Lower Chesapeake Bay (lower Bay)	CB8.1, CB7.4, CB7.4N, CB7.3, CB7.3E, CB6.4
James River	CB8.1E, LE5.6, LE5.5-W, LE5.4, LE5.3, LE5.2, LE5.1, RET5.2
Elizabeth River	LFB01, LFA01, SBE5, SBE2, EBE1, ELE01, EBB01, ELD01, ELI2

Table 7: Summary of Mean Absolute Differences for surface and bottom salinity (2010 - 2013) between scenarios w/ SLC and scenarios w/o SLC, respectively.

Mean Absolute Differences for Surface and Bottom Salinity (PSU)								
	'Base 2S' – 'Base 2'		'3-2S' – '3-2'		'4-2S' – '4-2'		'5-2S' – '5-2'	
	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
Lower Bay	0.65	0.58	0.64	0.57	0.65	0.58	0.64	0.57
James River	2.03	2.52	1.99	2.48	2.03	2.52	2.00	2.48
Elizabeth River	1.85	1.99	1.74	1.86	1.85	1.98	1.74	1.85

Table 8: Summary of Mean Absolute Differences for surface and bottom salinity (2010 - 2013) strictly between Base 2S and 3-2S, 4-2S, 5-2S, respectively, excluding Base 2S

Mean Absolute Differences for Surface and Bottom Salinity (PSU)						
	'3-2S' – 'Base 2S'		'4-2S' – 'Base 2S'		'5-2S' – 'Base 2S'	
	Surface	Bottom	Surface	Bottom	Surface	Bottom
Lower Bay	0.28	0.17	0.02	0.01	0.29	0.17
James River	0.20	0.19	0.01	0.01	0.21	0.19
Elizabeth River	0.48	0.43	0.09	0.08	0.56	0.49

4. Discussion and summary

The Virginia Port Authority (VPA) and the Army Corps of Engineers, Norfolk District adopted the medium high scenario of 1-meter sea-level change (SLC) by 2100 as an average of the high end of semi-empirical, global SLC projections for the evaluation. The impacts of different dredging condition under SLC on tidal dynamics and salinity was investigated in this study.

From a tidal dynamics point of view, the 1-meter mean sea-level rise increases the water depth in the channel and also increases the horizontal extent of the Bay water coverage. Essentially, tide is propagating in a deeper and wider channel under the SLC condition. The SCHISM model has a wetting and drying scheme in treating the shoreline as the movable boundary and thus allows the low-lying dry land to be inundated under a sea-level rise condition. The SCHISM simulation, with this wetting and drying scheme not treating the shoreline as the vertical wall, shows that the tidal range mostly decreases. This decrease of tidal amplitude, not proportional to the changes in the mean sea level, is consistent with findings from Lee et al. (2017), who attributed the decrease of tidal range to the increased dissipation over the shallow water and newly inundated areas that compensate for the reduced dissipation in deep water, leading to a smaller tidal range. The tidal phase angle also leads as the result of a faster propagation speed of the tidal wave, which is proportional to the square root of the total water depth. The largest change of amplitude in the M_2 tidal component is about 0.1% of the post-dredged channel depth and the largest change of the phase is about 0.78% for the N_2 tidal component.

For the impact on salinity, the SCHISM simulation shows that the salinity intrusion limit increases and both surface and bottom salinities increase, similar to those found in Puget Sound by Yang and Wang (2015). The SCHISM results found that the vertical stratification can increase due to the fact that increase of salinity at the bottom is more than that at the surface, as suggested by Hong and Shen (2012). The SLC has the largest impacts in James River where the increase of surface and bottom salinities reach 2 and 2.5 PSU, respectively. The smallest changes near the project area are in the main stem of the lower Chesapeake Bay with ~ 0.6 PSU changes at both surface and bottom. The changes in Elizabeth River is intermediate at 1.75 – 1.85 PSU for surface salinity and 1.85 – 2 PSU for bottom salinity. The inter-comparison of the net impacts strictly between different dredging conditions: (3-2S, 4-2S, and 5-2S) under SLC is also assessed by excluding the influence of base -2S. The results show that the impacts are the largest under the combination of Norfolk Harbor and Elizabeth River dredging, followed by the dredging in Norfolk Harbor. The dredging in the Southern Branch alone has the least impact on the salinity, which is consistent with the results under the “without” SLC condition (Zhang et al., 2017).

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