Assessment of Hydrodynamic and Water Quality Impacts for Channel Deepening in the Thimble Shoals, Norfolk Harbor, and Elizabeth River Channels

Final report on the “hydrodynamic modeling”

to

Virginia Port Authority

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Executive Summary

For over twenty years, the U. S. Army Corps of Engineers (USACE) and the Virginia Port Authority (VPA), representing the Commonwealth Secretary of Transportation, have collaborated on projects key to port development that also preserve the environmental integrity of both Hampton Roads and the Elizabeth River. The USACE and the VPA are working to investigate channel deepening in this region to provide access to a new generation of cargo ships (e.g., Panamax-class). The main goal of this project is to investigate the feasibility for Norfolk Harbor channel deepening in the lower James and Elizabeth Rivers and assess the environmental impact of the shipping channels dredging in Atlantic Ocean Channel, Thimble Shoal Channel, Elizabeth River channel, and the Southern Branch. Specifically, we support the request of "Planning and Engineering Services for Norfolk Harbor" in three areas: (1) using high-resolution hydrodynamic modeling to evaluate the change of hydrodynamics resulting from Channel Deepening (2) assessment of water quality modeling using the Hydrodynamic Eutrophication Model (HEM3D) (3) conducting the statistical measure of impacts resulting from Channel Deepening.

Virginia Institute of Marine Science (VIMS) team has applied a3D unstructured-grid hydrodynamic model (SCHISM, Zhang et al., 2016) in the study of impact of channel dredging on hydrodynamics in the project area. The model was adopted due to its flexible gridding systems used: hybrid triangular-quadrangular unstructured grids in the horizontal and flexible vertical coordinate system in the vertical (Zhang et al. 2015). High resolution (up to 15m) is used to faithfully resolve the channels and other important features such as tunnel islands etc.

We first validate the model in the lower Chesapeake Bay that includes the project area, under the existing condition ('Base1'). The simulated elevations, depth-averaged velocity, salinities, and temperatures in the lower Bay, James River and Elizabeth River region have an averaged RMSE of 6cm, 8cm/s, <2 ppt, <2^{o}C respectively, and the model captured key processes (salt intrusion, periodic stratification-destratification) well.

The model is then applied to study the response from various scenarios under the channel dredging project. Given two base conditions and three scenarios with each scenario built on either Base 1 or Base 2, altogether we have conducted eight model runs. The two base runs are (1) Base 1- Current without project (2) Based 2- future without project including CIEE (Craney Island Eastward Expansion) built out. The three scenarios are (1) Norfolk Harbor channel dredging only (2) Southern Branch channel dredging only, (3) both Norfolk Harbor channel and Southern Branch channel dredging (see Figure 11). Comparison of all of the scenarios with 'Base 1' or 'Base 2' demonstrates the following characteristics:

(1) the salinity increase on average of 0.6 ppt in Elizabeth River is the largest over the project site. The maximum change, though, can and reach 2 ppt when compared to 'Base 1' in Jan-March in most parts of the Elizabeth river (cf. Fig. 33 &34);

(2) the salinity increase in the James River is up to 0.2 ppt on average;

(3) the increases are generally small (~0.1 ppt) in the rest of lower Chesapeake Bay (with a distance exceeding ~30 km from the project area);

(4) when scenarios are compared to ‘Base 1’, the 3 scenarios built on ‘Base 2’ generally result in larger salinity increase than those built on ‘Base 1’ due to the additional effects of CIEE built out;

(5) the salinity increase is the smallest with only the Southern Branch being dredged, followed by Norfolk Harbor channel dredging; the combined dredging in both channels leads to the largest change.

Quantitatively, the impact of dredging on the hydrodynamics is relatively minor and localized over the project site. Among the 3 regions, the salinity change is the largest in the Elizabeth River, followed by James River, and the lower Chesapeake Bay is the smallest in the case both Norfolk Harbor and Elizabeth River are chosen to be deepening.

1. Background

The nature of global trade is changing and the shipping industry is in transformation from traditional vessels to larger mega-ships. For example, the Panama Canal now has a third lane that can accommodate mega-ships nearly three times larger than any vessel that has ever transited the isthmus over the past century. America is taking a great stride in the international trade strategy with the pursuit resulting from the expansion of the Panama Canal. The Virginia Port Authority (VPA) continually strives to maximize the efficiency of its present and future marine terminal operations for the benefit of all citizens of the Commonwealth of Virginia. The Panamax-class ships of today enter into Chesapeake Bay via channels with navigable depths of less than 50 feet. The VPA has a concern about the channel deepening necessary to accommodate these next generation cargo ships (Post Panamax-ships), which are 1,200 feet in length and carry three times the cargo of the 965-feet-long Panama ships (Haider, 2015). These ships are able to reach the U.S. East Coast since the completion of the Third Set of Locks Project at the Panama Canal (Ison, 2015), a project recently completed in 2016. For over twenty years, the U. S. Army Corps of Engineers (USACE) and the Virginia Port Authority (VPA), representing the Commonwealth Secretary of Transportation, have collaborated on projects key to port development that also preserve the environmental integrity of both Hampton Roads and the Elizabeth River. The selection of the present design for Craney Island Eastward Expansion (CIEE) and its legal authorization were major milestones leading to the onset of the CIEE construction. Building on existing collaboration, the USACE and the VPA are now working to investigate channel deepening in this region to provide access to a new generation of cargo ships.

Virginia Institute of Marine Science of the College of William and Mary has been actively engaged with VPA's activities. The numerical model known as HEM-3D (Hydrodynamic and Eutrophication Model in 3 Dimensions) was developed and used in several key environmental impact studies in the James and Elizabeth Rivers over the past two decades. It was first used to assess the environmental impacts for highway crossing alternatives of the proposed third crossing of Hampton Roads (Boon et al., 1999). After refining the Elizabeth River portion of the model grid to a resolution of 123 m, HEM-3D was utilized to determine both global (i.e., far field) and local environmental impacts of each of a series of land expansions for Craney Island (Wang et al., 2001). The current project is a natural continuation of the previous efforts.

To investigate the feasibility for Norfolk Harbor channel deepening in the lower James and Elizabeth Rivers, one of the key services of the project is to evaluate the impacts of the shipping channels dredging for Atlantic Ocean Channel to 55 feet (from 50 feet), Thimble Shoal Channel to 55 feet (from 50 feet), Elizabeth River (north of Lambert Point) to 50 feet (from 45 feet) and the Southern Branch (north of the I64 Bridge) to about 50/45/45 feet in its three reaches (Elizabeth River Reach, middle Reach and lower Reach). In theoretical terms, the shipping channel dredging will result in enhancement of estuarine gravitational circulation, accentuate the tidal and wind wave influence upstream, and affect the ecosystem dynamics in the lower Bay, particularly, dissolved oxygen (DO) in the James River and Elizabeth River. The real question is how much is that impact? Can it be quantitatively evaluated? Can the risk be measured temporally and spatially? VIMS scientists are working with engineers of Moffatt and Nichol and the Norfolk District of the U. S. Army Corps of Engineers to evaluate the impact of channel deepening on the dynamics and dissolved oxygen (DO), and the flushing capabilities of the Lower James and Elizabeth Rivers, and to provide statistical measures to assess the impact resulting from channel deepening both locally and globally. This document provides key findings of the hydrodynamic model results related to environment assessment.

2. The SCHISM model set-up and observation data

The unstructured-grid (UG) SCHISM model (Zhang et al. 2016) is used to simulate the circulation in lower Chesapeake Bay that includes the project sites (Atlantic Channel, Thimble Shoal, Newport News Channel, Elizabeth River channel). The UG has 24520 nodes, 40593 mixed triangular-quadrangular elements in the horizontal dimension (Fig. 1), with resolution varying from 15m to 6.3km (Fig. 2), and finer resolution used in the lower Bay-James River-Elizabeth River region. The flexibility provided by the UG model allows us to simulate the processes in the entire Bay and continental shelf as a whole, thus greatly simplifying the boundary condition (B.C.) requirement. A flexible LSC^2 (Localized Sigma Coordinates with Shaved Cells) vertical grid (Zhang et al. 2015) is used that efficiently covers depths from deep to shallow regions, with a maximum of 80 levels used at the maximum depth of ~3600 m (found near the continental shelf break), 29-41 levels for the shipping channel, and minimum of 5 levels for the shallow area. On average there are 28 levels used in the vertical. The use of flexible horizontal and vertical grids ensures that the gravitational circulation (2-layer exchange flow) is accurately and efficiently represented in the 3D model. The main bathymetry source we used is from FEMA (Blanton et al. 2011), with further modifications provided by Moffatt and Nichol and the Norfolk District of the U. S. Army Corps of Engineers (including the Navy dredging that has been completed).

The model is forced by USGS-measured flows from the 7 major tributaries of the Bay (Susquehanna, Patuxent, Potomac, Rappahannock, York, James, and Choptank). 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 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 observation from the monthly surveys conducted by EPA's Bay Program (http://www.chesapeakebay.net/data/downloads/cbp_water_quality_database_1984_present). Years 2010-2013 was chosen by the project team due to better availability of observational data.

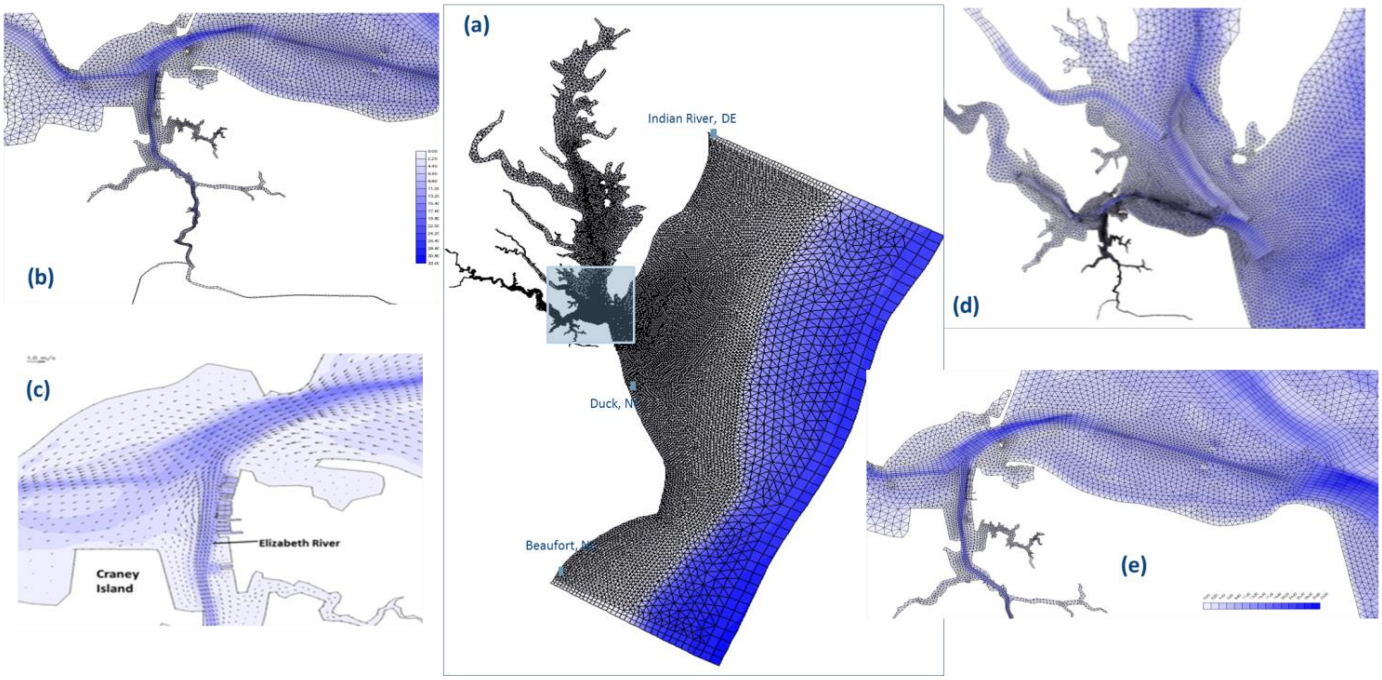


Figure 1: SCHISM grid for Chesapeake Bay and its adjacent shelf. (b-e) show zoom-in near Eliz Elizabeth River, mouth of Elizabeth River, lower Bay and James-Elizabeth Rivers, and Thimble Shoal respectively.

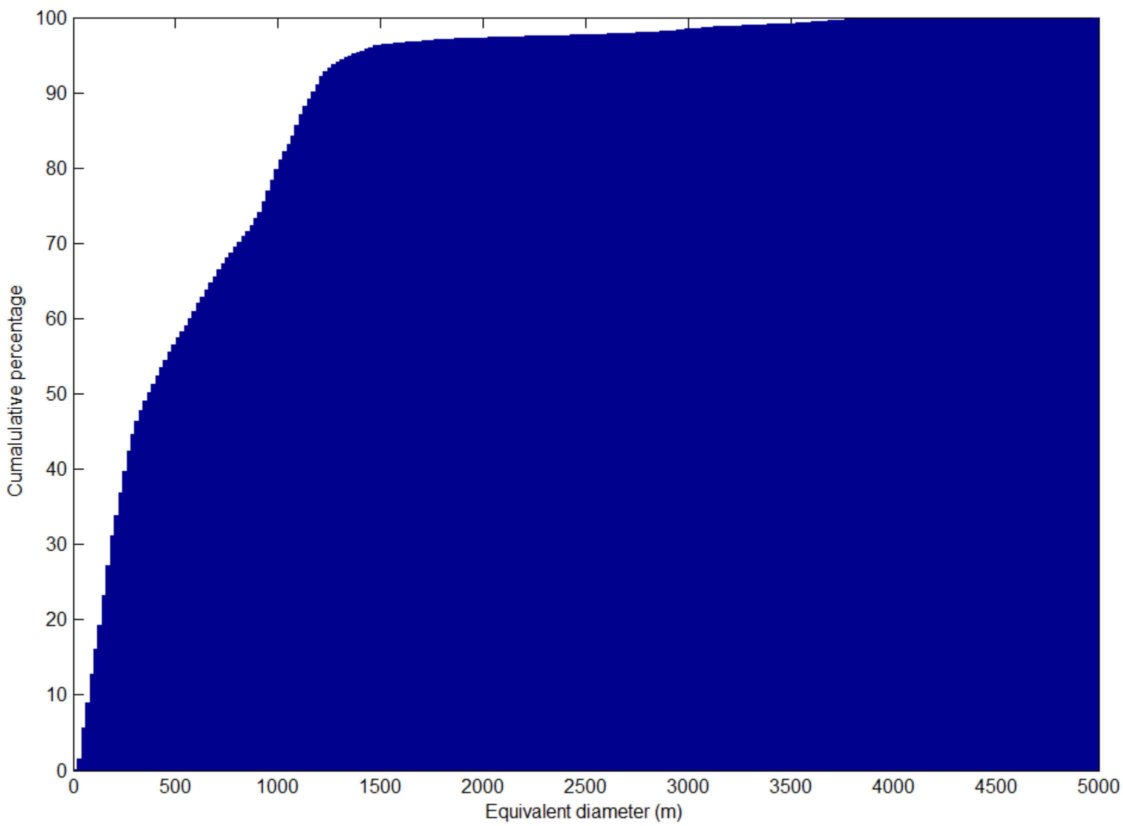


Figure 2: Histogram of grid resolution (shown as equivalent diameters of elements). About 40% of the elements have resolution finer than 250m.

3. The validation of SCHISM for base condition

We first validate the model under the existing (i.e., pre-project) 'Base 1' condition for 2011. The elevation comparison is presented in 3 forms: tidal harmonics (Fig. 3), sub-tidal time series (Fig. 4) and total elevation (Fig. 5). The predicted major M2 amplitude and phases are within 1cm and 1.5^o of the observed values (Fig. 3 & Table 1), and the Mean Absolute Errors (MAE's) for the sub-tidal elevation are no more than 4cm (Fig. 4), indicating a satisfactory model skill.
The comparison of velocity profiles at 4 ADCP stations is shown in Fig. 6. The two-layer structure is well captured by the model, although the model occasionally under-estimates the surface velocity magnitude. The correlation coefficients exceed 0.7 at all stations, and are mostly between 0.8-0.95. The comparison of depth-averaged along-channel velocity also shows satisfactory skill, with an averaged Root-Mean-Square-Error (RMSE) of 8cm/s (Fig. 7).
For brevity, the salinity and temperature validations are presented in aggregate format. Fig. 8 shows the seasonally averaged salinity profiles along a channel transect from lower Bay into James River. In this report salinities are presented in either PSU (practical salinity unit) or ppt (parts per thousand), and the two units are essentially the same for our purpose. The observed averages at 6 stations are plotted as circles overlaid on top of modeled values in the form of a Hovmoller diagram: the disappearance of the data would indicate a perfect score. The *x*-axis of the Hovmoller diagram represents the along-channel distance (measured from an arbitrary location), and the *y*-axis is the depth. The continuous colors represent the averaged model salinities along the channel, and the colored circles are the average observed salinities. The model tends to over-intrude near station 3 but generally captures the temporal and spatial variability and stratification well.
The overall statistics of the salinity and temperature are summarized in the form of target diagrams (Fig. 9 and 10). The *x*-axis shows the unbiased RMSE (i.e. with mean removed) scaled by the standard deviation of the observation, with positive values (x>0) indicating that the model standard deviation over-estimates that of the observation, and vice versa. The *y*-axis shows the model bias scaled by the standard deviation of the observation. The RMSE's are all within 2 ppt and 2^{o}C, which are small compared to the standard deviation of the salinity and temperature data used to validate the model.

Based on these results, the model is deemed to have sufficient skill and can be used to assess the impact of channel dredging.

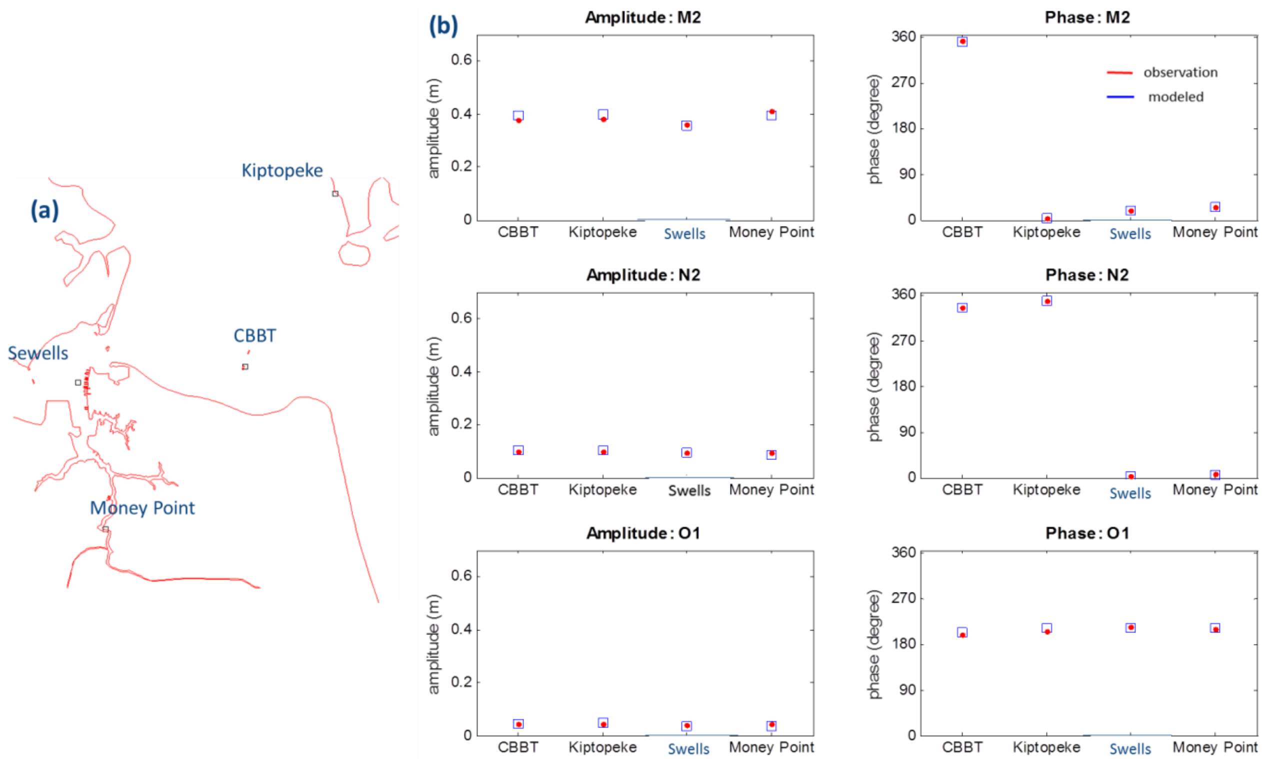


Figure 3: Comparison of tidal constituents at 4 lower Bay gauges shown in (a).

Figure 4: Comparison of sub-tidal signals (with cut-off frequency at 30 hours) at 4 lower Bay gauges shown in Fig. 3a. The model curves mostly coincide with the observation curves, with only minor deviations on, e.g., Day 350 etc.

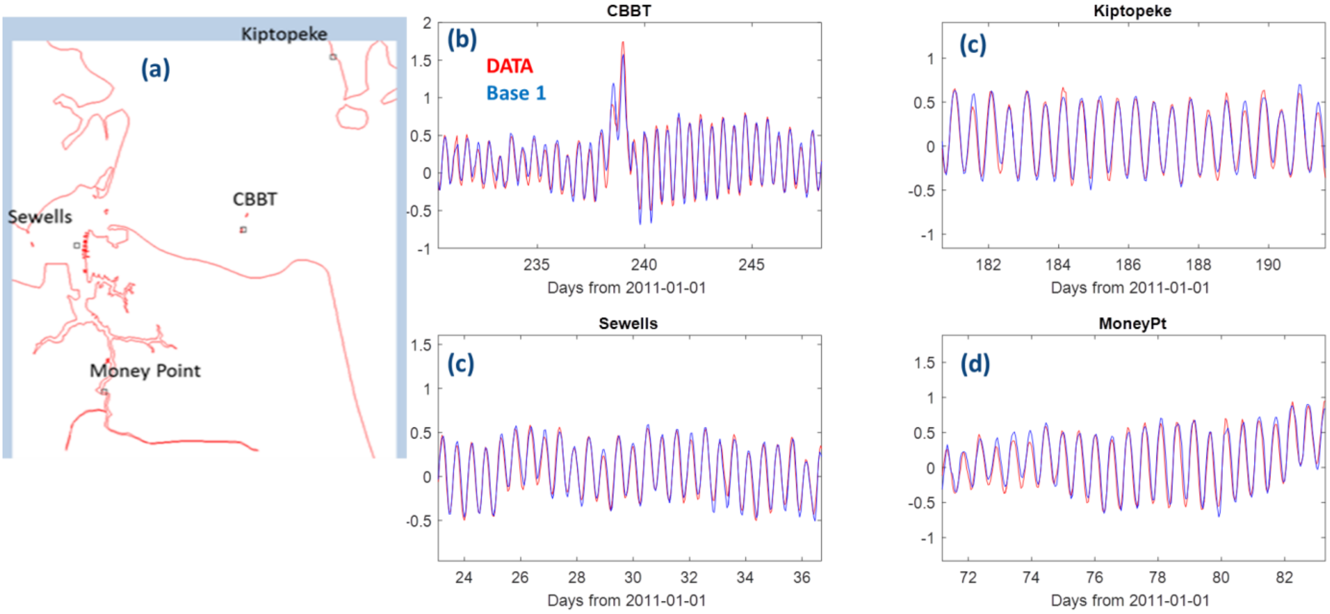


Figure 5: Comparison of total elevations at 4 lower Bay gauges shown in (a).

Table 1: Comparisons of (a) amplitudes and (b) phases at 4 stations in the lower Bay.

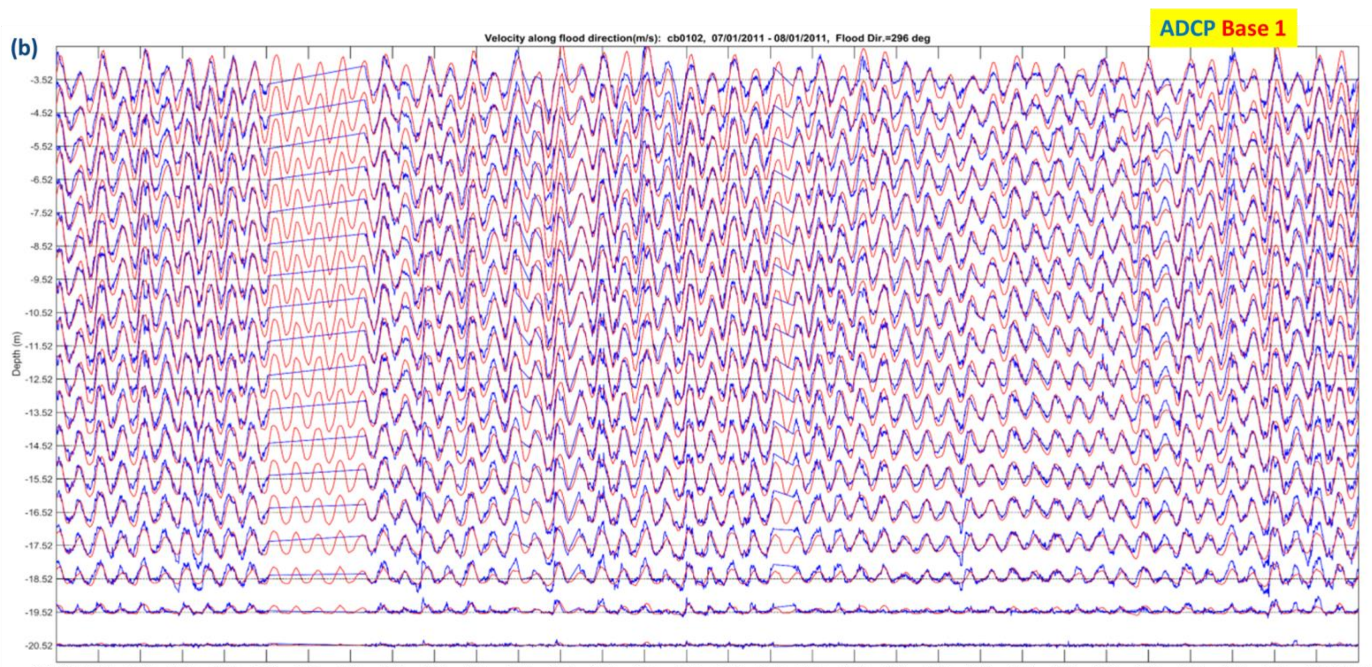
(a) Amplitude (m)

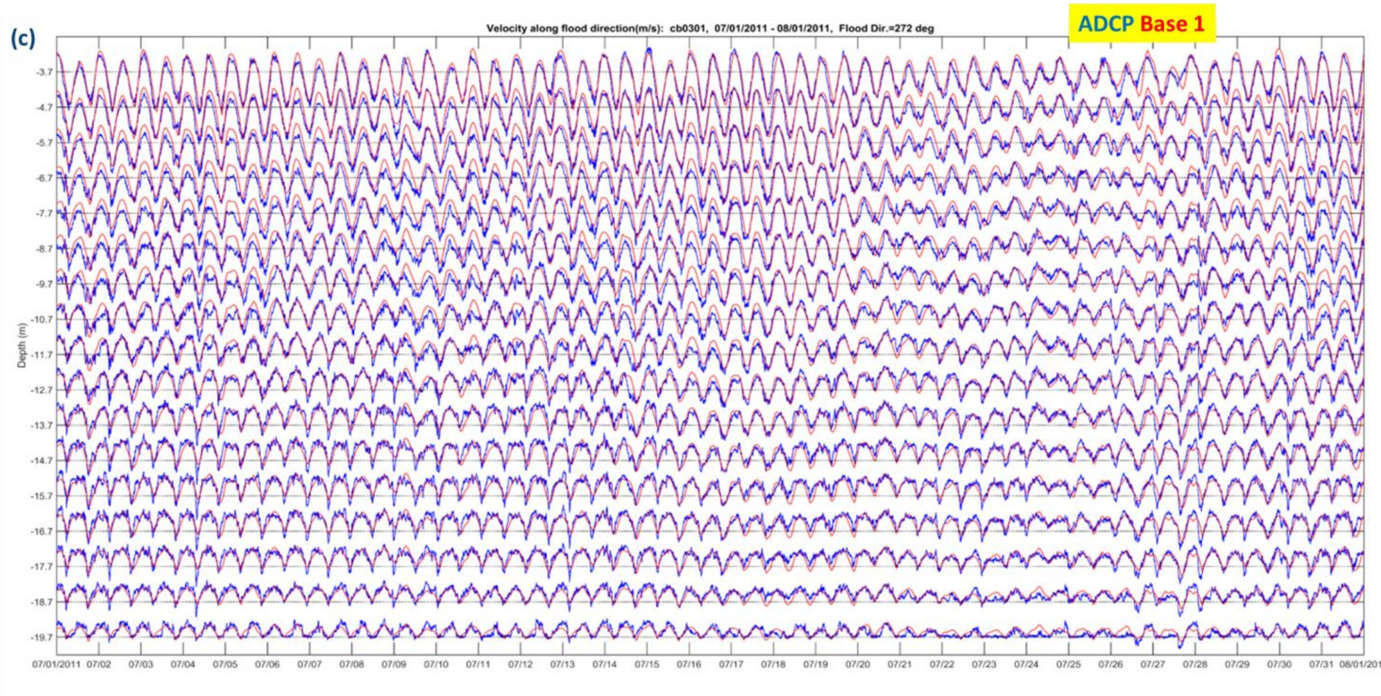
		M2			N2			O1	
		Model	Obs		Model	Obs		Model	Obs
CBBT		0.3937	0.3766		0.1052	0.1007		0.04338	0.04317
Kiptopeke		0.397	0.3829		0.104	0.09987		0.04702	0.04591
Sewells		0.3569	0.3594		0.09343	0.09388		0.03658	0.03944
Money Pt		0.3934	0.4098		0.08854	0.09586		0.03768	0.04266

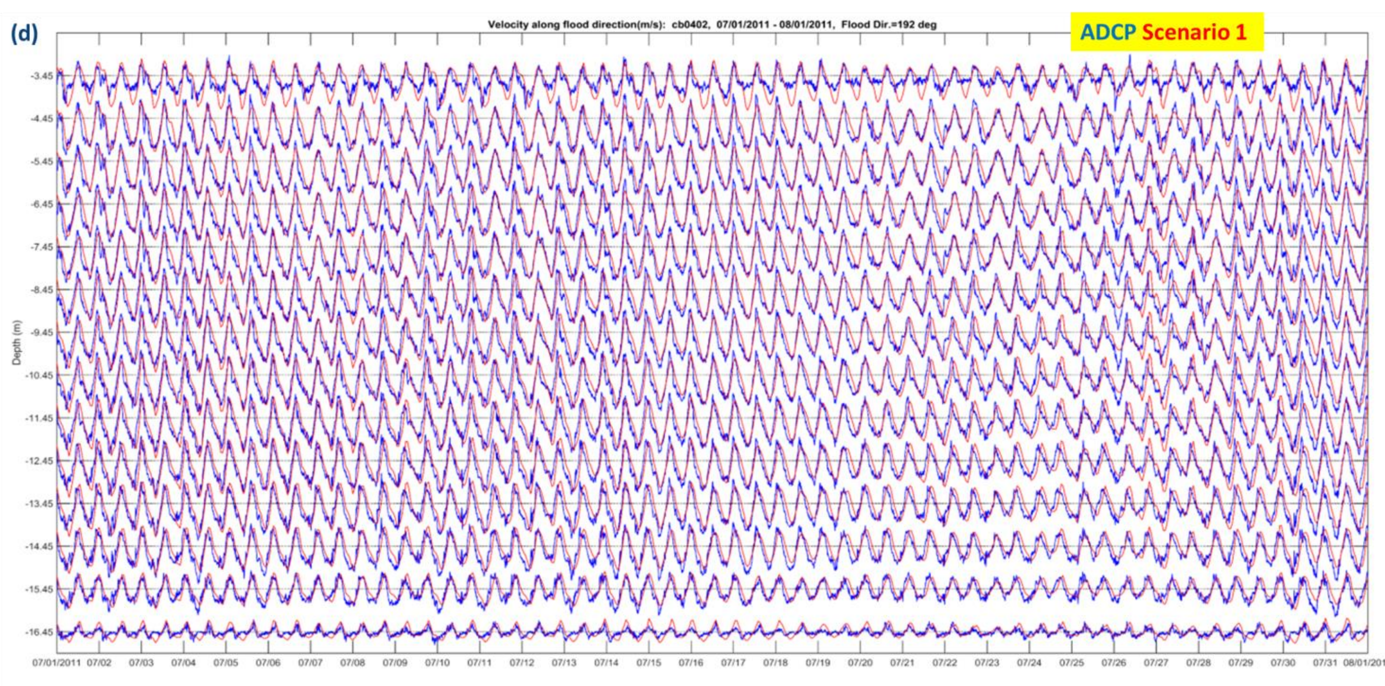
(b) Phase (degree)

		M2			N2			O1	
		Model	Obs		Model	Obs		Model	Obs
CBBT		350.9	352.4		335.2	336.1		204	200
Kiptopeke		4.242	4.384		347.9	348		212.8	206.4
Sewells		18.06	17.89		2.475	2.732		213.1	214.5
Money Pt		24.2	24.97		6.4	8.331		211.4	210.3


(a)
cb0301
cb0402
cb0601
cb0102
Newport News
Hampton
Norfolk
Portsmouth
Virginia Beach
Kiptopeke
Poquoson


(b)
Velocity along flood direction(m/s): cb0102, 07/01/2011 - 08/01/2011, Flood Dir.=296 deg
ADCP Base 1
Depth (m)


(c)
Velocity along flood direction(m/s): cb0301, 07/01/2011 - 08/01/2011, Flood Dir.=272 deg
ADCP Base 1
Depth (m)
-3.7
-4.7
-5.7
-6.7
-7.7
-8.7
-9.7
-10.7
-11.7
-12.7
-13.7
-14.7
-15.7
-16.7
-17.7
-18.7
-19.7
07/01/2011 07/02 07/03 07/04 07/05 07/06 07/07 07/08 07/09 07/10 07/11 07/12 07/13 07/14 07/15 07/16 07/17 07/18 07/19 07/20 07/21 07/22 07/23 07/24 07/25 07/26 07/27 07/28 07/29 07/30 07/31 08/01/2011


(d)
Velocity along flood direction(m/s): cb0402, 07/01/2011 - 08/01/2011, Flood Dir.=192 deg
ADCP Scenario 1
Depth (m)
-3.45
-4.45
-5.45
-6.45
-7.45
-8.45
-9.45
-10.45
-11.45
-12.45
-13.45
-14.45
-15.45
-16.45
07/01/2011 07/02 07/03 07/04 07/05 07/06 07/07 07/08 07/09 07/10 07/11 07/12 07/13 07/14 07/15 07/16 07/17 07/18 07/19 07/20 07/21 07/22 07/23 07/24 07/25 07/26 07/27 07/28 07/29 07/30 07/31 08/01/2011

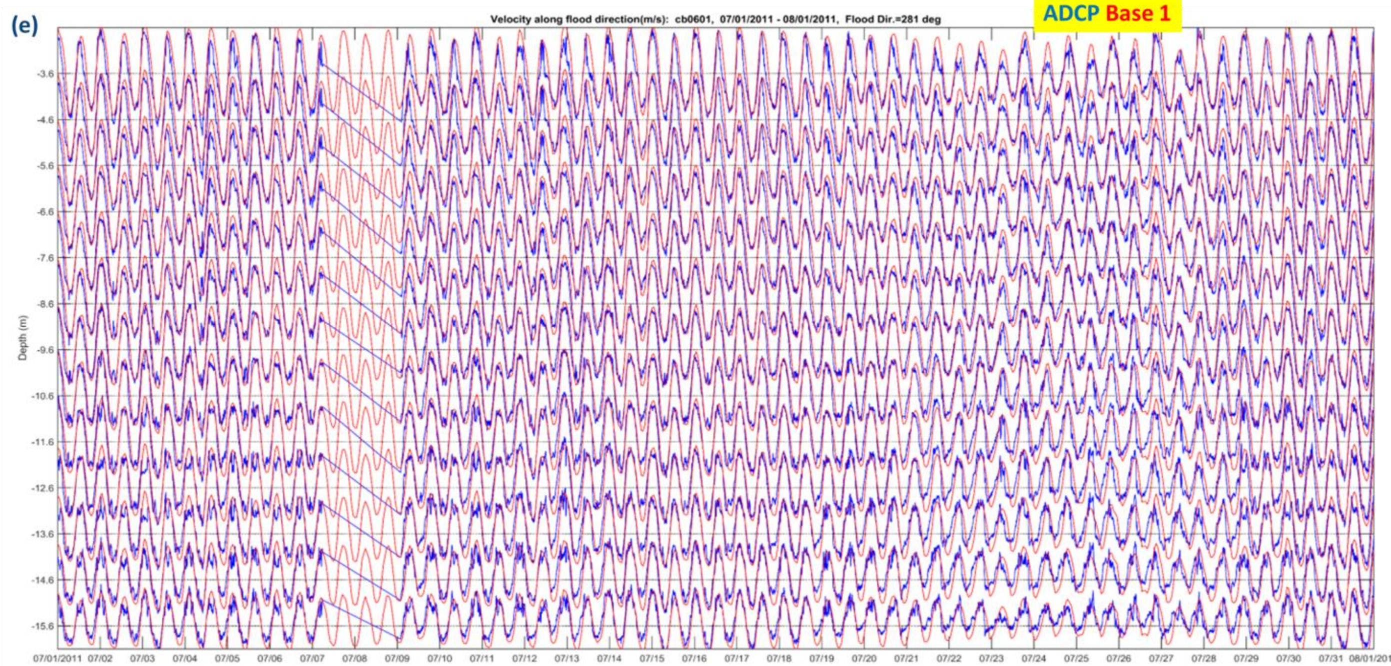


Figure 6: Comparison of along-channel velocity profiles at 4 NOAA stations at multiple depths. (a) Station location; (b) CB0102; (c) CB0301; (d) CB0402; (e) CB0601. 'ADCP' is the observed velocity and 'Base' is the model result.

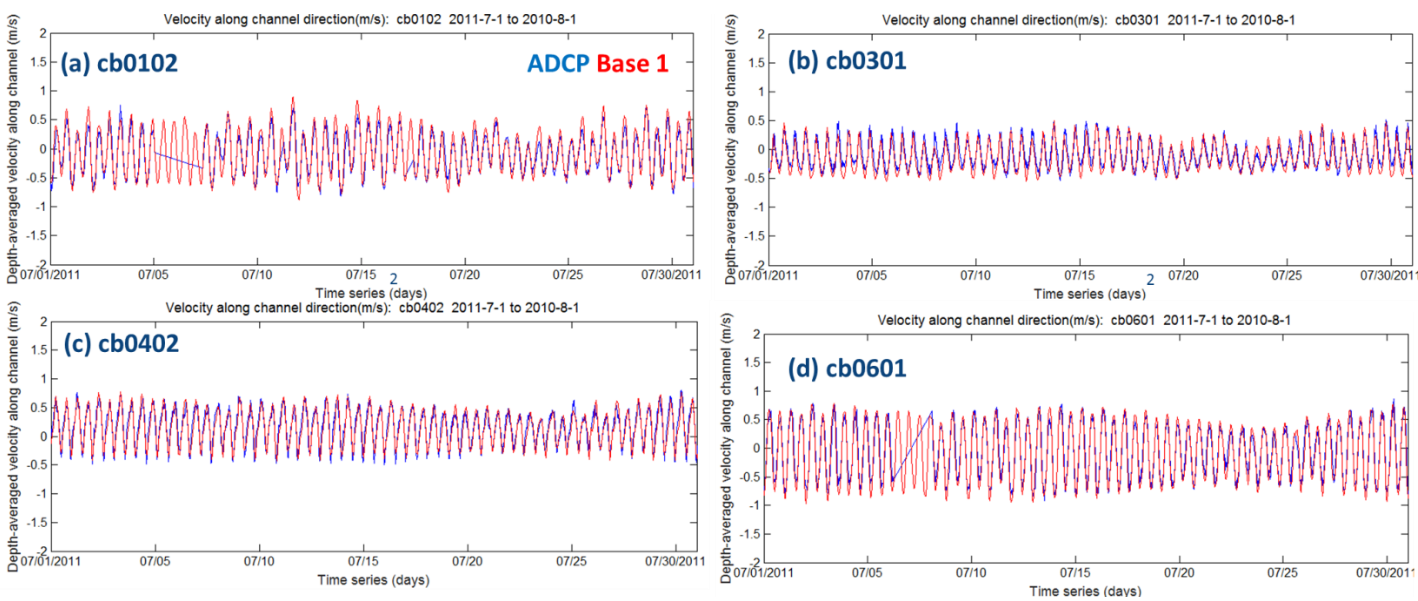


Figure 7: Comparison of depth-averaged velocity at the 4 ADCP stations shown in Fig. 6a. 'ADCP' is the observed velocity and 'Base' is the model result.

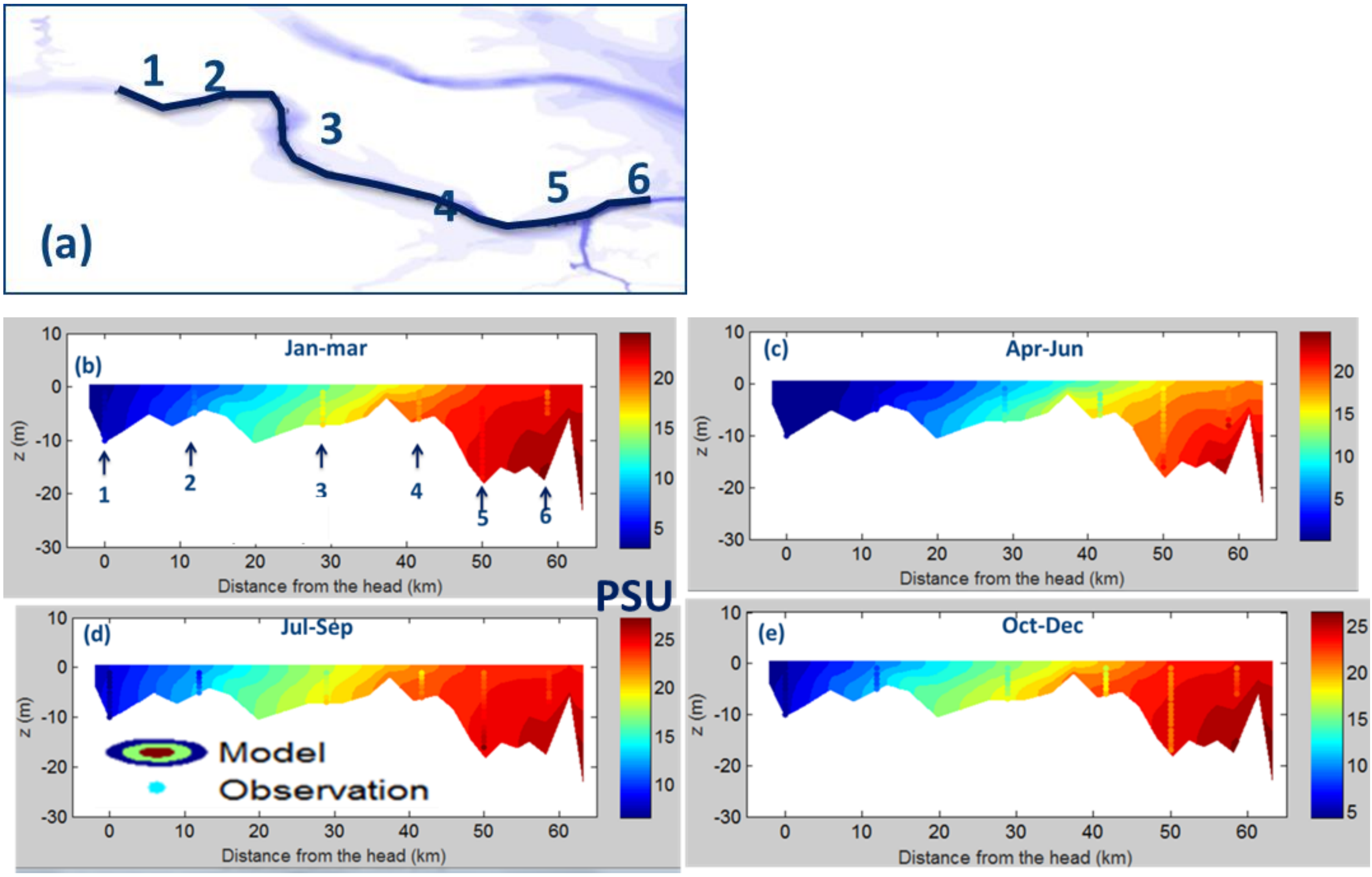
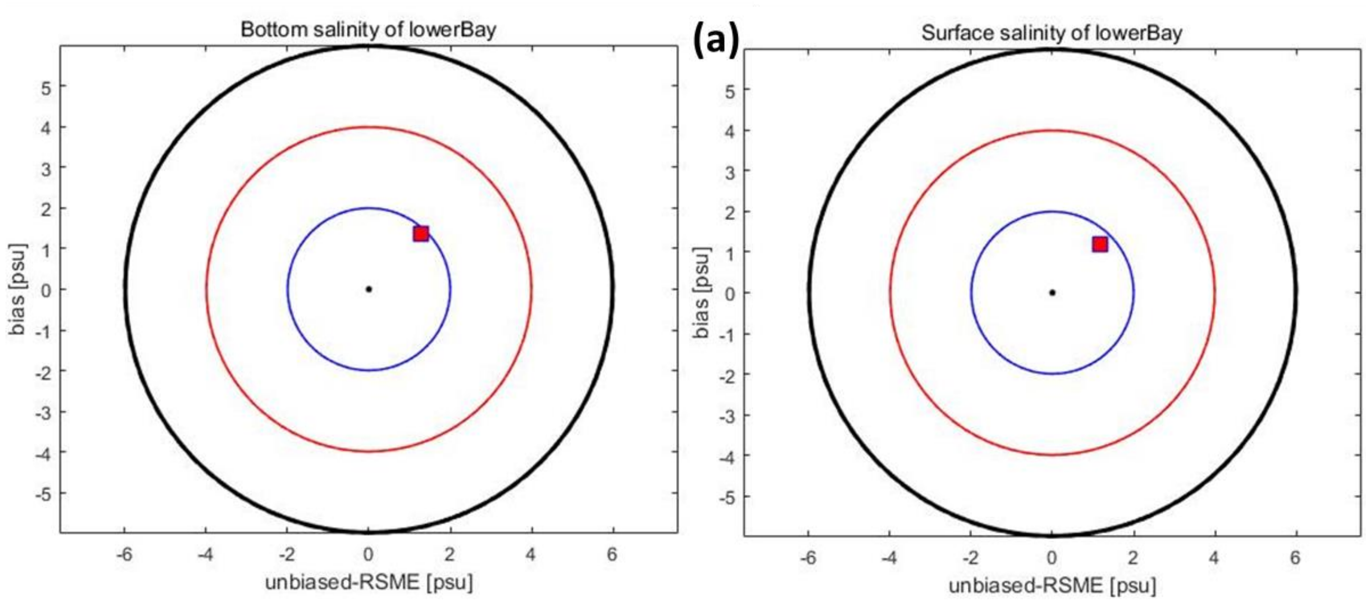


Figure 8: Comparison of averaged salinity profiles in 2011 along a transect location in the James River shown in (a). (b) From January to March; (c) April to June; (d) July to September; (e) October to December. The filled colors are model results and the circles represent the observation.



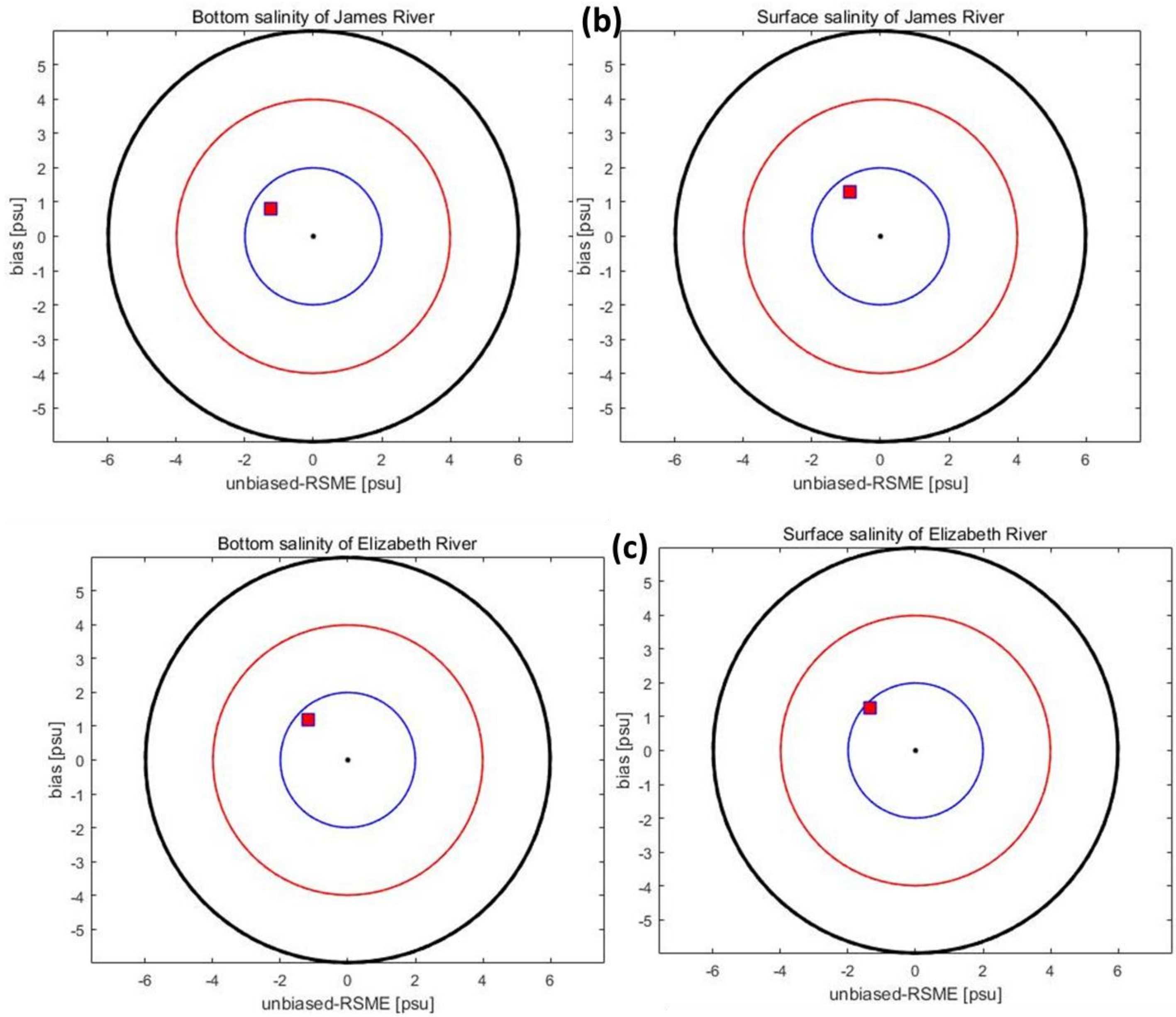
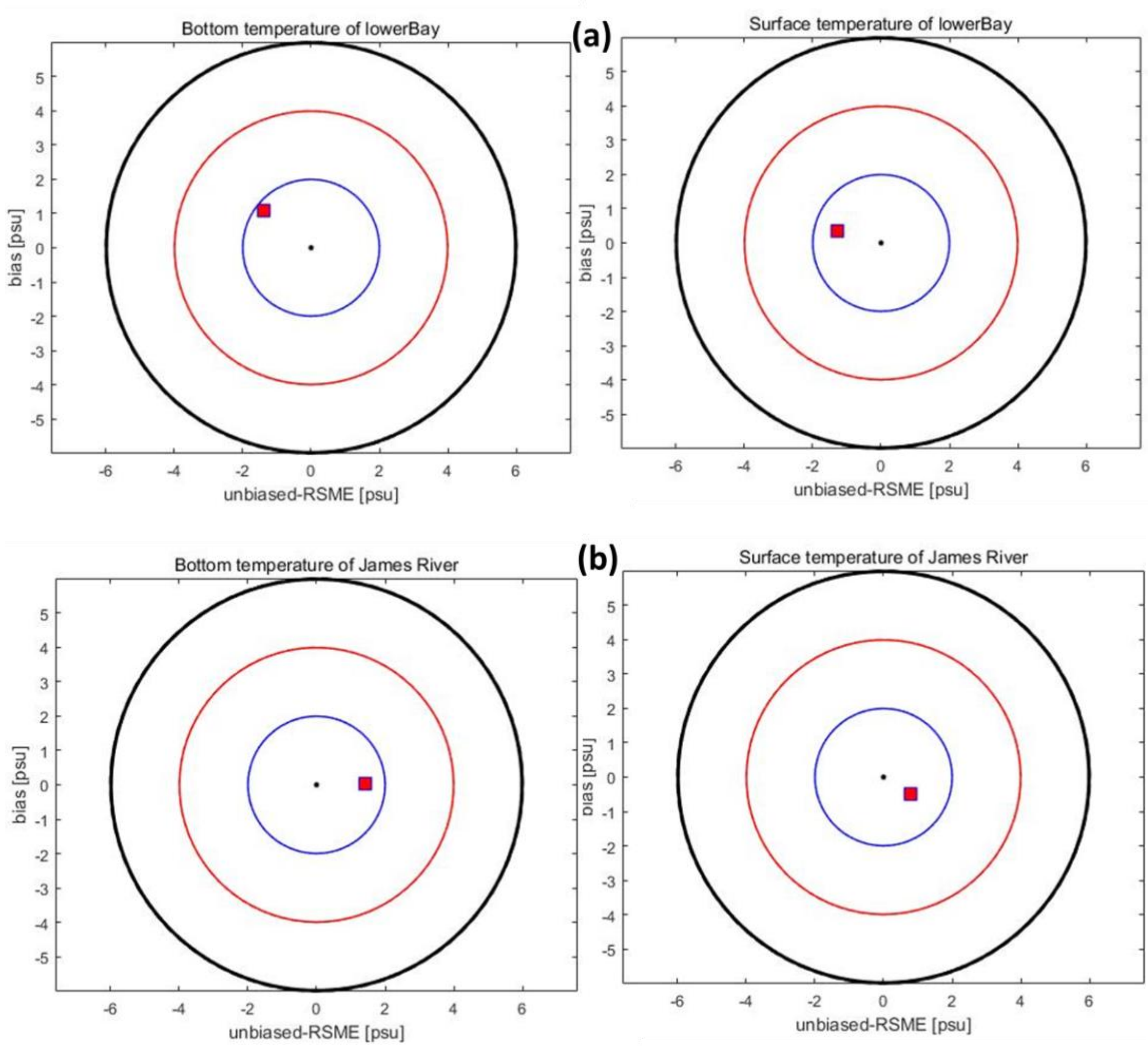


Figure 9: Target diagrams of salinity skill for (a) lower Bay; (b) James River; (c) Elizabeth River. The left panels show the bottom salinity skill and the right panels show the surface salinity skill. The *x*-axis shows the unbiased RMSE (i.e. with mean removed) scaled by the standard deviation of the observation, with positive values (*x*>0) indicating that the model standard deviation over-estimates that of the observation, and vice versa. The *y*-axis shows the model bias scaled by the standard deviation of the observation.


(a)
Bottom temperature of lowerBay
bias [psu]
unbiased-RSME [psu]
Surface temperature of lowerBay
bias [psu]
unbiased-RSME [psu]
(b)
Bottom temperature of James River
bias [psu]
unbiased-RSME [psu]
Surface temperature of James River
bias [psu]
unbiased-RSME [psu]

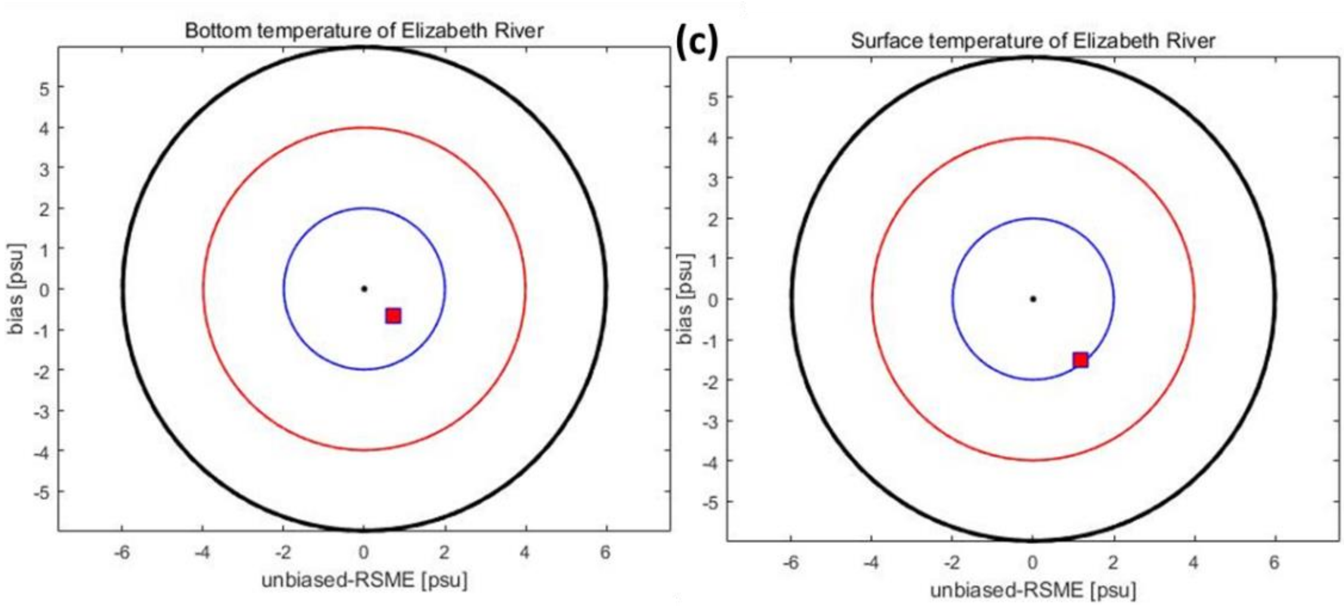


Figure 10: Target diagrams of temperature skill for (a) lower Bay; (b) James River; (c) Elizabeth River. See Fig. 9 for detailed explanations.

4. The scenarios runs results

All scenarios considered in this project are listed in Figure 11. The main differences between 'Base 1' (existing condition) and 'Base 2' (future without project) are the Craney Island Eastward Expansion (CIEE) built-out and removal of NIT piers near the entrance to Elizabeth River. Scenarios '3-1','4-1' and '5-1' are based on Base 1, with dredging in different stretches; '5-1' is essentially a combination of '3-1' and '4-1'. Similarly, Scenarios '3-2','4-2' and '5-2' are based on Base 2, with dredging in different stretches.
To assess the salinity change, we present the averaged differences for bottom and surface salinity, both in plan view and also along 2 channel transects. Time series of comparisons can be found in project archive. We first compare all scenarios to 'Base 1', and the time average is done from 2010-2013. Note that it might be more appropriate to compare the 'future with project' scenarios (e.g., '3-2' etc) to Base 2, but we use Base 1 as the basis of comparisons here so one can see the changes in each scenario from the current condition. By doing so, the comparisons with Base 2 can also be inferred from the 'difference of the difference' (e.g., '4-2' – 'Base 2' = ['4-2' – 'Base 1'] – ['Base 2' – 'Base 1']). Fig. 34 also shows direct comparisons between '*-2' scenarios and Base 2.
Between Base 2 and Base 1, most of larger salinity differences occur near the dredged access channel (from ~5m to ~15m); salinity differences are much smaller elsewhere (~0.1 ppt or less) (Fig. 12). As in all scenarios, the bottom salinity exhibits more channelized pattern than the surface salinity.

For the rest of comparisons, we note that scenarios '4-X' (where X=1 , 2) show smallest changes from 'Base 1', followed by scenarios '3-X'; scenarios '5-X', which combine the bathymetry changes from '3-X' and '4-X', show the largest changes from 'Base 1' (Figs. 13-18). Salinity increases from scenarios 'Y-2' (where Y=3,4,5) are larger than from scenarios 'Y-1', as the former also incorporate the bathymetry changes near the entrance of Elizabeth River etc. Therefore the largest changes (from ‘Base 1’) are found in scenario ‘5-2’.

The salinity increases along 2 along-channel transects in James and Elizabeth Rivers reveal that the gravitational circulation is generally enhanced with channel dredging, especially so near the mesohaline regions (Figs. 19-32). Since the strength of the gravitational circulation is a function of freshwater inflow, seasonal variability of salinity changes are seen in all transects. This is especially obvious in Elizabeth River, where the largest increases of 1-2 ppt are found in most parts of Elizabeth River during winter and spring months with large river discharge from upstream of James River (Dec-Jan, April-May). As a result, the salt intrusion via ship channel from the bottom layer is the strongest which combined with freshwater discharge sets up both the horizontal and vertical salinity gradient. The differences in the salinity increase over time suggest that the increase is correlated to stratification; in the asymptotic case of no freshwater inflow/stratification, channel deepening would not lead to any change in salinity as the water is uniformly of marine origin. This seasonal salinity increase can change the location of the limit of salt intrusion and turbidity maximum and enhance the flushing time through the strengthening of the gravitational circulation and thus impact the water quality (c.f. the water quality assessment report).

It should be emphasized that the salinity increases are mostly confined in the vicinity of the project area in the lower James River and Elizabeth River and the impact on the rest of the Bay is much smaller (<0.1 ppt). The largest change is found in Elizabeth River (especially during spring, winter and high flow months), followed by lower James River; and outside these regions the changes are mostly negligible (Figs. 12-18). Similar pattern may be inferred for DO as the latter is closely related to the density stratification. When the Southern Branch is dredged, the salinity changes in the Elizabeth River are found intruding all the way upstream of the Southern Branch (e.g., Figs. 18, 32), suggesting a rather efficient connectivity with the James River.

The overall statistics of salinity changes in the 3 regions are summarized in Figs. 33 & 34. In general, the 3 scenarios built on ‘Base 2’ result in larger salinity increase than those built on ‘Base 1’. Consistent with the results above, the salinity increase is smallest in ‘4-X’, followed by ‘3-X’ and ‘5-X’. The maximum change as found in ‘5-2’ in Elizabeth River is ~0.6 ppt (but can reach 2 ppt as mentioned above). The 2nd largest increase is found in the James River (~0.2 ppt). The smallest increase is found in the lower Bay area, with ~0.1 ppt on average. To put these values in perspective, the natural variability in salinity in lower Bay, James River and Elizabeth River, expressed as the standard deviations of the observed salinity, are 3, 2.4 and 2.3 ppt respectively. We also remark that even the largest increase in salinity is within the model uncertainty (since the RMSE is ~2ppt). The fact that the largest *relative* change occurs in the Elizabeth River is not surprising because the bathymetry/geometry alteration is the greatest at CIEE.

This report did not consider the impact of proposed 3rd crossing on “Future Without Project” condition. However, we are engaged in another project that assesses the impact of proposed 3rd crossing in the lower Hampton Roads area, and the results also suggest only localized impact (up to 1.5 ppt) near the crossings and minor impact (~0.1 ppt) in all areas 4 km away from the new crossings. On a global level, the 95th percentile values of the changes in hydrodynamic variables are shown to be within 2% of the existing condition, thus suggesting a relatively minor impact. Therefore it seems reasonable to exclude the 3rd Crossing detail from the “Future Without Project” condition.

Runs	Scenario	Description	Norfolk Harbor Deepened	So Branch Deepened
1	**1- Baseline – Existing Conditions**	**Current Without-project conditions/Baseline** **Includes:** • CIEE with the 2 cross dikes (as is conditions)– no fill between the dikes, or any dredging of the access channel	**No**	**No**
2	**2 -Baseline - Future Without Project Conditions**	**Future without-project** **Includes consideration of:** • CBBT – TSC parallel tunnel • HRBT – parallel tunnel • 3rd Crossing/ Patriots Crossing • NIT Piers 1 and 2 removed, with dredged area to -50' • CIEE full build out Note: VIMS will provide memo/input detailing how above is being taken into consideration.	**No**	**No**
3	**3-1**	***Exist Conditions with deepened NH channel*** *With Project Scenario* that includes a deepening of the Norfolk Harbor and Channels without the So Branch of the Elizabeth River, using existing conditions in Run 1.	Yes	No
4	**3-2**	***Future Conditions with deepened NH channel*** *With Project Scenario* that includes a deepening of the Norfolk Harbor and Channels without the So Branch of the Elizabeth River deepened, using future conditions noted in Run 2.	**Yes**	**No**
5	**4-1**	***Exist Conditions with deepened SB channel*** *With Project Scenario* that includes a deepening of the So Branch of the Elizabeth River without the Norfolk Harbor and Channels using existing conditions in Run 1.	**No**	**Yes**
6	**4-2**	***Future Conditions with deepened SB Channel*** *With Project Scenario* that includes a deepening of the So Branch of the Elizabeth River without the Norfolk Harbor deepened, using future conditions noted in Run 2.	**No**	**Yes**
7	**5-1**	***Exist Conditions with deepened NH & SB channels*** *With Project Scenario* that includes a deepening of both the Norfolk Harbor and Channels and the So Branch of the Elizabeth River using existing conditions in Run 1.	**Yes**	**Yes**
8	**5-2**	***Future Conditions with deepened NH & SB Channel*** *With Project Scenario* that includes a deepening of both the So Branch of the Elizabeth River and the Norfolk Harbor, using future conditions noted in Run 2.	**Yes**	**Yes**

Figure 11: Description of simulation scenarios.

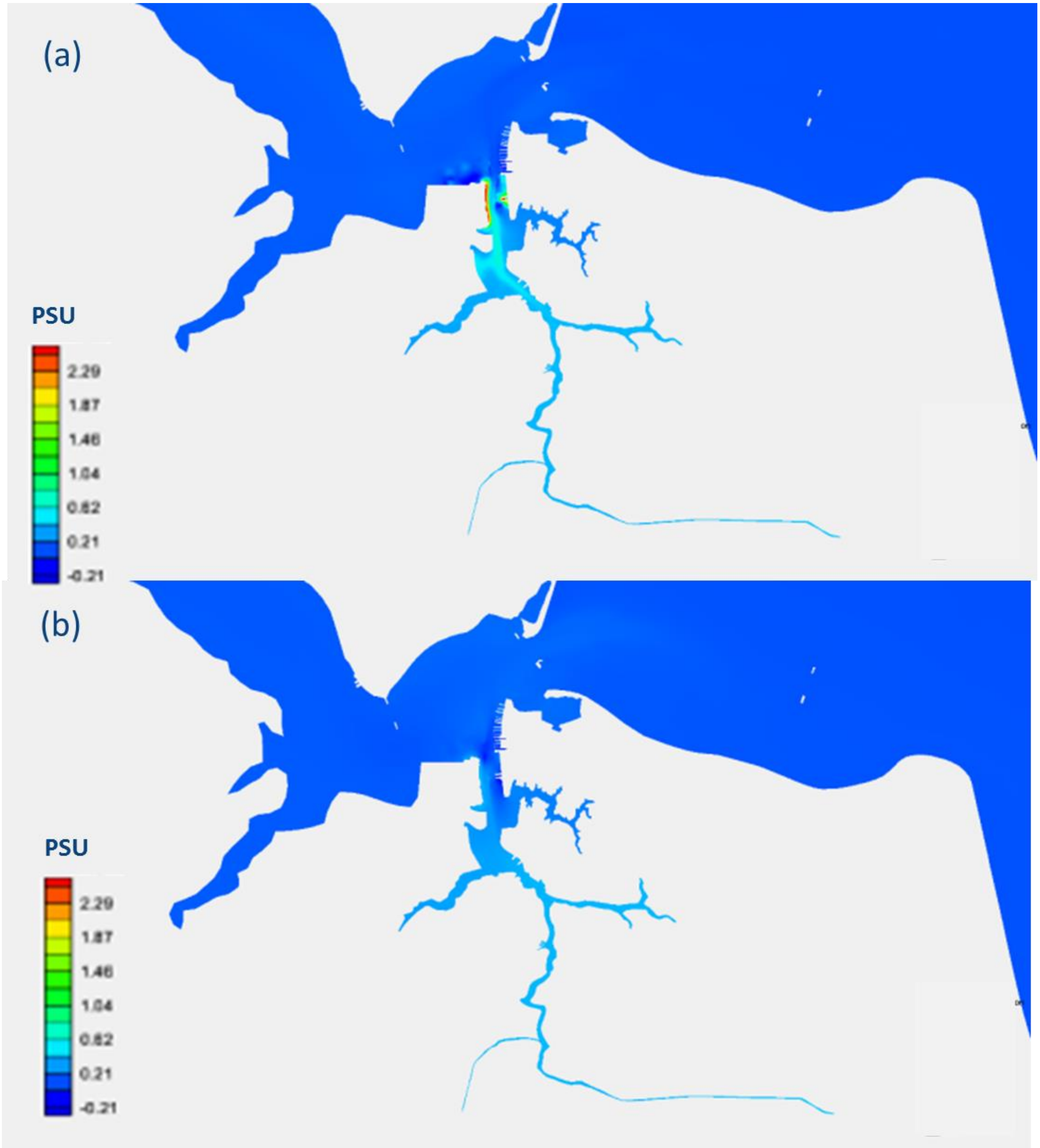


Figure 12: Time-averaged salinity differences (from 2010-2013) between Base 2 and Base 1 at (a) bottom and (b) surface.

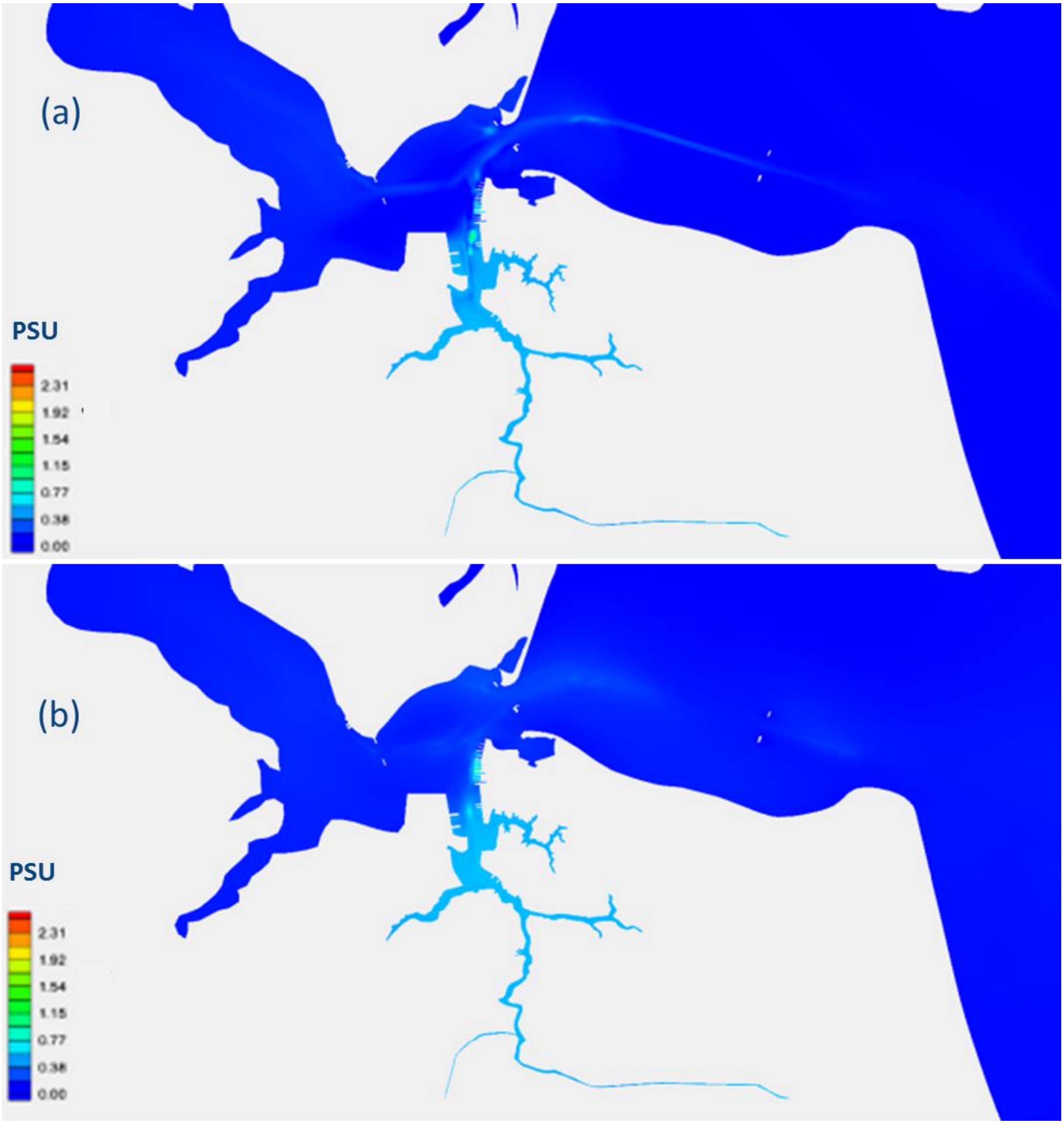


Figure 13: Time-averaged salinity differences between Scenario '3-1' and Base 1 at (a) bottom and (b) surface.

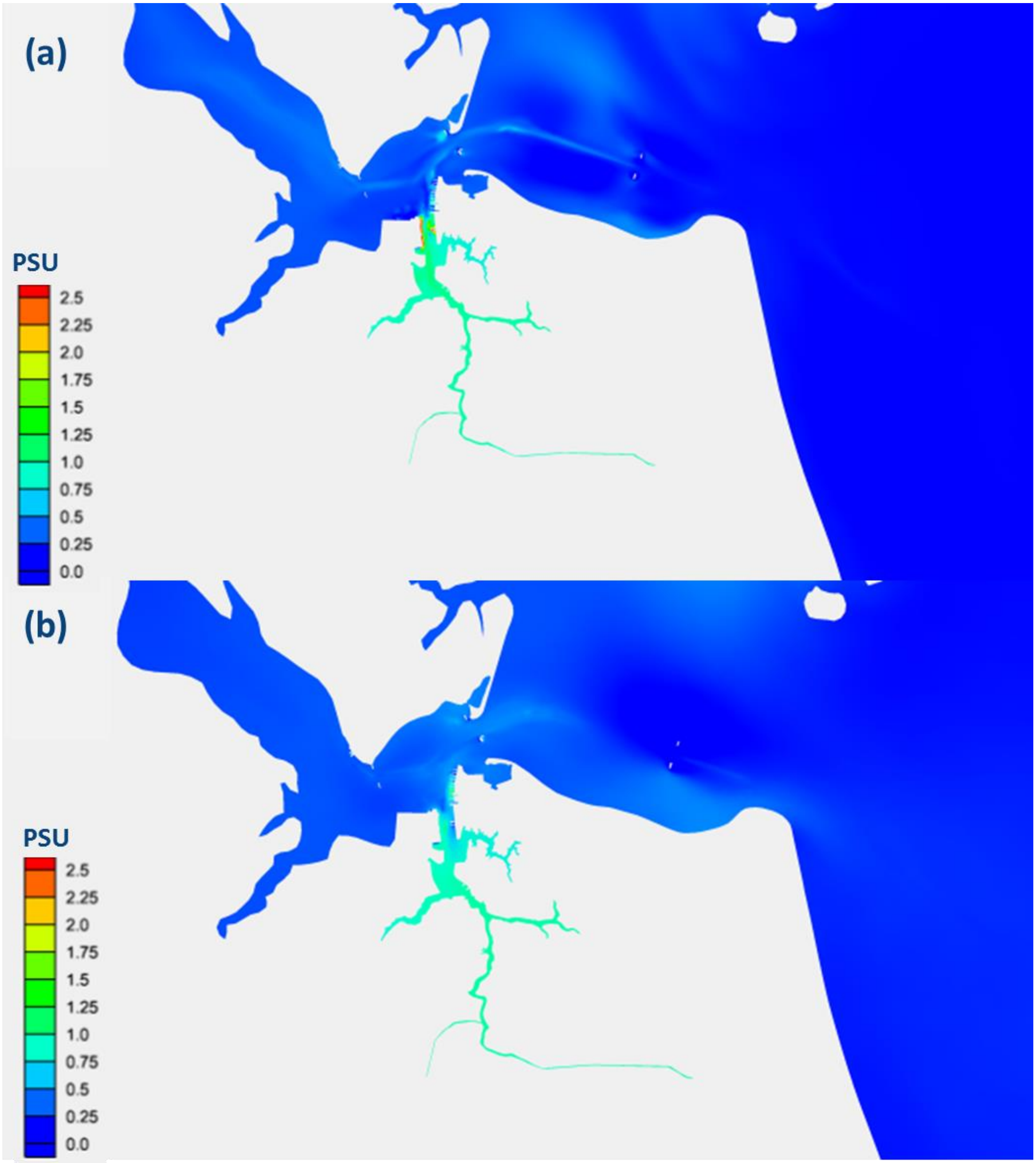


Figure 14: Time-averaged salinity differences between Scenario '3-2' and Base 1 at (a) bottom and (b) surface.

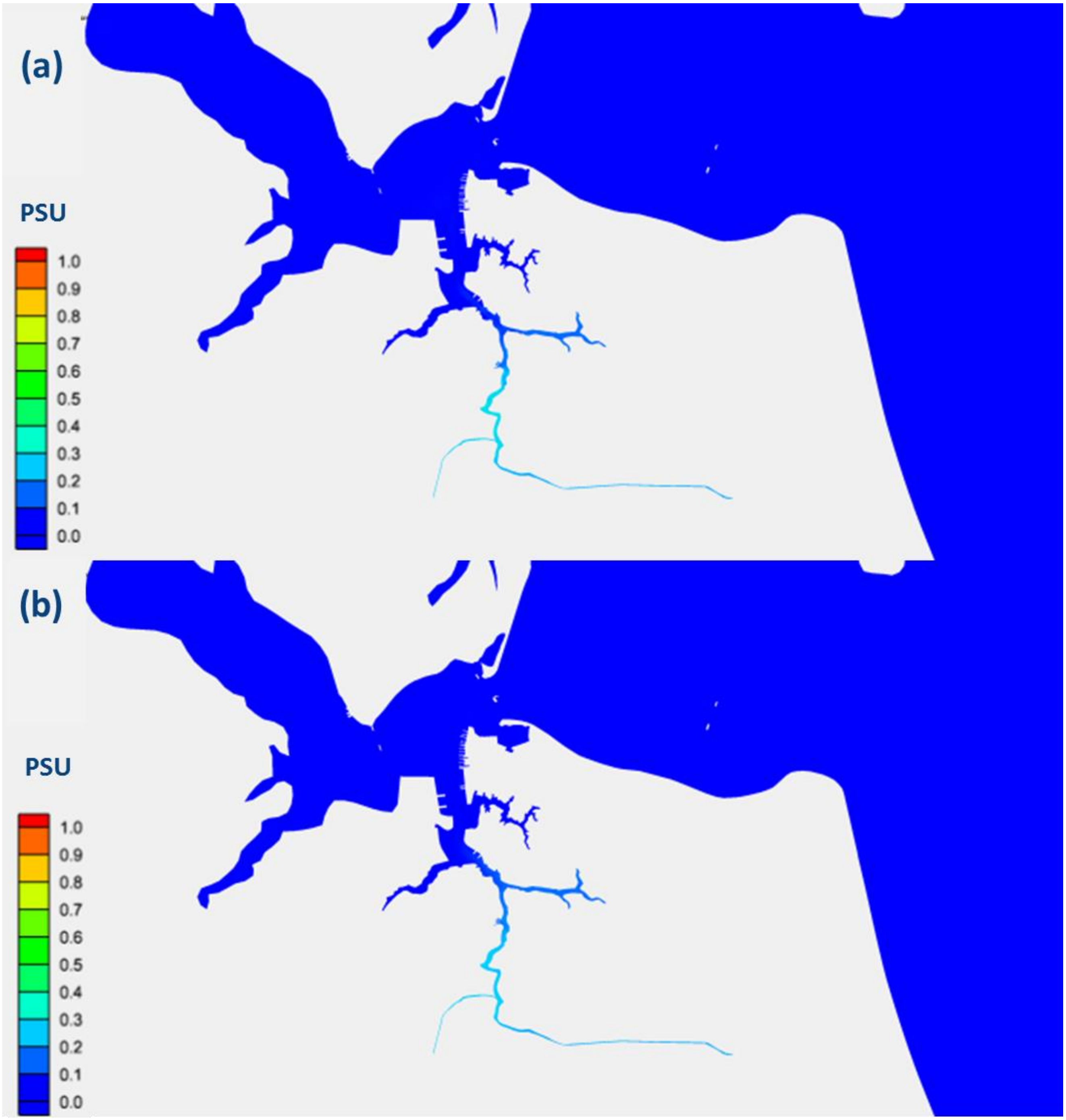


Figure 15: Time-averaged salinity differences between Scenario '4-1' and Base 1 at (a) bottom and (b) surface.

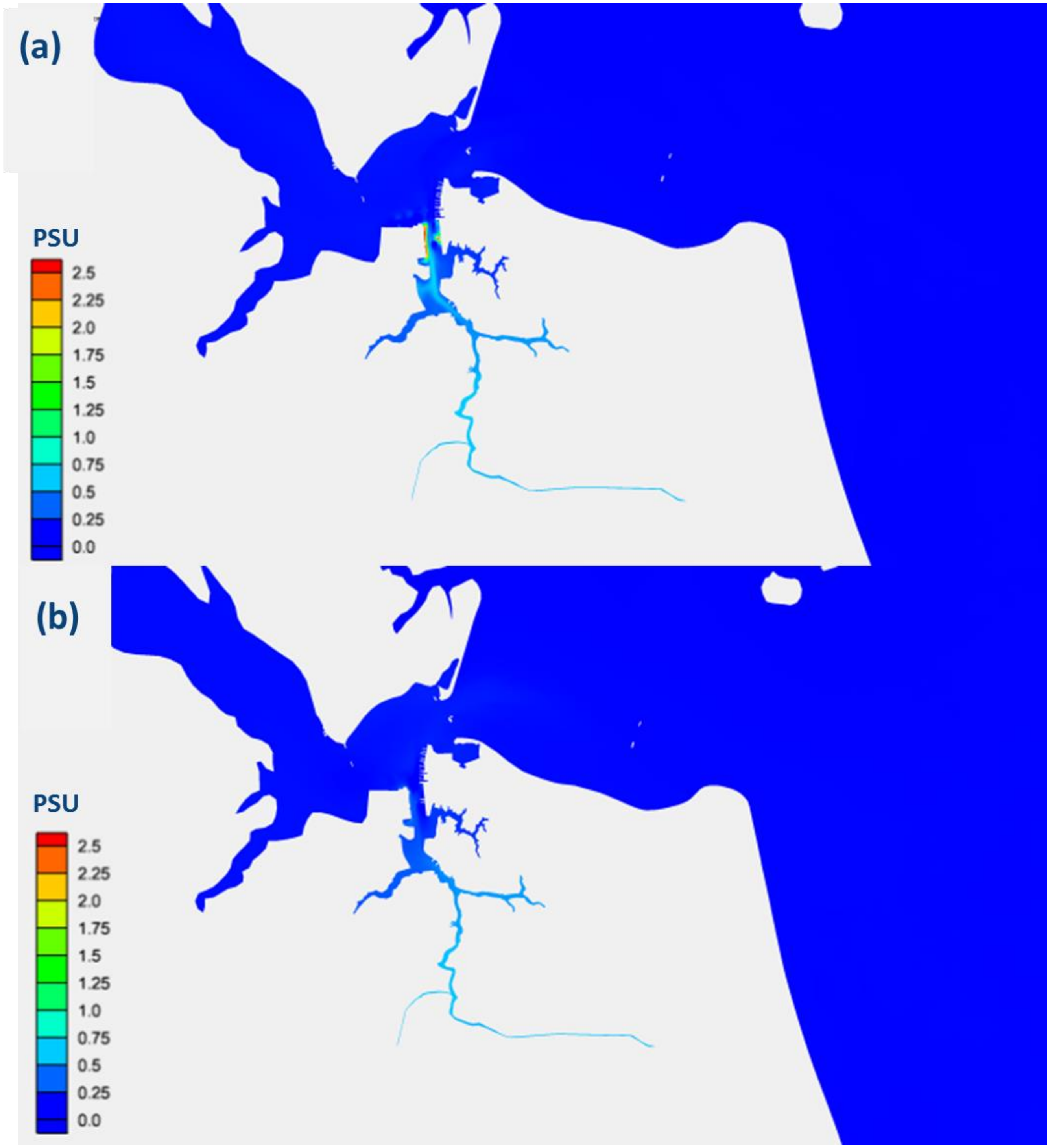


Figure 16: Time-averaged salinity differences between Scenario '4-2' and Base 1 at (a) bottom and (b) surface.

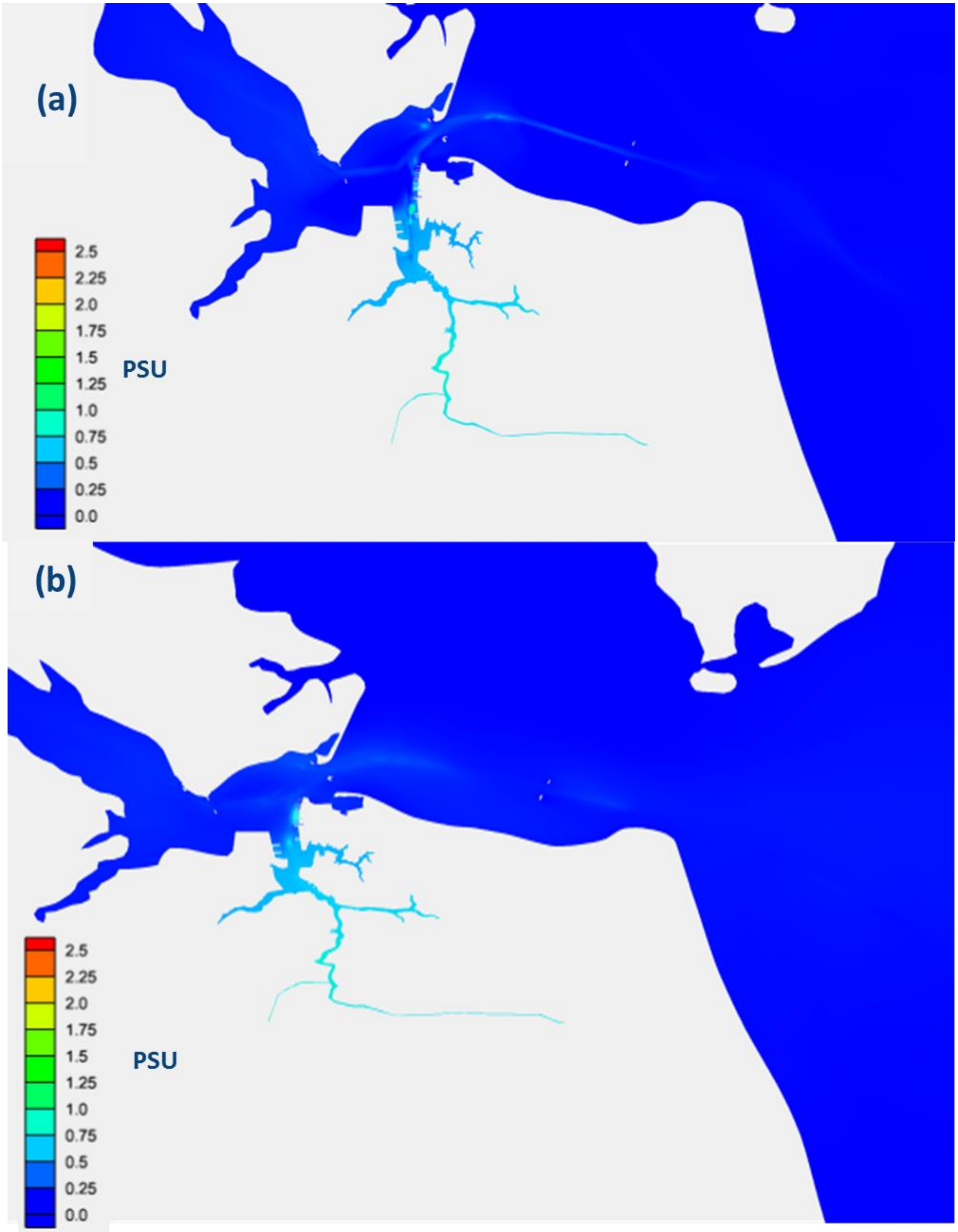


Figure 17: Time-averaged salinity differences between Scenario '5-1' and Base 1 at (a) bottom and (b) surface.

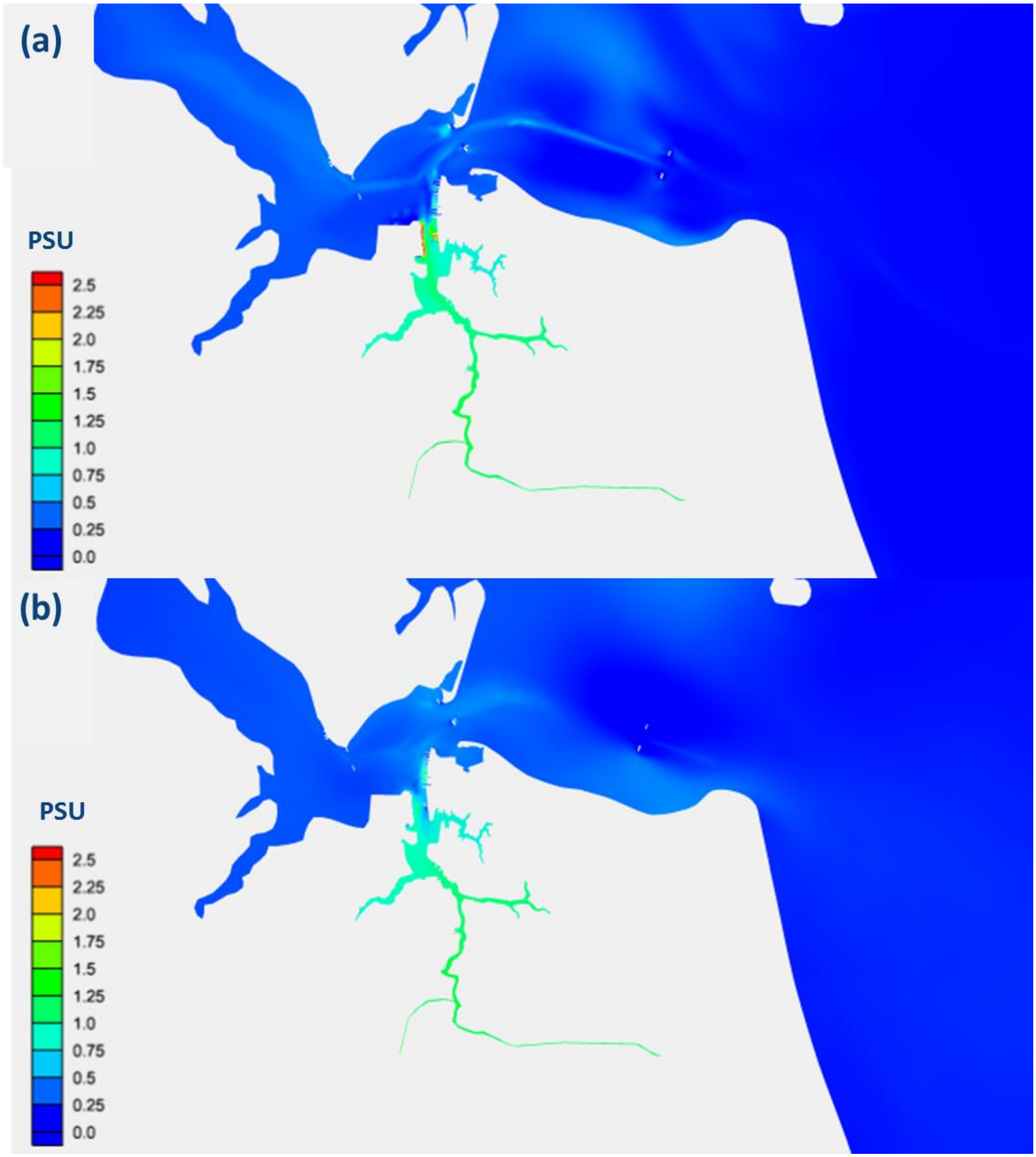
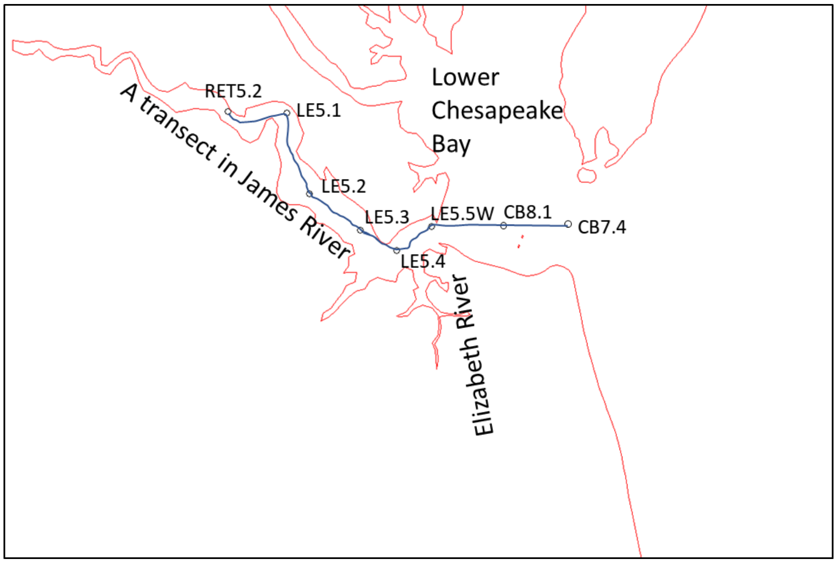
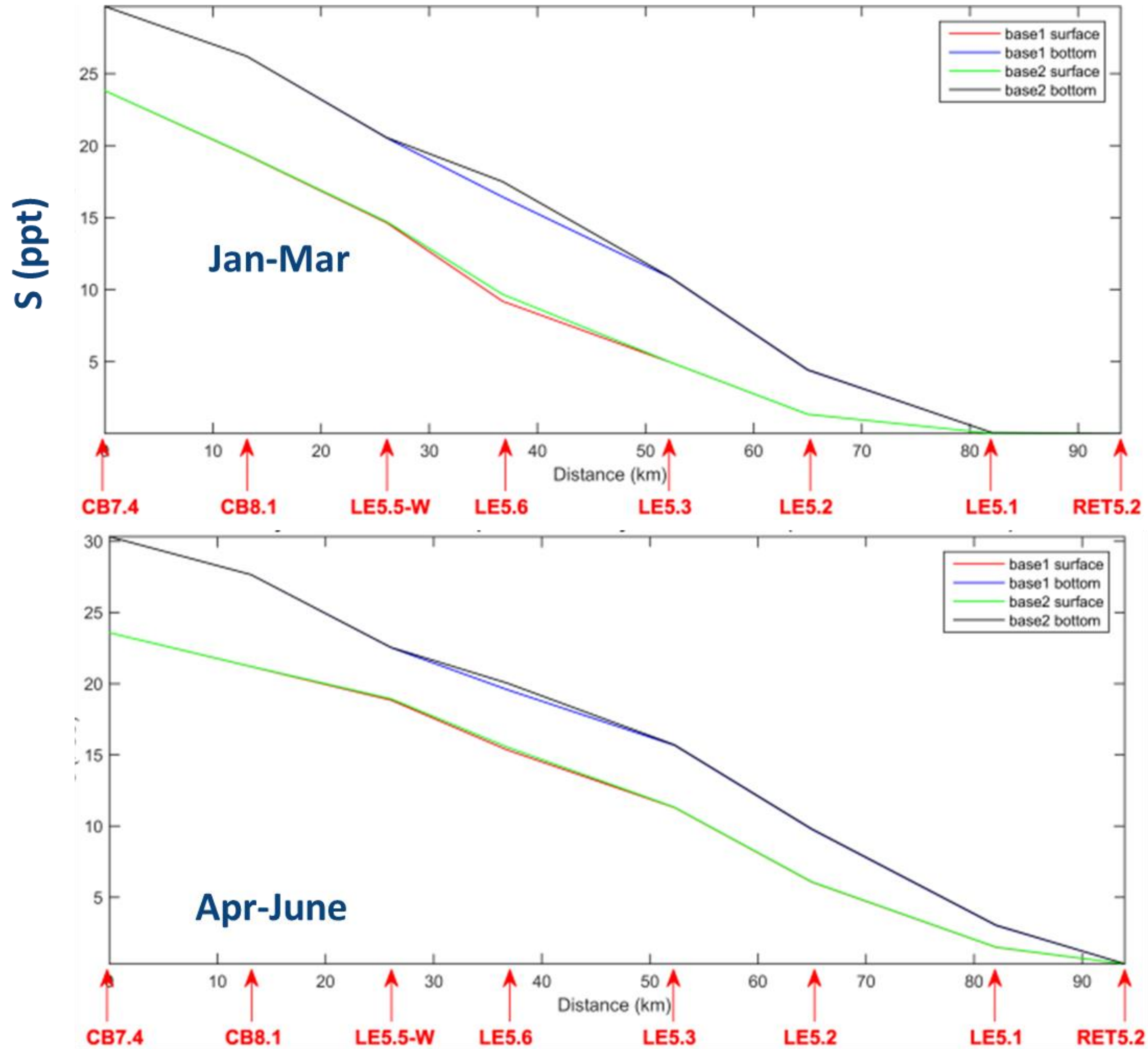


Figure 18: Time-averaged salinity differences between Scenario '5-2' and Base 1 at (a) bottom and (b) surface.


Lower
Chesapeake
Bay
RET5.2
LE5.1
A transect in James River
LE5.2
LE5.3
LE5.5W
CB8.1
CB7.4
LE5.4
Elizabeth River


S (ppt)
Jan-Mar
base1 surface
base1 bottom
base2 surface
base2 bottom
Distance (km)
CB7.4
CB8.1
LE5.5-W
LE5.6
LE5.3
LE5.2
LE5.1
RET5.2
Apr-June
base1 surface
base1 bottom
base2 surface
base2 bottom
Distance (km)
CB7.4
CB8.1
LE5.5-W
LE5.6
LE5.3
LE5.2
LE5.1
RET5.2

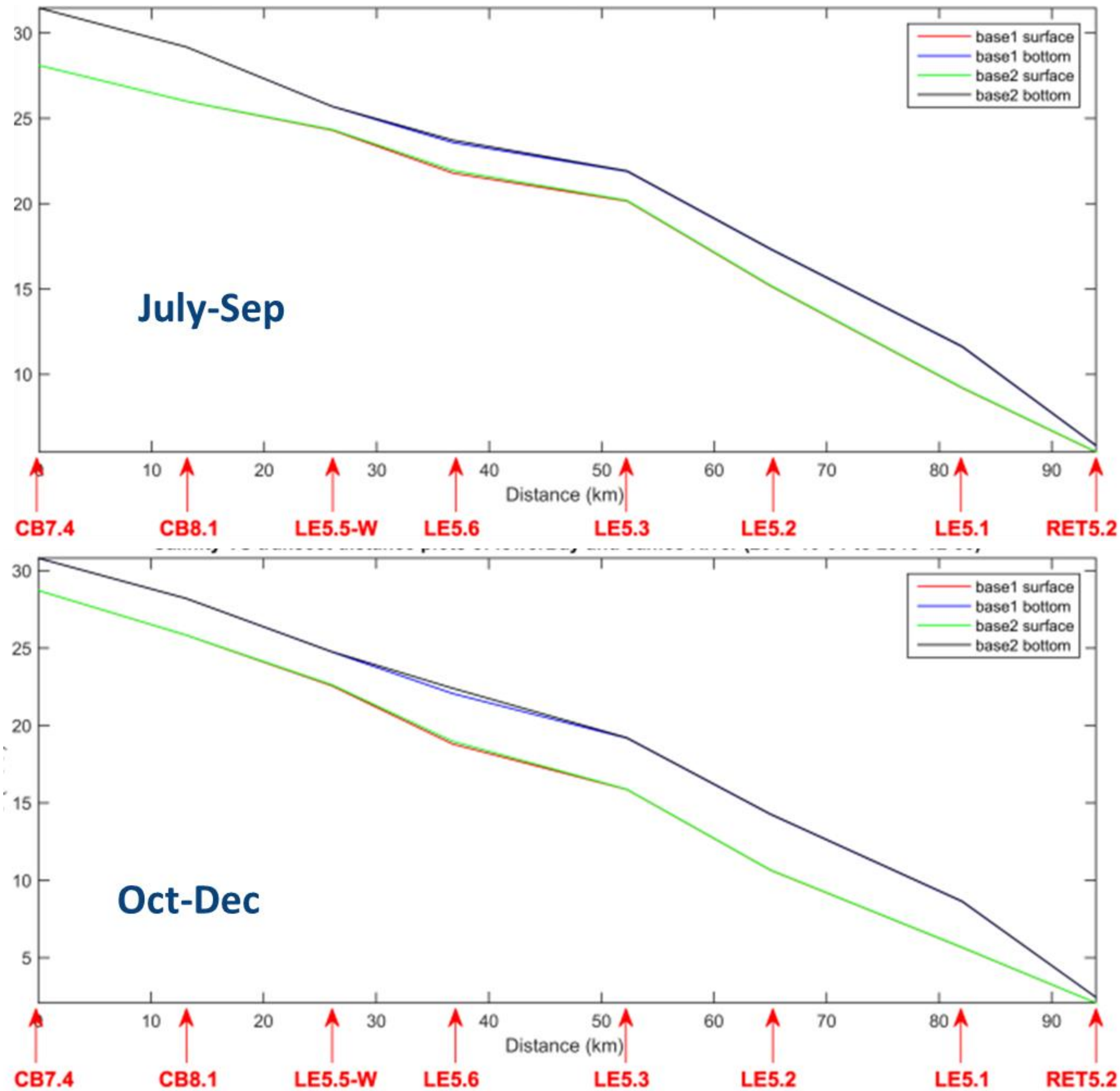
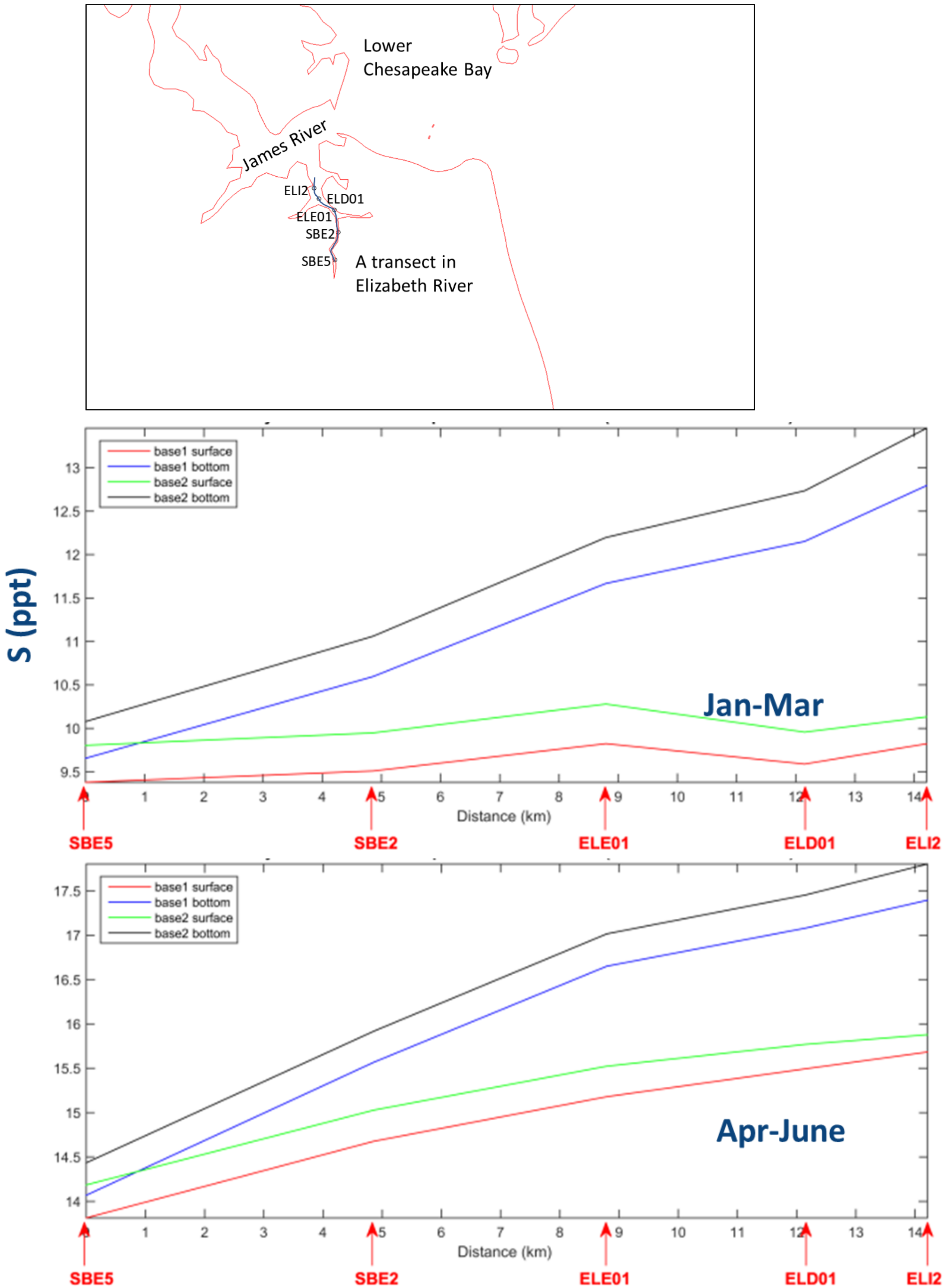


Figure 19: Averaged salinity differences (at surface and bottom) between Base 2 and Base 1 along a transect from lower Bay into James River. See the 1st panel for the transect location and corresponding observation stations. Differences are shown every 3 months and the averaging is done from 2010-2013.


Lower
Chesapeake Bay
James River
ELI2
ELD01
ELE01
SBE2
SBE5
A transect in
Elizabeth River
S (ppt)
base1 surface
base1 bottom
base2 surface
base2 bottom
Jan-Mar
Distance (km)
SBE5
SBE2
ELE01
ELD01
ELI2
base1 surface
base1 bottom
base2 surface
base2 bottom
Apr-June
Distance (km)
SBE5
SBE2
ELE01
ELD01
ELI2

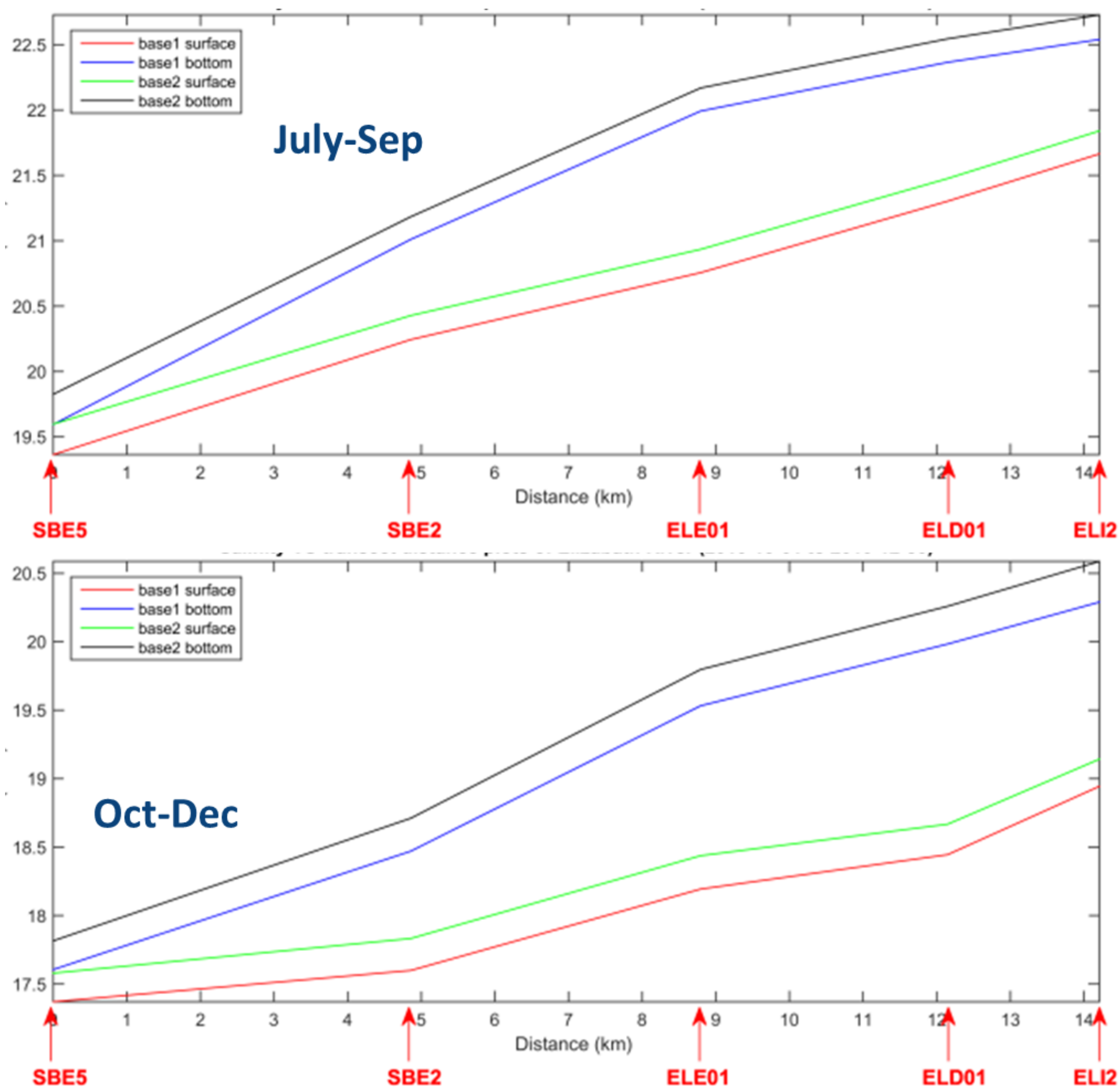
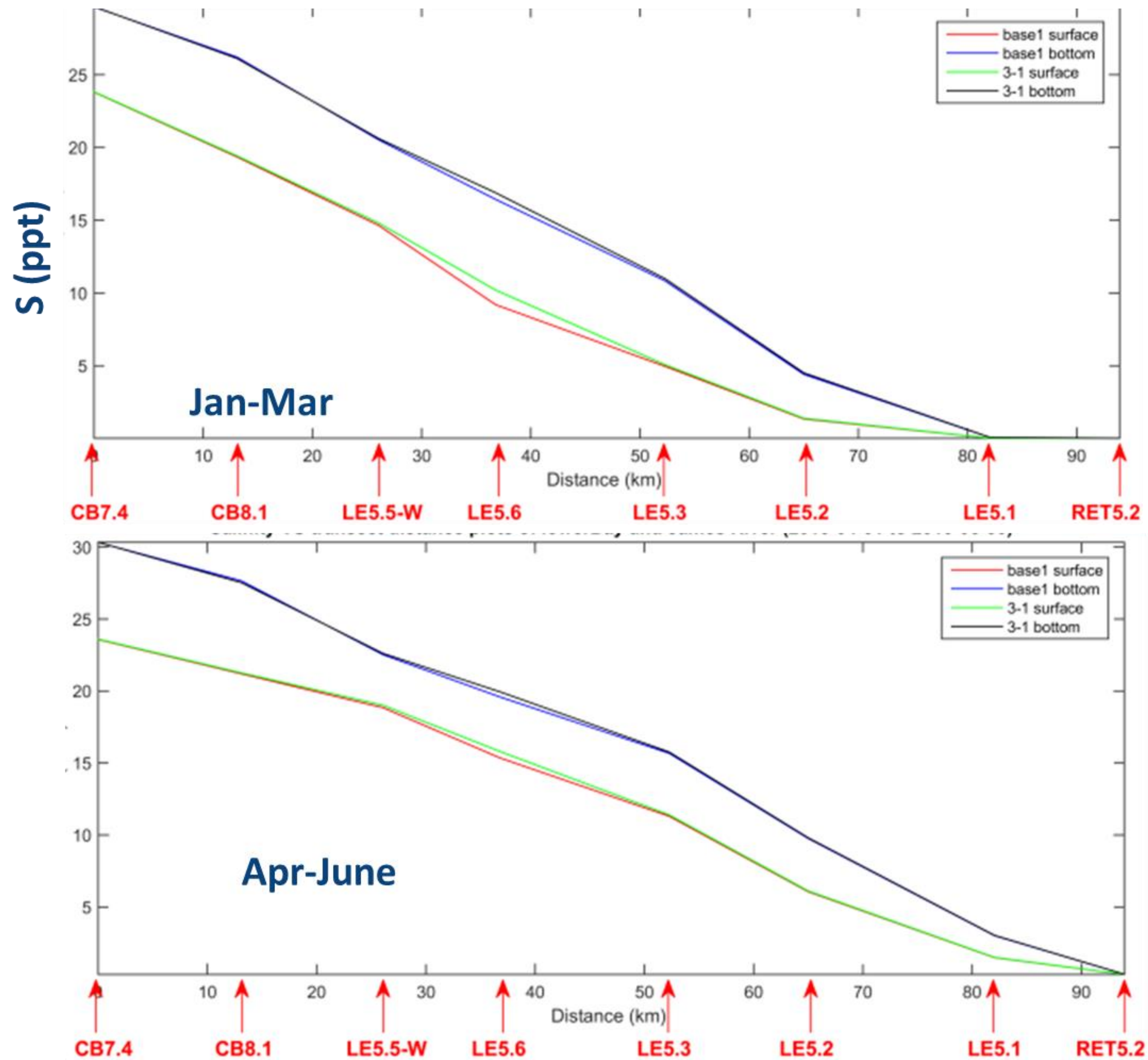


Figure 20: Averaged salinity differences (at surface and bottom) between Base 2 and Base 1 along a transect from Elizabeth River into James River. See the 1st panel for the transect location and corresponding observation stations. Differences are shown every 3 months.


S (ppt)
base1 surface
base1 bottom
3-1 surface
3-1 bottom
Jan-Mar
Distance (km)
CB7.4
CB8.1
LE5.5-W
LE5.6
LE5.3
LE5.2
LE5.1
RET5.2
base1 surface
base1 bottom
3-1 surface
3-1 bottom
Apr-June
Distance (km)
CB7.4
CB8.1
LE5.5-W
LE5.6
LE5.3
LE5.2
LE5.1
RET5.2

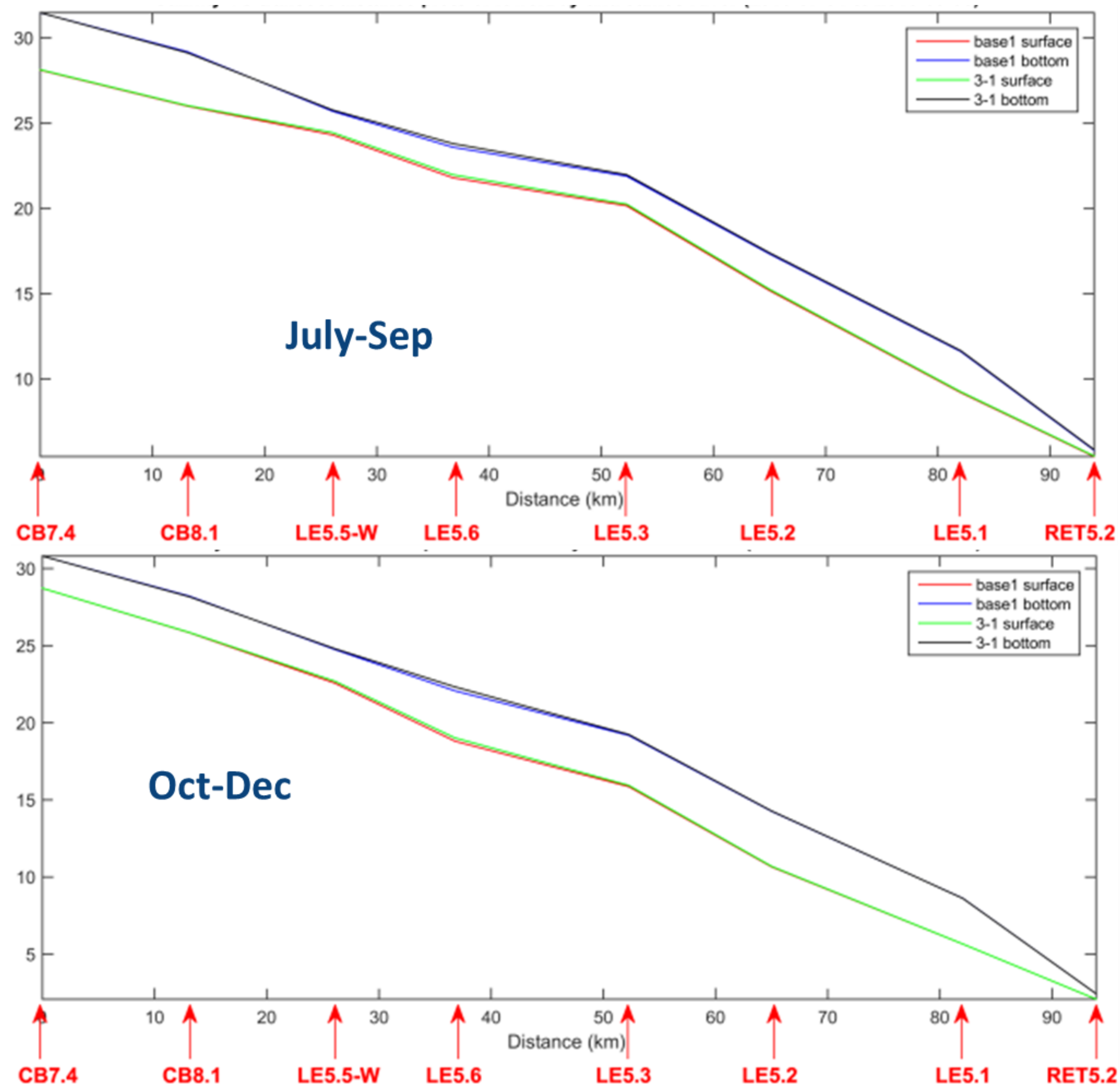
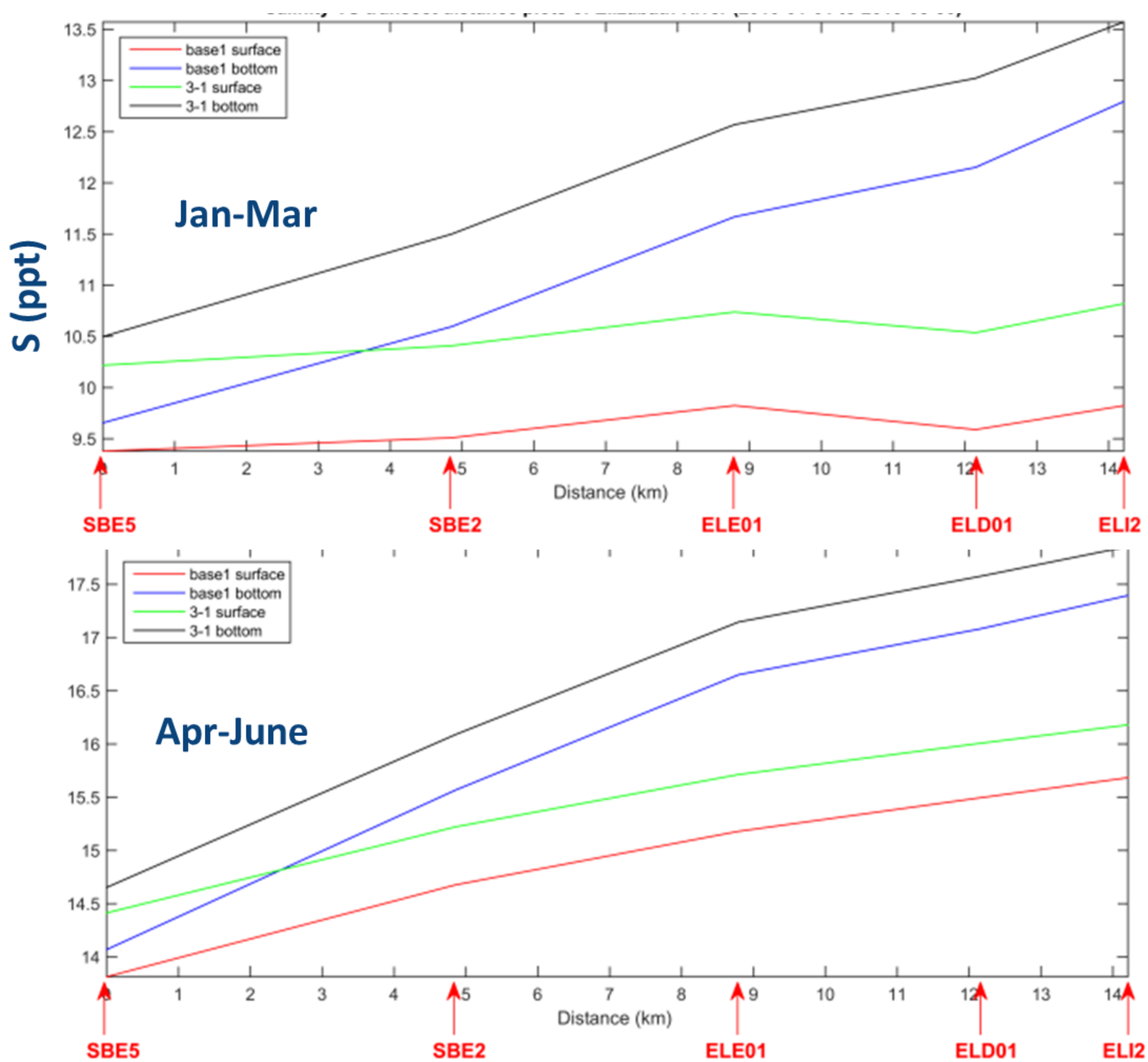


Figure 21: Averaged salinity differences (at surface and bottom) between '3-1' and Base 1 along a transect from lower Bay into James River. See Fig. 19 for the transect location. Differences are shown every 3 months.



base1 surface
base1 bottom
3-1 surface
3-1 bottom
Jan-Mar
S (ppt)
Distance (km)
SBE5
SBE2
ELE01
ELD01
ELI2
Apr-June

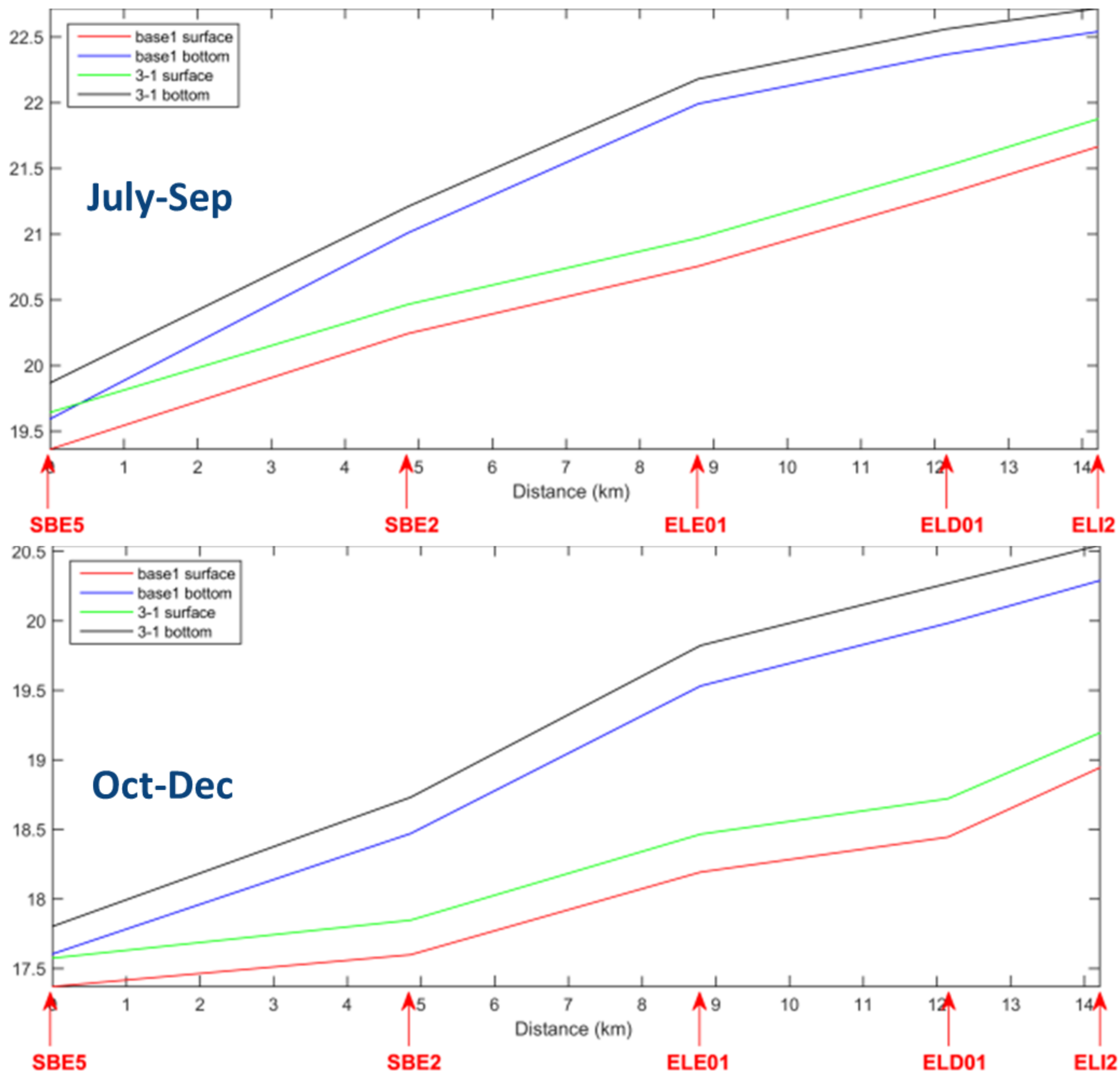
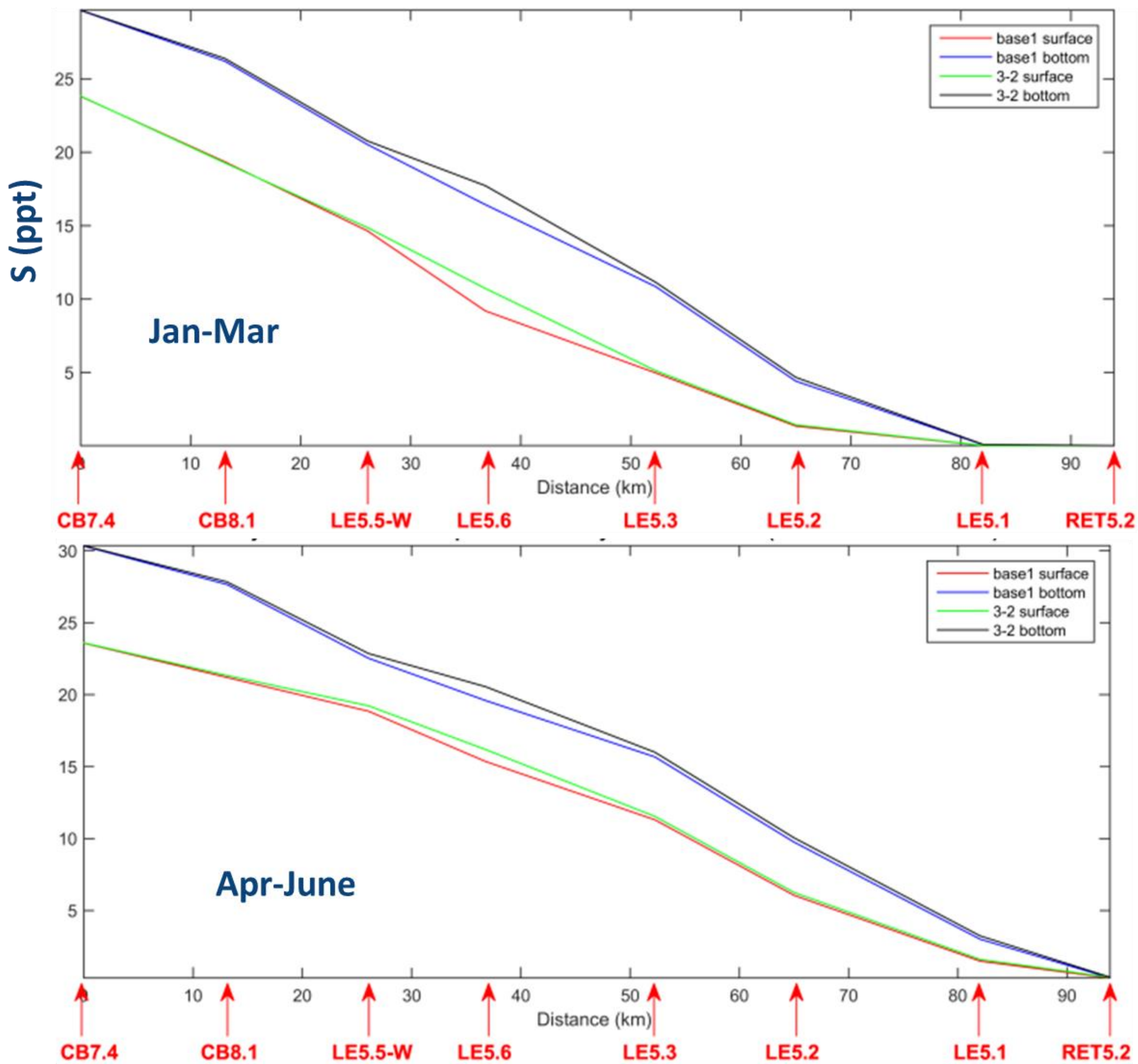


Figure 22: Averaged salinity differences (at surface and bottom) between '3-1' and Base 1 along a transect from Elizabeth River into James River. See Fig. 20 for the transect location. Differences are shown every 3 months.


S (ppt)
Jan-Mar
base1 surface
base1 bottom
3-2 surface
3-2 bottom
Distance (km)
CB7.4
CB8.1
LE5.5-W
LE5.6
LE5.3
LE5.2
LE5.1
RET5.2
Apr-June
base1 surface
base1 bottom
3-2 surface
3-2 bottom
Distance (km)
CB7.4
CB8.1
LE5.5-W
LE5.6
LE5.3
LE5.2
LE5.1
RET5.2

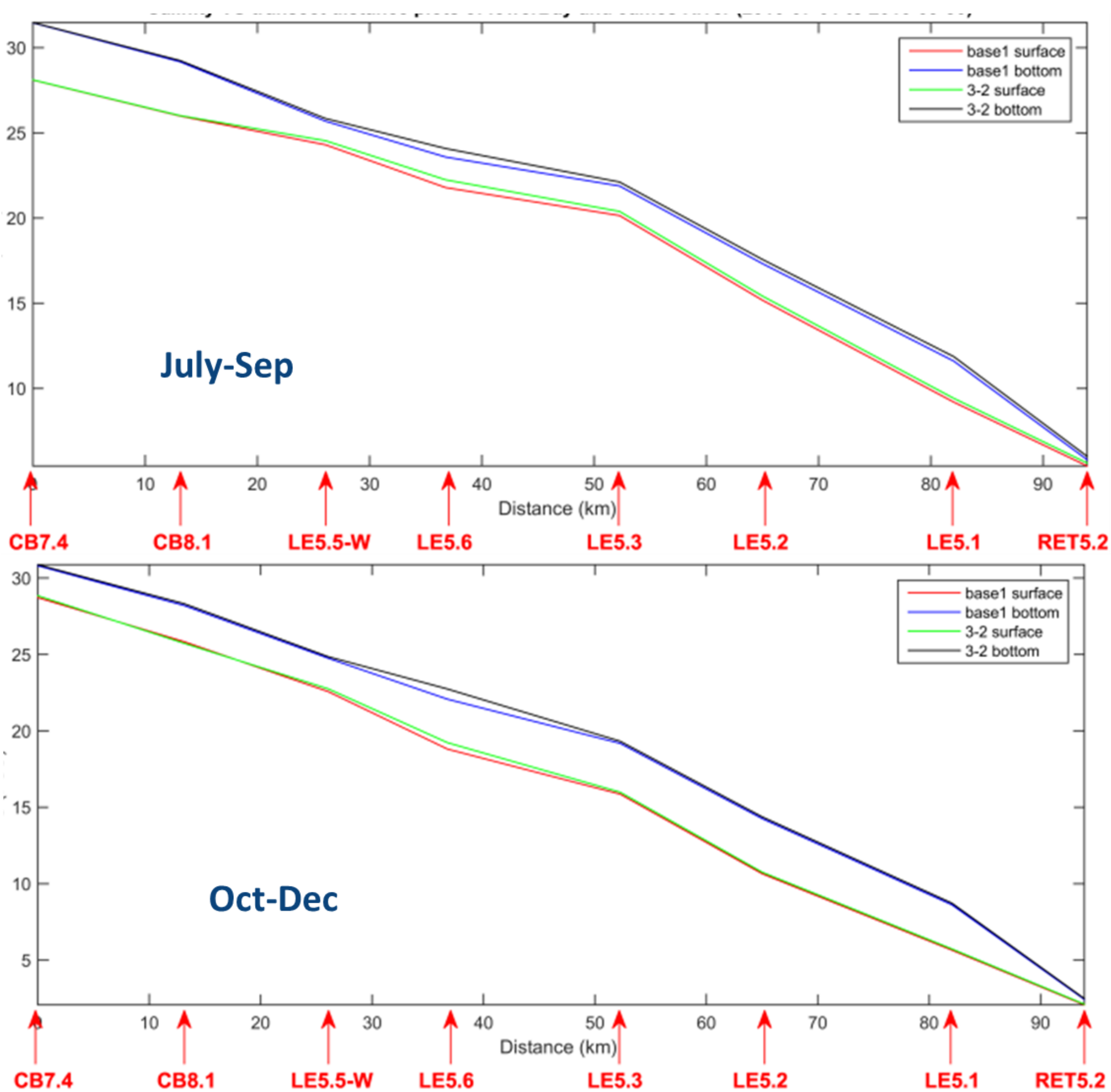
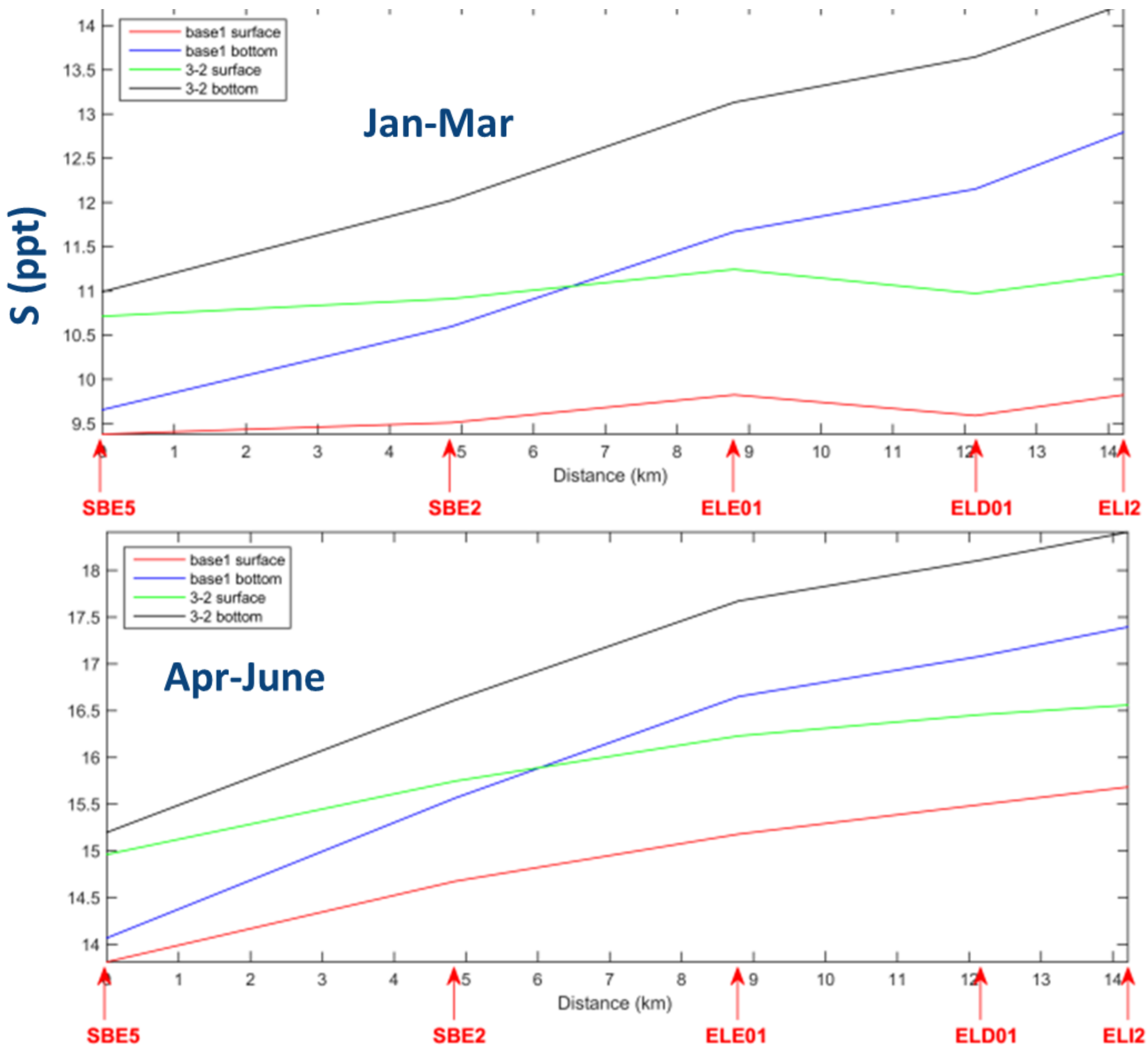


Figure 23: Averaged salinity differences (at surface and bottom) between '3-2' and Base 1 along a transect from lower Bay into James River. See Fig. 19 for the transect location. Differences are shown every 3 months.


S (ppt)
Jan-Mar
base1 surface
base1 bottom
3-2 surface
3-2 bottom
Distance (km)
SBE5
SBE2
ELE01
ELD01
ELI2
Apr-June
base1 surface
base1 bottom
3-2 surface
3-2 bottom
Distance (km)
SBE5
SBE2
ELE01
ELD01
ELI2

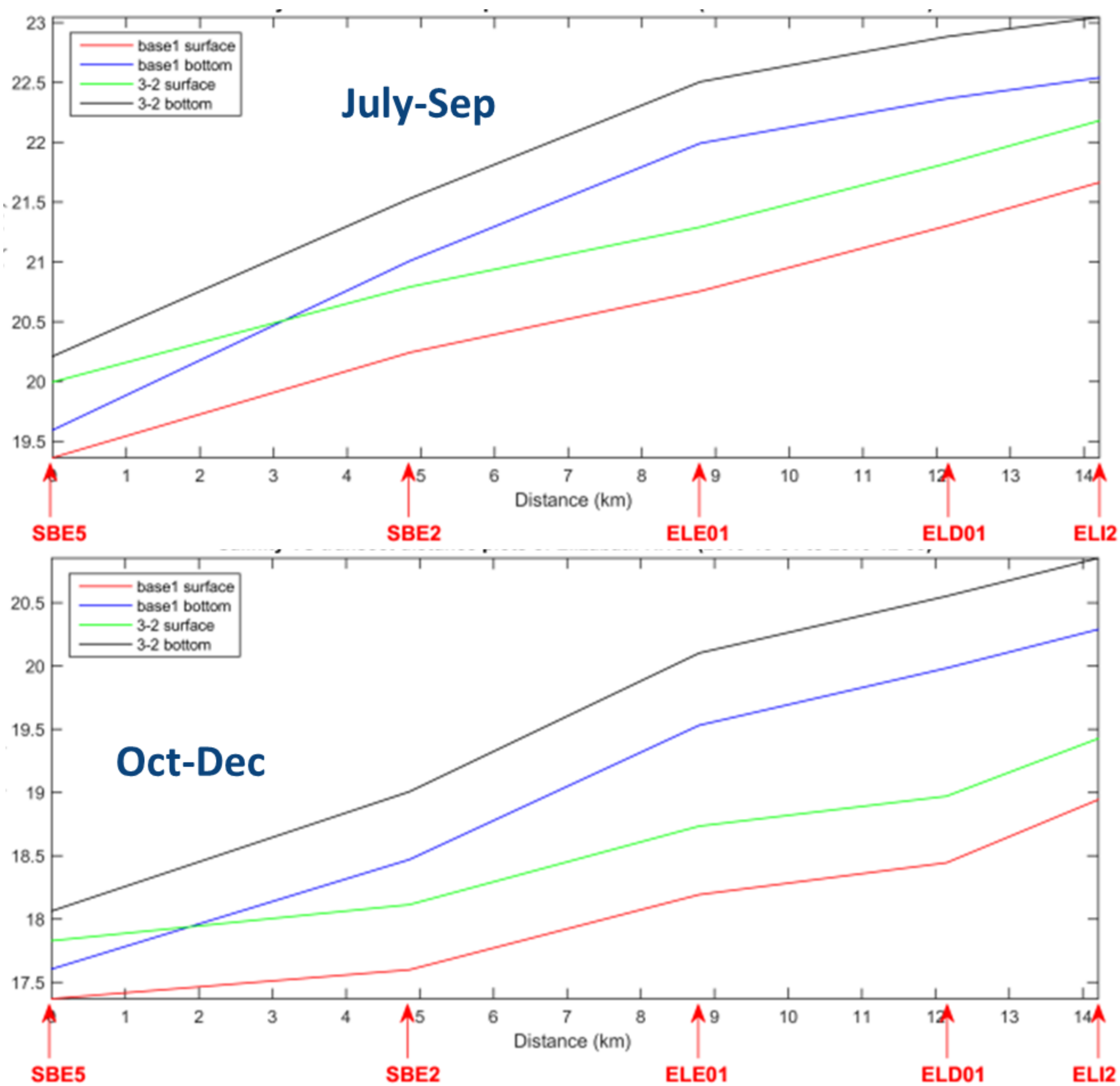
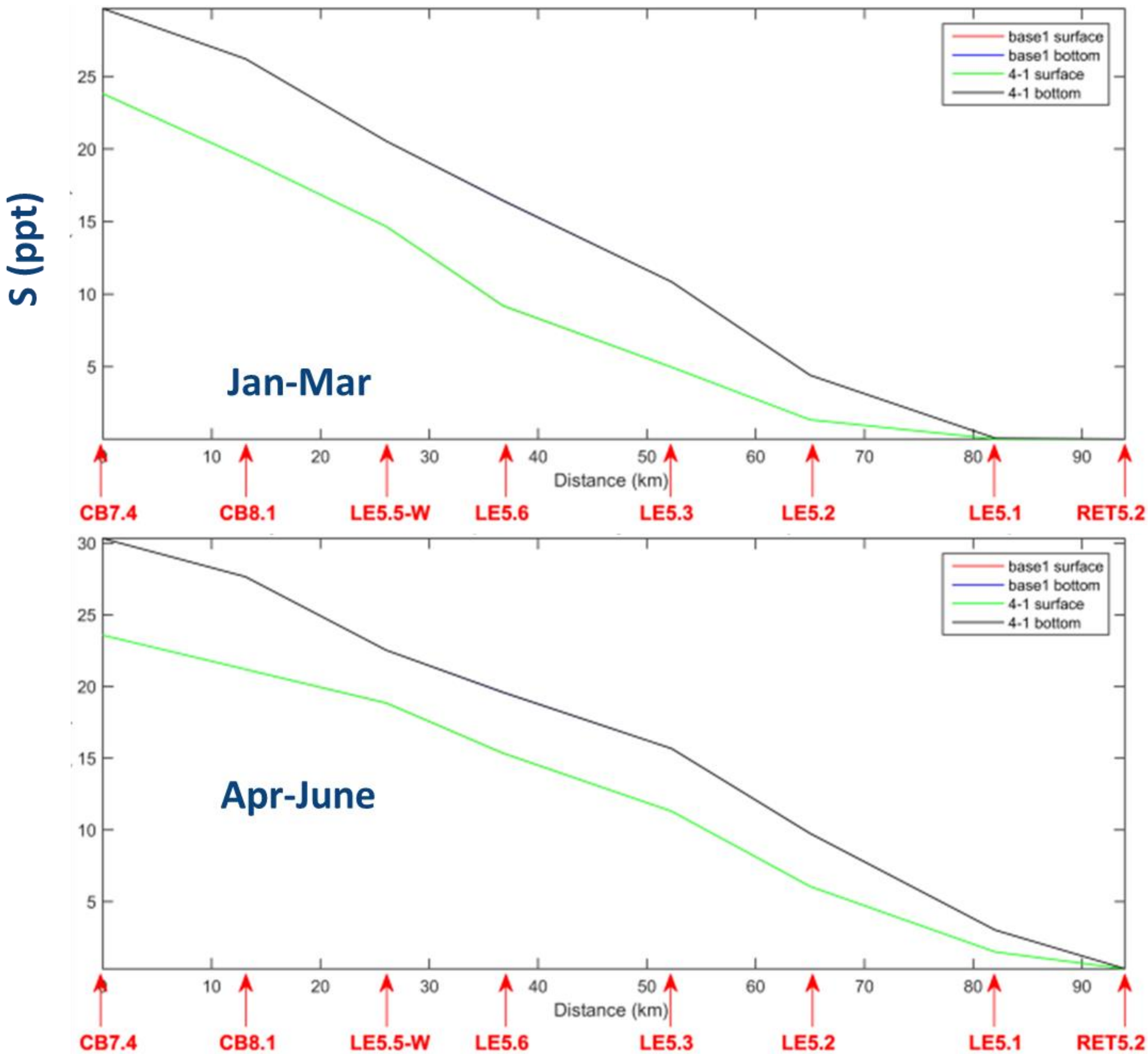


Figure 24: Averaged salinity differences (at surface and bottom) between '3-2' and Base 1 along a transect from Elizabeth River into James River. See Fig. 20 for the transect location. Differences are shown every 3 months.



S (ppt)
Jan-Mar
Apr-June
base1 surface
base1 bottom
4-1 surface
4-1 bottom
Distance (km)
CB7.4
CB8.1
LE5.5-W
LE5.6
LE5.3
LE5.2
LE5.1
RET5.2

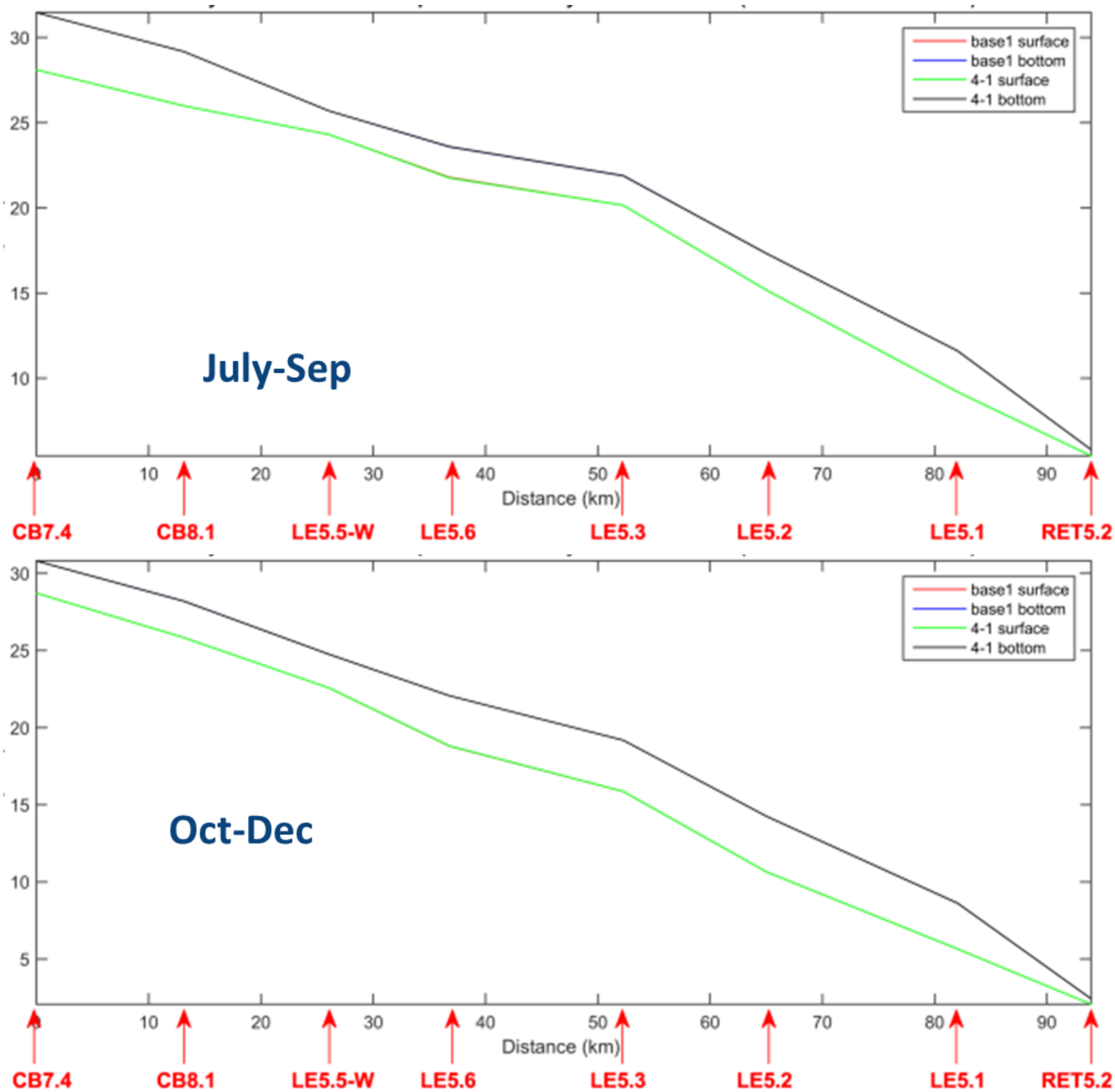
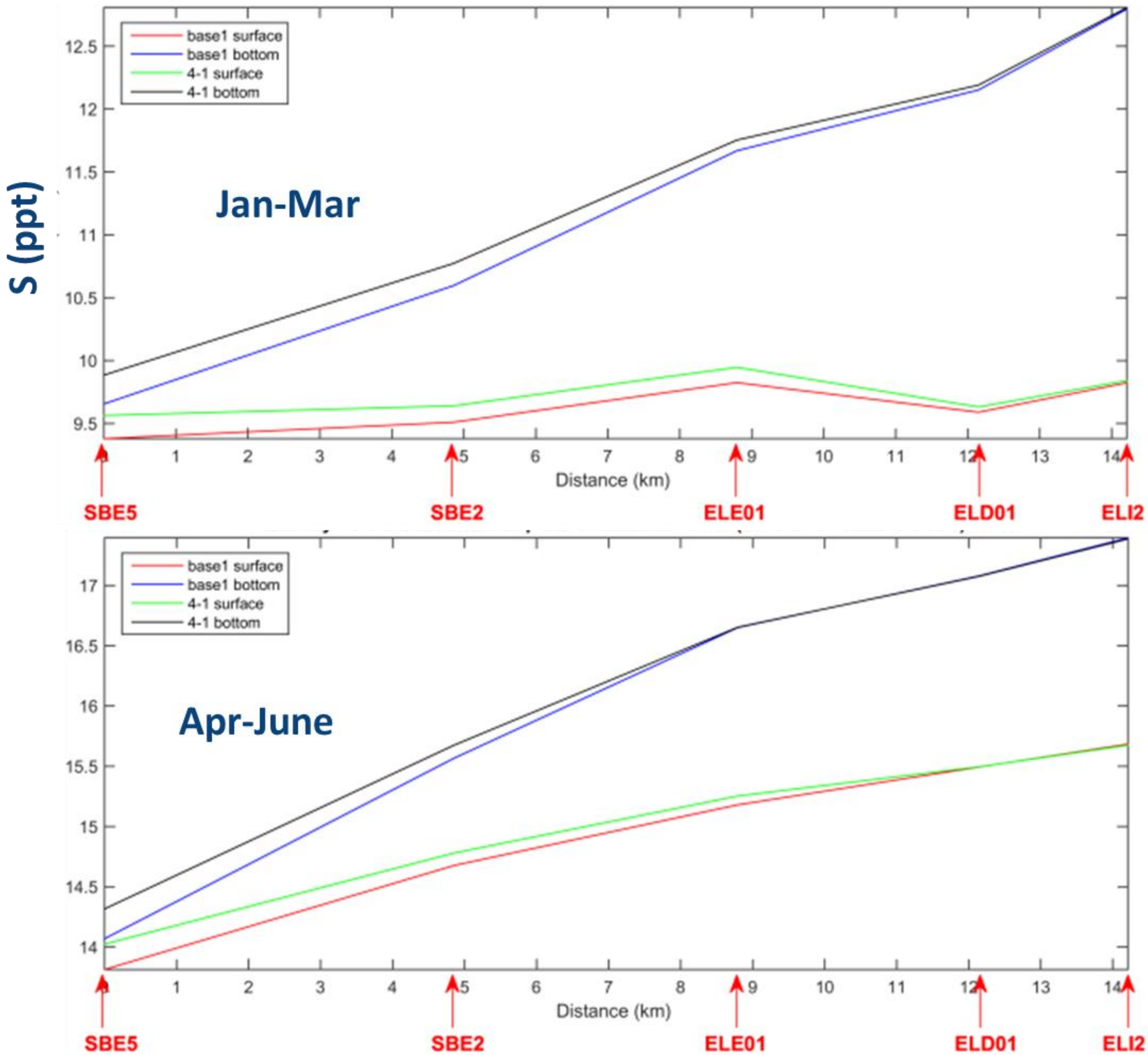


Figure 25: Averaged salinity differences (at surface and bottom) between '4-1' and Base 1 along a transect from lower Bay into James River. See Fig. 19 for the transect location. Differences are shown every 3 months.


S (ppt)
Jan-Mar
base1 surface
base1 bottom
4-1 surface
4-1 bottom
Distance (km)
SBE5
SBE2
ELE01
ELD01
ELI2
Apr-June
base1 surface
base1 bottom
4-1 surface
4-1 bottom
Distance (km)
SBE5
SBE2
ELE01
ELD01
ELI2

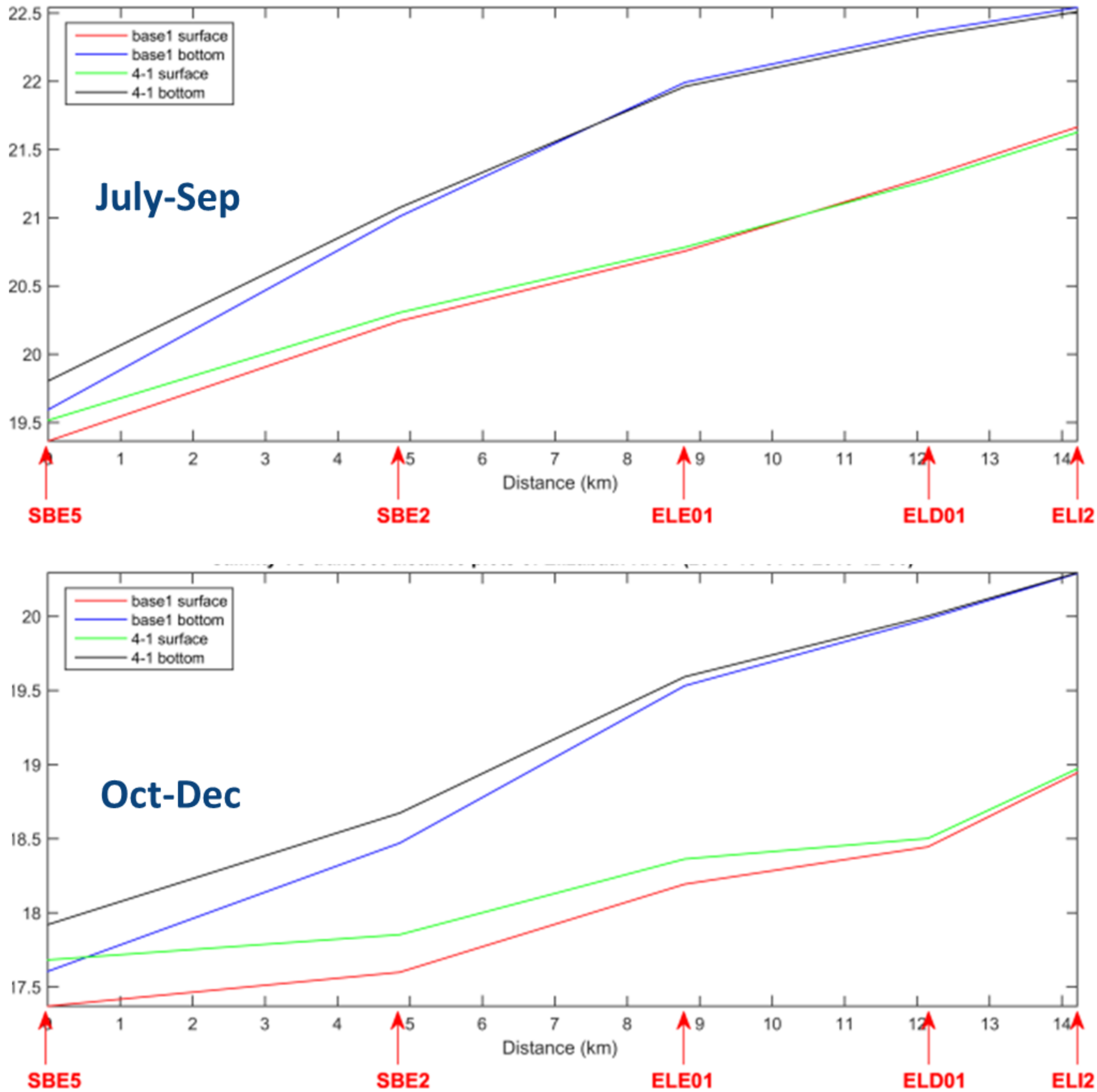
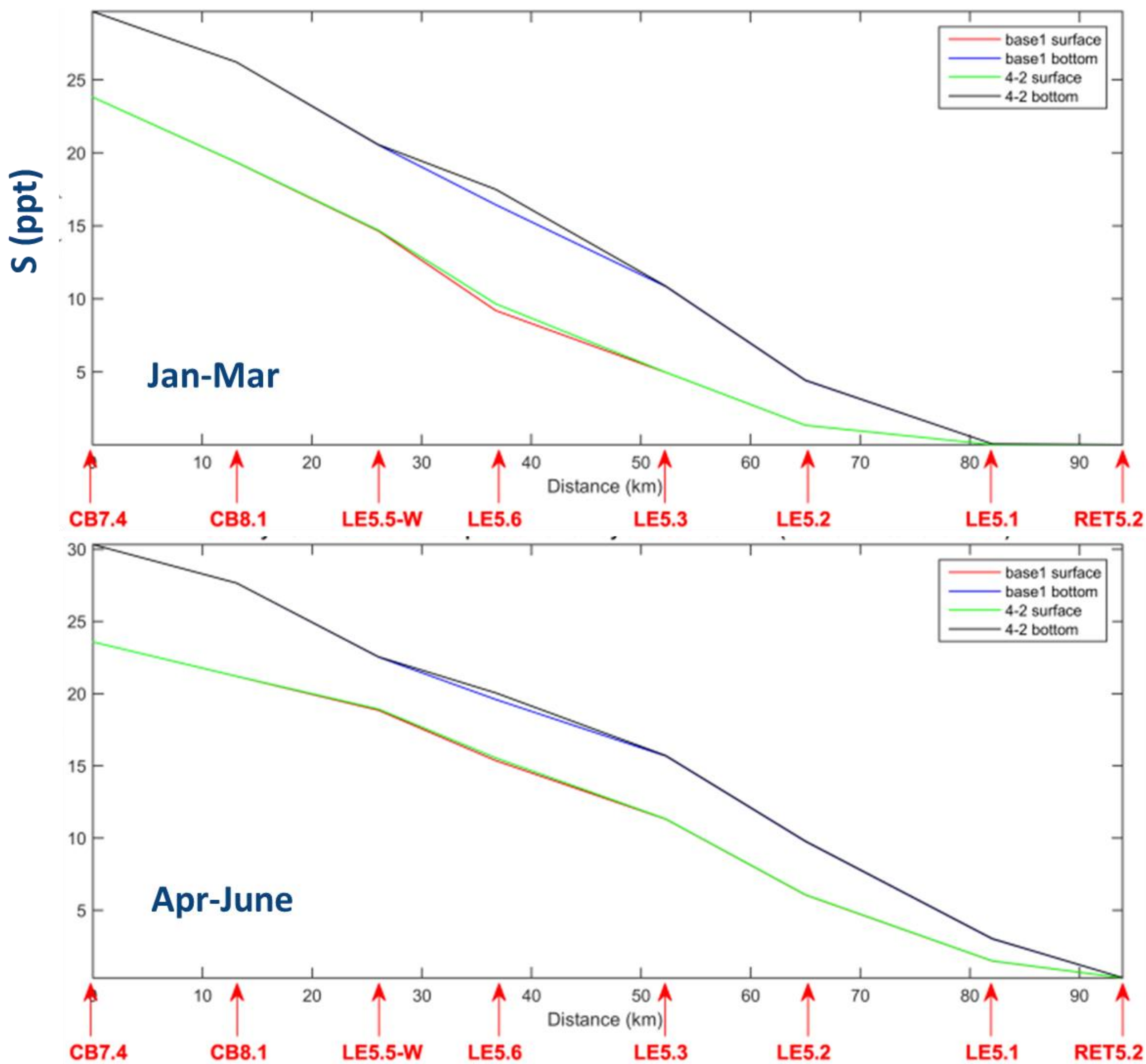


Figure 26: Averaged salinity differences (at surface and bottom) between '4-1' and Base 1 along a transect from Elizabeth River into James River. See Fig. 20 for the transect location. Differences are shown every 3 months.



S (ppt)
Jan-Mar
Apr-June
base1 surface
base1 bottom
4-2 surface
4-2 bottom
Distance (km)
CB7.4
CB8.1
LE5.5-W
LE5.6
LE5.3
LE5.2
LE5.1
RET5.2

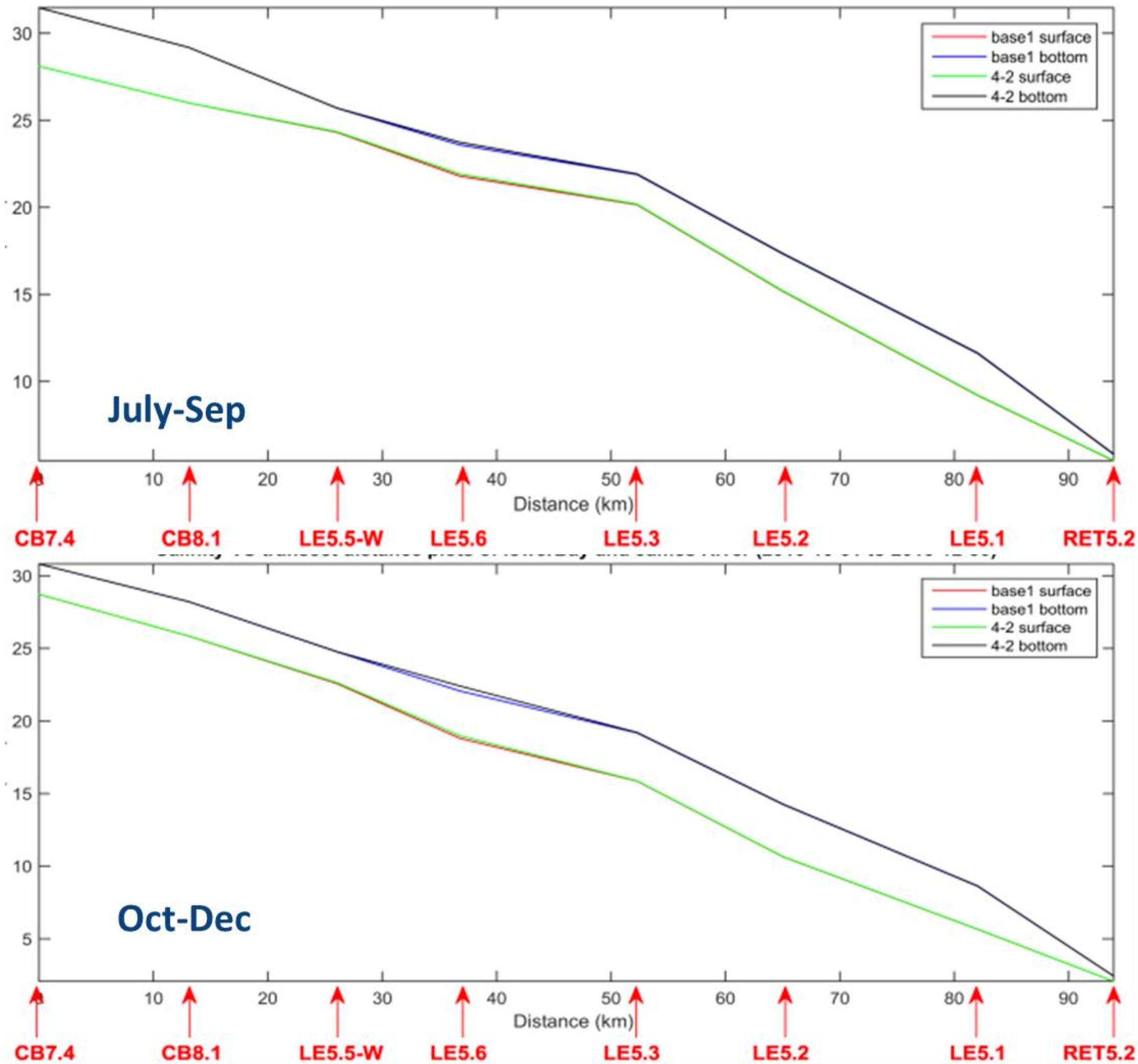
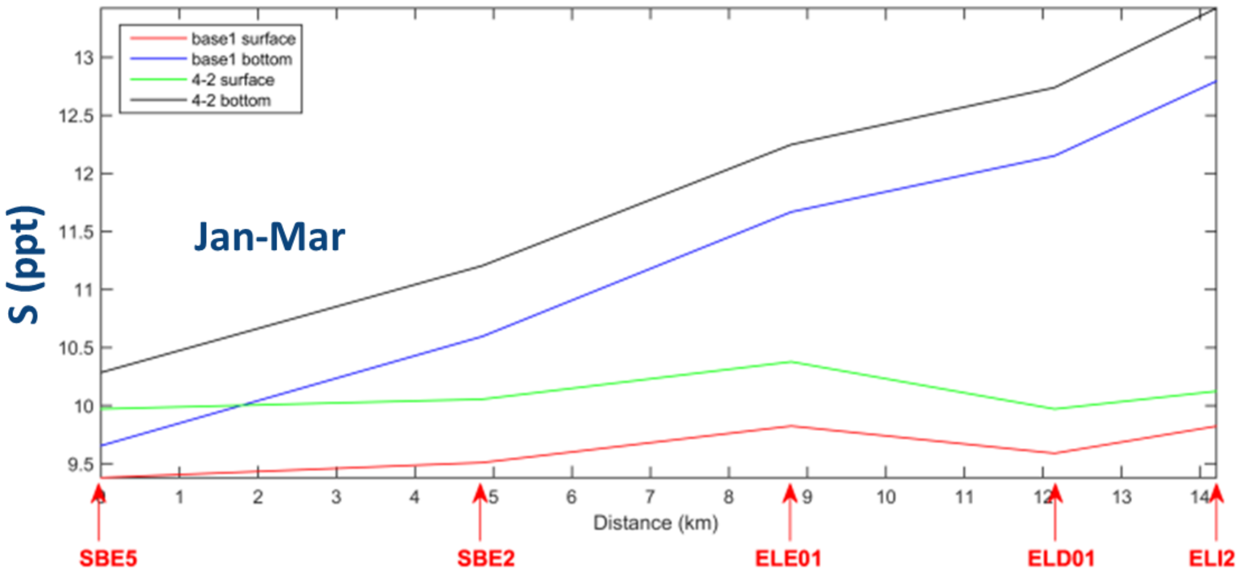
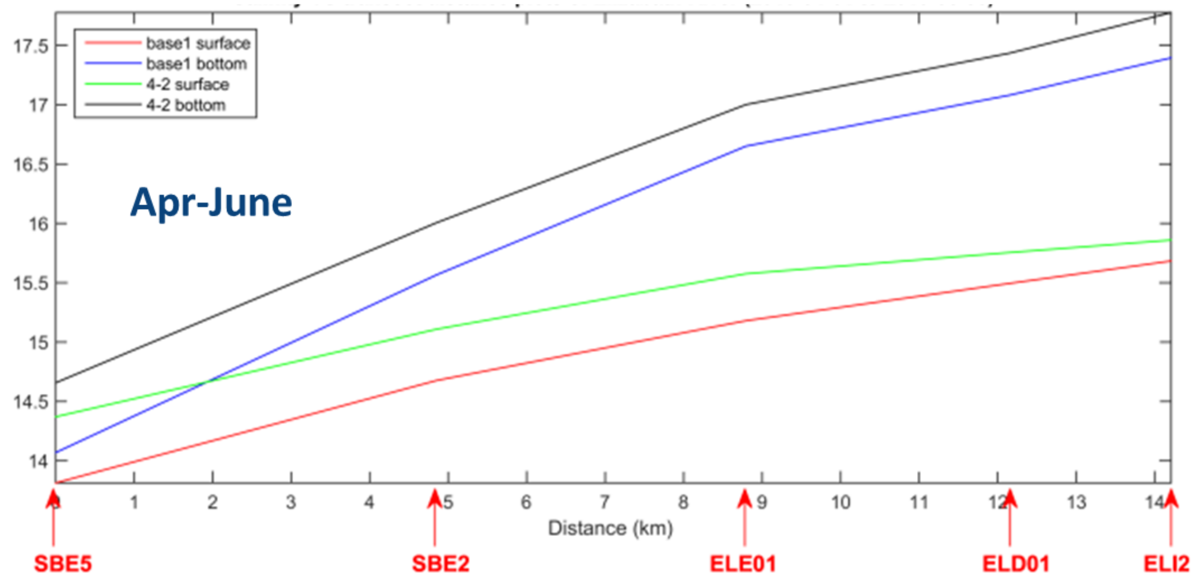


Figure 27: Averaged salinity differences (at surface and bottom) between '4-2' and Base 1 along a transect from lower Bay into James River. See Fig. 19 for the transect location. Differences are shown every 3 months.


base1 surface
base1 bottom
4-2 surface
4-2 bottom
S (ppt)
Jan-Mar
Distance (km)
SBE5
SBE2
ELE01
ELD01
ELI2


base1 surface
base1 bottom
4-2 surface
4-2 bottom
Apr-June
Distance (km)
SBE5
SBE2
ELE01
ELD01
ELI2

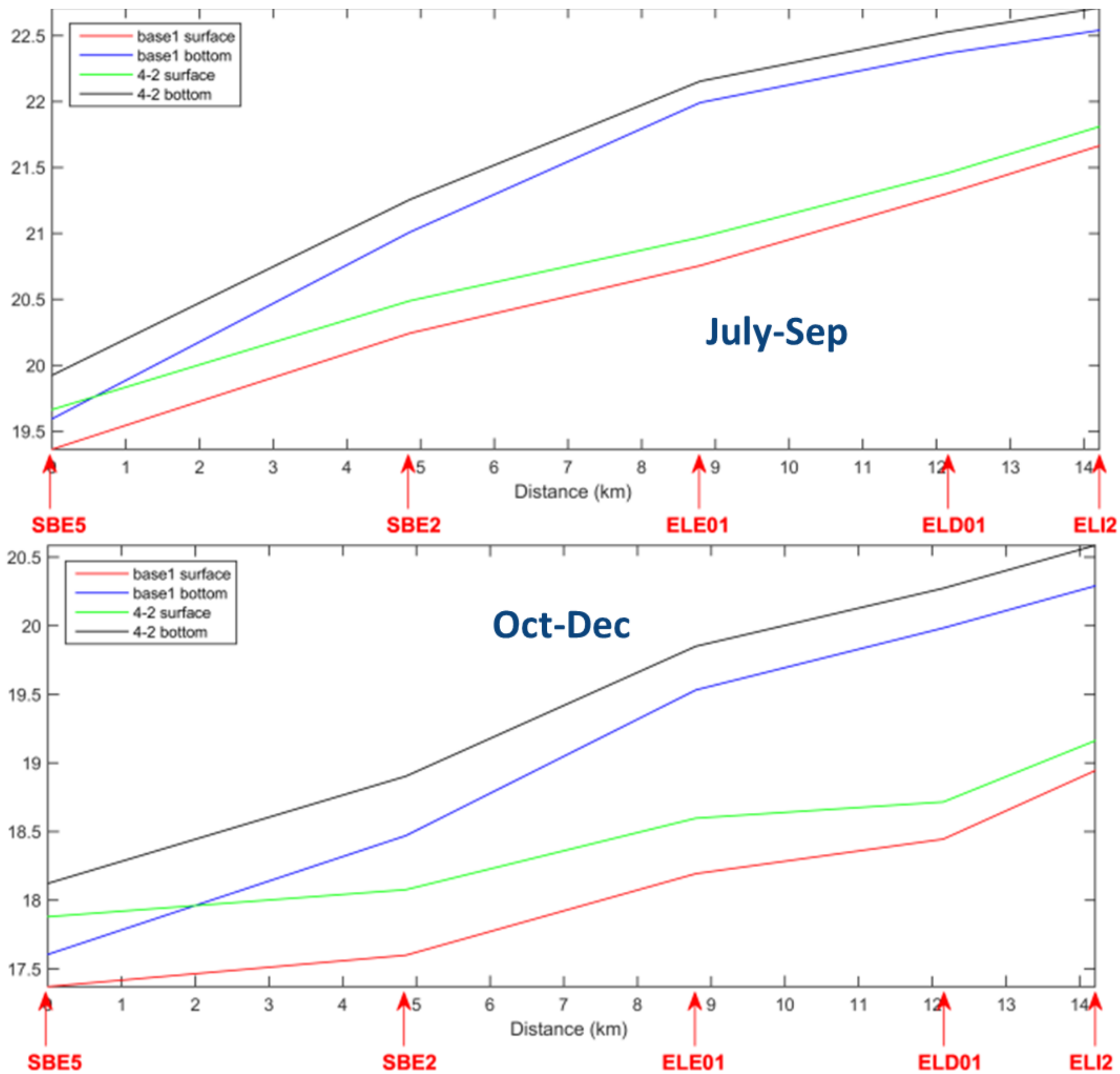
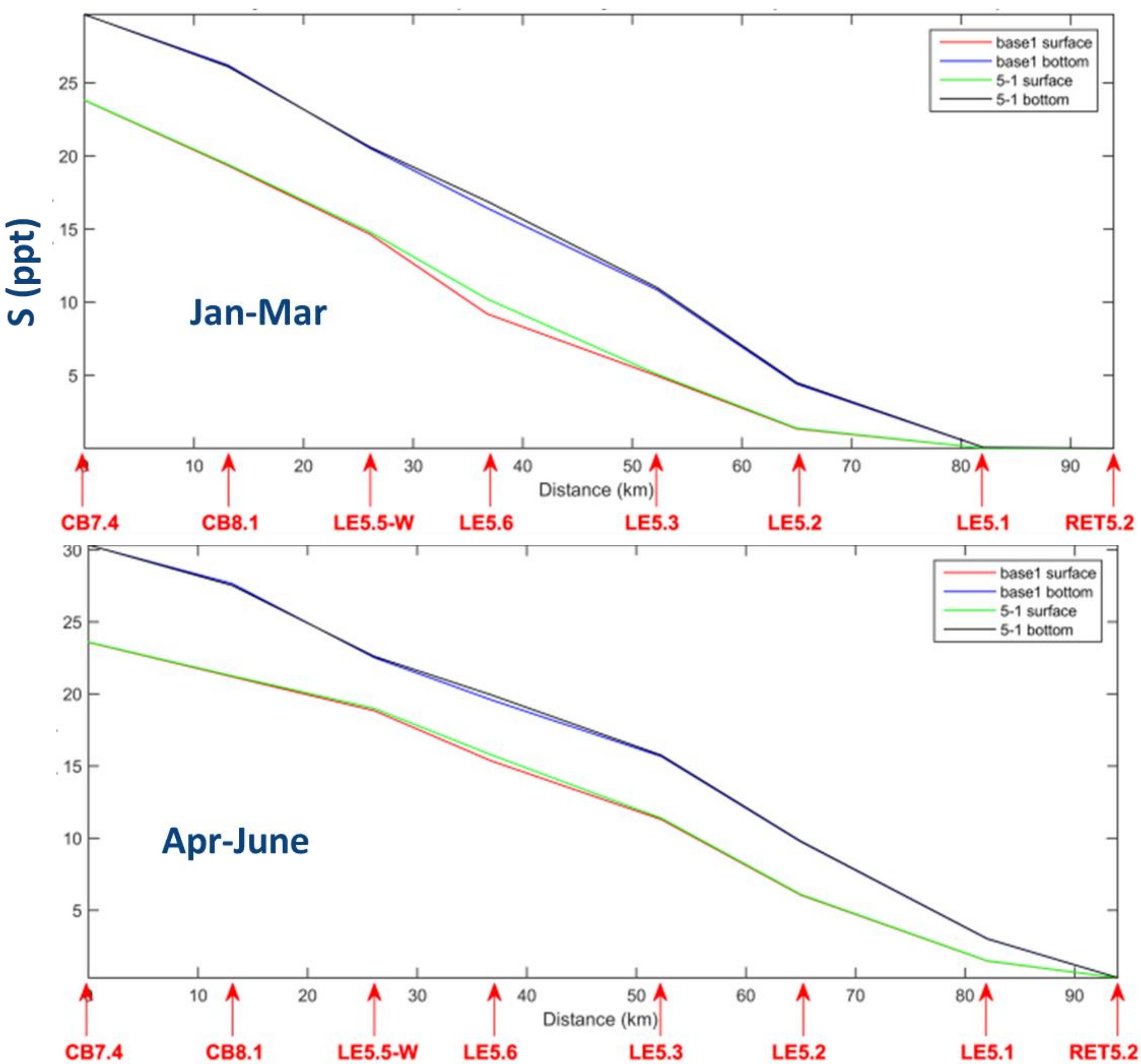


Figure 28: Averaged salinity differences (at surface and bottom) between '4-2' and Base 1 along a transect from Elizabeth River into James River. See Fig. 20 for the transect location. Differences are shown every 3 months.



S (ppt)
Jan-Mar
base1 surface
base1 bottom
5-1 surface
5-1 bottom
Distance (km)
CB7.4
CB8.1
LE5.5-W
LE5.6
LE5.3
LE5.2
LE5.1
RET5.2
Apr-June
base1 surface
base1 bottom
5-1 surface
5-1 bottom
Distance (km)
CB7.4
CB8.1
LE5.5-W
LE5.6
LE5.3
LE5.2
LE5.1
RET5.2

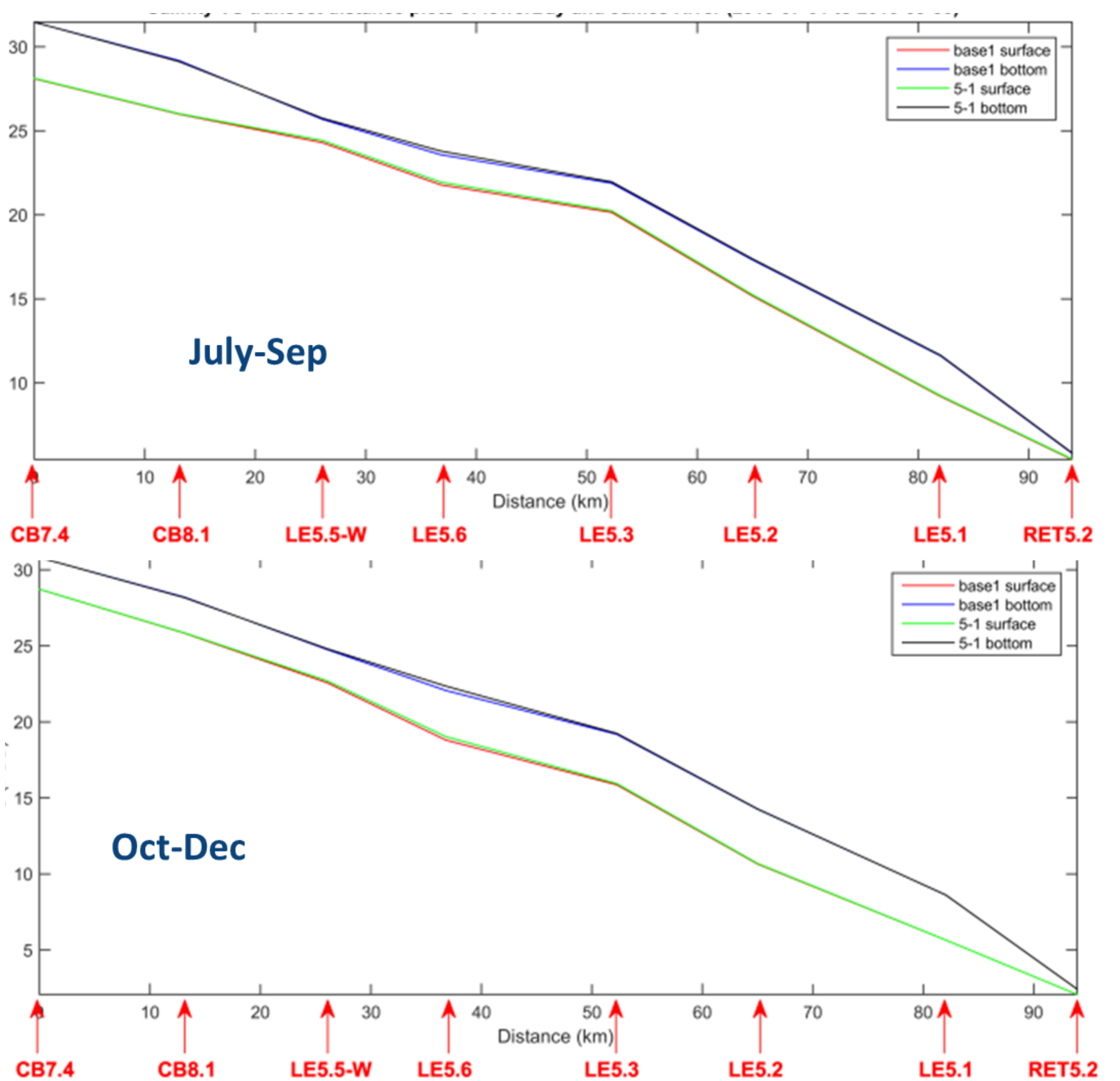
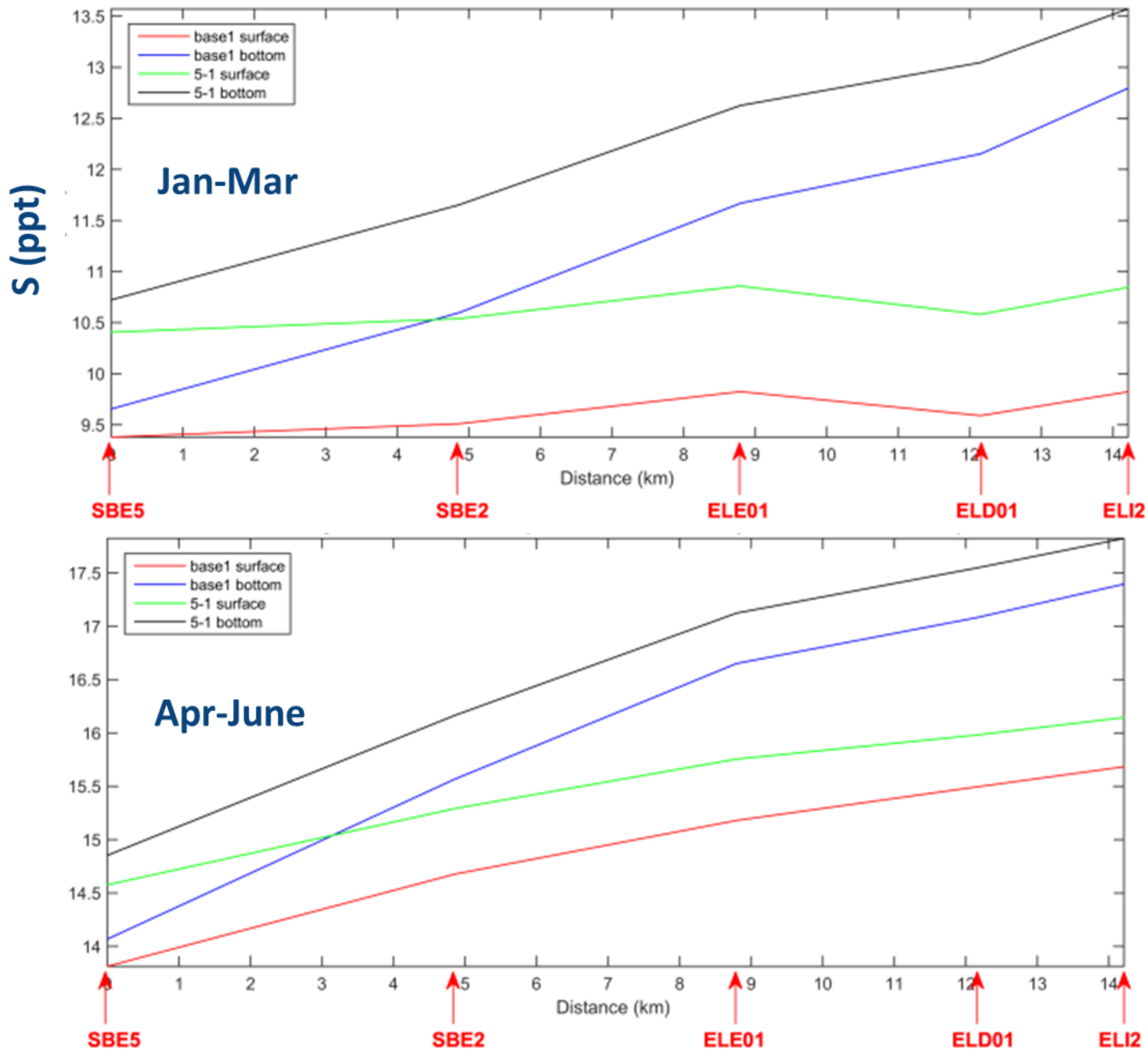


Figure 29: Averaged salinity differences (at surface and bottom) between '5-1' and Base 1 along a transect from lower Bay into James River. See Fig. 19 for the transect location. Differences are shown every 3 months.


S (ppt)
Jan-Mar
base1 surface
base1 bottom
5-1 surface
5-1 bottom
Distance (km)
SBE5
SBE2
ELE01
ELD01
ELI2
Apr-June
base1 surface
base1 bottom
5-1 surface
5-1 bottom
Distance (km)
SBE5
SBE2
ELE01
ELD01
ELI2

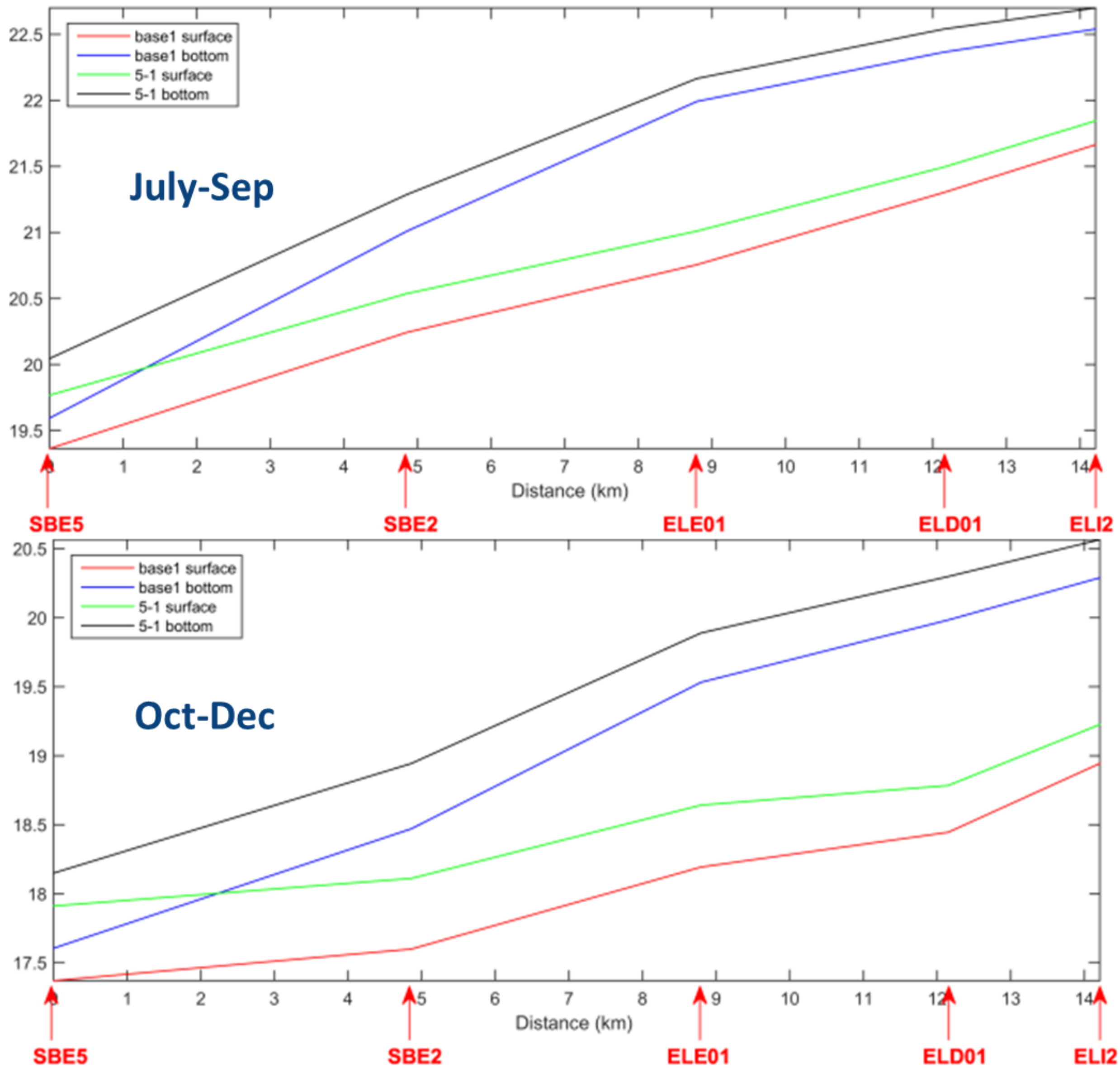
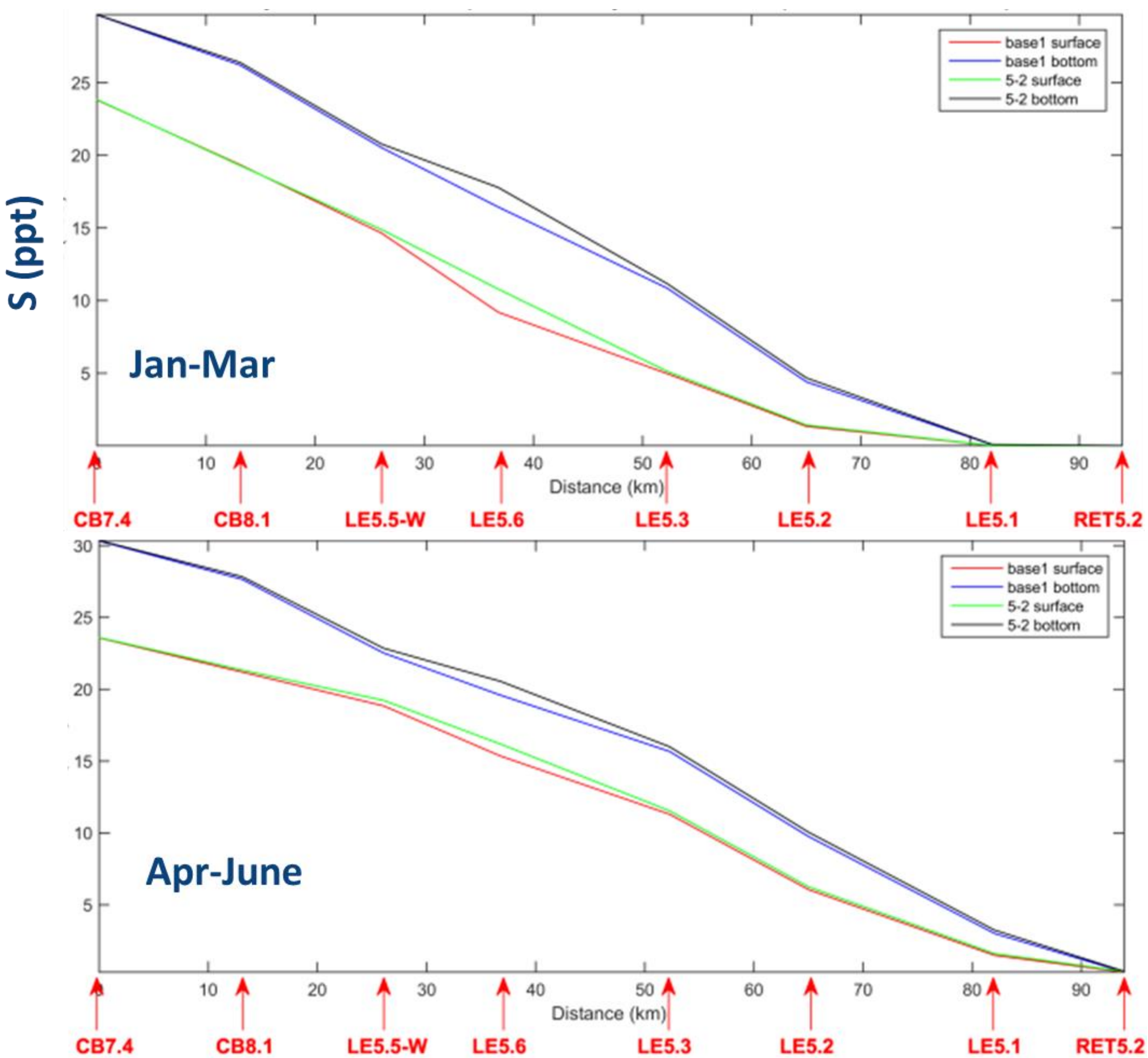


Figure 30: Averaged salinity differences (at surface and bottom) between '5-1' and Base 1 along a transect from Elizabeth River into James River. See Fig. 20 for the transect location. Differences are shown every 3 months.


S (ppt)
Jan-Mar
Apr-June
base1 surface
base1 bottom
5-2 surface
5-2 bottom
Distance (km)
CB7.4
CB8.1
LE5.5-W
LE5.6
LE5.3
LE5.2
LE5.1
RET5.2

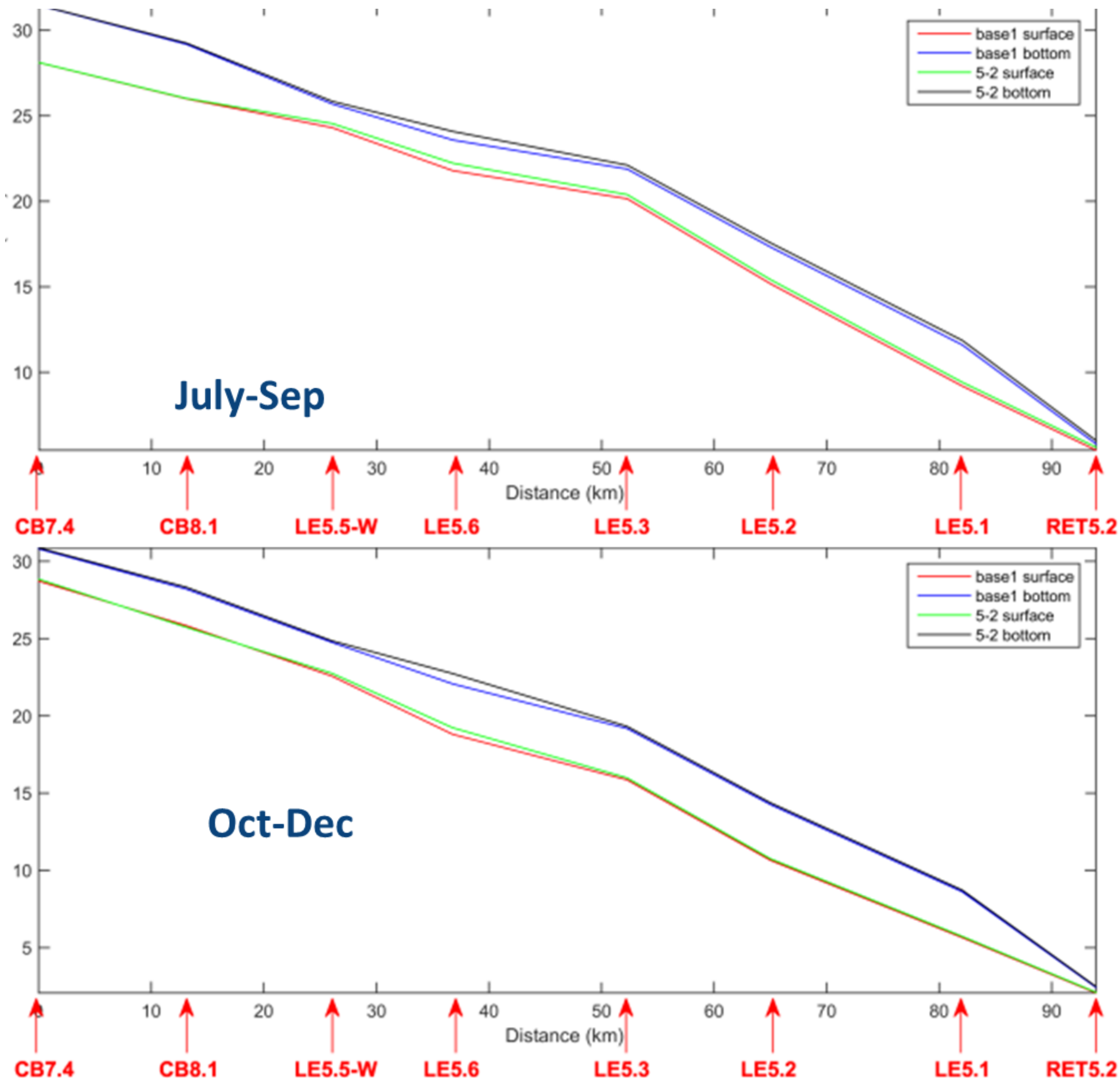
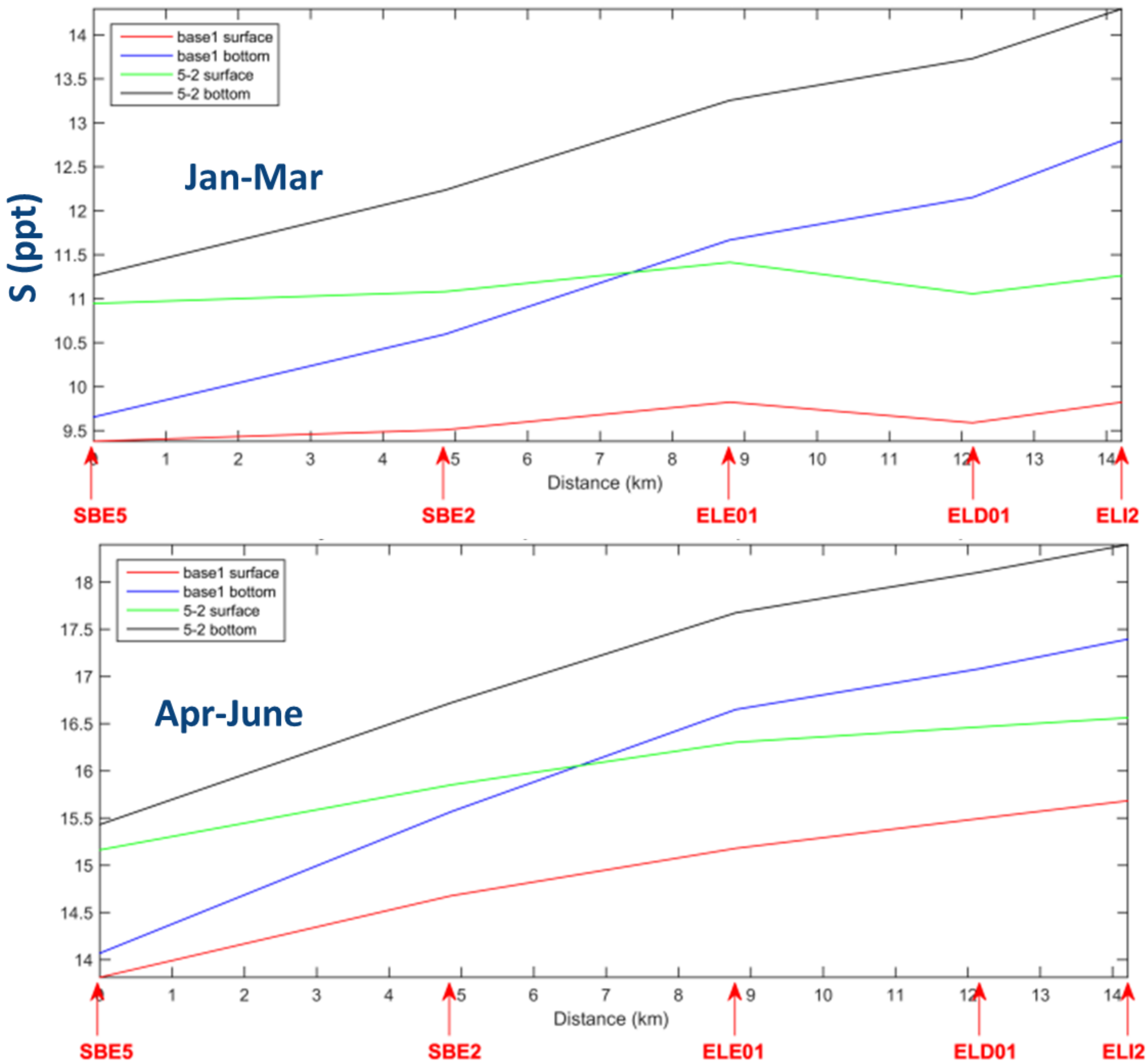


Figure 31: Averaged salinity differences (at surface and bottom) between '5-2' and Base 1 along a transect from lower Bay into James River. See Fig. 19 for the transect location. Differences are shown every 3 months.


S (ppt)
Jan-Mar
base1 surface
base1 bottom
5-2 surface
5-2 bottom
Distance (km)
SBE5
SBE2
ELE01
ELD01
ELI2
Apr-June
base1 surface
base1 bottom
5-2 surface
5-2 bottom
Distance (km)
SBE5
SBE2
ELE01
ELD01
ELI2

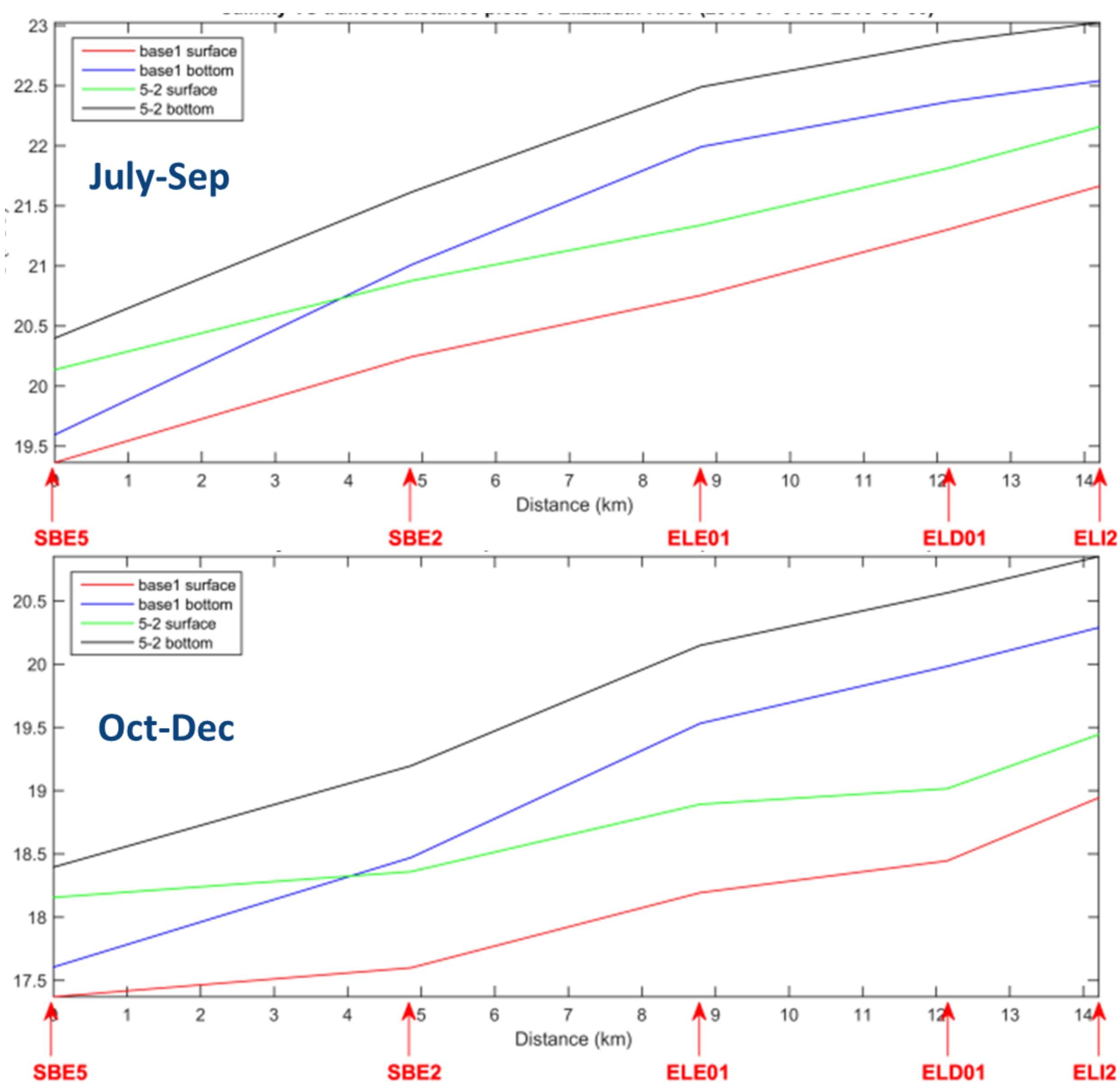


Figure 32: Averaged salinity differences (at surface and bottom) between '5-2' and Base 1 along a transect from Elizabeth River into James River. See Fig. 20 for the transect location. Differences are shown every 3 months.

Base 2 vs Base 1

	surfMD	botMD
Lower Bay	0.005	0.002
James R	0.046	0.079
Elizabeth R	0.222	0.266

(3-1) vs Base 1

	surfMD	botMD
Lower Bay	0.0017	0.018
James R	0.099	0.081
Elizabeth R	0.44	0.41

(4-1) vs Base 1

	surfMD	botMD
Lower Bay	0.000677	0.000076
James R	0.000059	0.000108
Elizabeth R	0.085824	0.073198

(5-1) vs Base 1

	surfMD	botMD
Lower Bay	0.002	0.018
James R	0.100	0.081
Elizabeth R	0.515	0.474

Figure 33: Summary of Absolute Mean Difference for surface and bottom salinity (from 2010-2013) between Base 1 and scenarios.

(3-2) vs Base 2

	surfMD	botMD
Lower Bay	0.1478	0.1400
James R	0.1801	0.1779
Elizabeth R	0.5500	0.5220

(4-2) vs Base 2

	surfMD	botMD
Lower Bay	0.000256	0.000108
James R	0.001358	0.000665
Elizabeth R	0.0804	0.0657

(5-2) vs Base 2

	surfMD	botMD
Lower Bay	0.1479	0.1397
James R	0.1815	0.1789
Elizabeth R	0.6368	0.5930

Figure 34: Summary of Absolute Mean Difference for surface and bottom salinity (from 2010-2013) between '*-2' scenarios and Base 2.

5. Summary

We have validated SCHISM for lower Chesapeake Bay with higher resolution used in the project area. The simulated elevations, depth-averaged velocity, salinities, and temperatures in the lower Bay, James River and Elizabeth River region have an averaged RMSE of 6cm, 8cm/s, <2 ppt, <2°C respectively, and the model captured key processes (salt intrusion, periodic stratification-destratification) well.

The model is then applied to study the response from various scenarios under the channel dredging project. Results from 7 scenarios ('Base 2', '3-1','3-2','4-1','4-2','5-1','5-2') are compared with those from the existing condition ('Base 1' or 'Base 2' respectively). We found that channel dredging generally enhances gravitational circulation (i.e. 2-layer circulation) especially near the mesohaline region, and '5-2' generated the largest response among all scenarios, with salinity change exceeding 2 ppt in most parts of Elizabeth River during Jan-March. Also, when compared to existing condition 'Base 1', scenarios derived from the 'future conditions' ('3-2','4-2' and '5-2') led to larger salinity increases than scenarios derived from the 'existing conditions' ('3-1','4-1' and '5-1'). However, the increases are generally small (~0.1 ppt) in the rest of Bay (with a distance exceeding ~30km from the project area) and therefore relatively localized. We also remark that even the largest increase in salinity is within the model uncertainty.

6. References

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