Memo

Date:	Friday, January 06, 2023
Project:	LIS-HWQMS
To:	DEP
From:	HDR
Subject:	ROMS WY95 Hydrodynamic Model Testing

1. Introduction

1.1. Background

The New York City Department of Environmental Protection (DEP) and United States Environmental Protection Agency (EPA) are funding the development of a coupled hydrodynamic/water quality model of Long Island Sound (LIS) to replace the existing System-wide Eutrophication Model (SWEM). SWEM used a combination of the Estuarine and Coastal Ocean Model (ECOM) and the Row-Column Advanced Ecological Modeling Program (RCA). The current project is using the Regional Ocean Modeling System (ROMS) hydrodynamic model coupled with the RCA water quality model for the updated LIS model (HDR, 2021).

This memorandum presents testing of the ROMS hydrodynamic model using the SWEM validation period of water year 1995 (WY95) (10/1/1994-9/30/1995) and, to the extent possible, the original SWEM ECOM inputs. In addition, various adjustments to ROMS model inputs were tested to determine how the adjustments could improve upon the existing SWEM ECOM model and to inform the initial calibration of the ROMS hydrodynamic model to calendar years 2005-2006 (CY05-06). The LIS Model Evaluation Group (MEG) strongly suggested that no effort should be expended on model calibration to the WY95 data, so this memorandum follows that recommendation. It should be noted that ECOM and ROMS have different underlying model algorithms, so not all the ECOM inputs are compatible with the required ROMS inputs. Comparisons between SWEM ECOM and ROMS outputs are presented, but minimal effort was made to make ROMS results reproduce SWEM ECOM results.

1.2. Shortcomings of SWEM

The University of Connecticut performed a detailed independent evaluation of the prior SWEM development (O'Donnell et al., 2010, 2014) and identified a number of modeling issues. During the application and calibration of SWEM, the vertical eddy coefficients calculated by the hydrodynamic model (ECOM) were reduced in the water quality model (RCA) to improve model-data comparisons of near-bottom dissolved oxygen (DO) levels in western LIS during the summer. Although the vertical mixing adjustment in the water quality model was presented to and approved by the SWEM Model Evaluation Group , it will not be adjusted in the new LIS water quality model.

It was also noted that work on mixing in the coastal ocean and comparison of SWEM ECOM results to observations in LIS suggested that the original vertical mixing values calculated by SWEM ECOM were actually realistic (O'Donnell et al., 2014), and that the values imposed by the SWEM RCA vertical eddy coefficient reduction were much too small. In addition, observations in LIS indicated that both algal respiration and production were significantly underestimated in SWEM RCA (O'Donnell et al., 2010). Recommendations from these evaluations included eliminating vertical mixing adjustment in RCA, use of more recent estimates of algal respiration and production, refinement of the model grid to provide finer spatial resolution, and use of open-source models and data sharing standards (O'Donnell et al., 2014).

ROMS and the increased computing power available since SWEM was developed provide the opportunity to refine the model grid with finer spatial resolution and use an open-source model with data sharing standards. Better horizontal and vertical resolution as well as direct coupling between ROMS and RCA should eliminate the need for vertical mixing adjustments in RCA. Finer horizontal model grid resolution allows the model to develop stronger vertical density gradients by improving lateral mixing and reducing upslope mixing, which can reduce vertical mixing and provide more vertical stratification. Also, direct coupling between the hydrodynamic and water quality models allows the models to communicate on a time-step basis and eliminates the need to average hydrodynamic model transport when transferring to the water quality model. When SWEM was developed, an hourly arithmetic average was used when saving hydrodynamic transport information for the water quality model. HDR's experience with ECOM and RCA since then has shown that an arithmetic average gives too much weight to short, high mixing events resulting in too much vertical mixing. For these reasons, we believe that a finer horizontal model grid will help improve the hydrodynamic model calculation of vertical mixing and improve representation of vertical stratification.

1.3. ROMS

ROMS is a free-surface, terrain-following, primitive equations ocean model widely used by the scientific community for a diverse range of applications (https://www.myroms.org/). Primitive equations include formulations for the conservation of mass, momentum and equations of state for salinity and temperature. ROMS can be used to model how a waterbody responds to physical forcings such as heating, wind, and freshwater inputs. Physical schemes are based on governing equations of continuity, conservation of momentum, and transport equations of tracer variables. ROMS also includes several vertical mixing schemes, multiple levels of nesting grids. ROMS is a very modern and modular code written in F90/F95. ROMS was developed in the early 2000's evolving from the S-Coordinates Rutgers University Model (SCRUM). It has extensive pre- and post-processing software for data preparation, analysis, plotting, and visualization. The entire input and output data structure of the model is via NetCDF, which facilitates the interchange of data between computers, the user community, and other independent analysis software. ROMS applications include investigations in LIS (Whitney et al., 2011, 2014, 2016; Schmidt and Whitney, 2018); the Middle Atlantic Bight (Levin et al., 2018); and Barnegat Bay (Defne et al., 2017).

1.4. Study Objectives

It is believed that some of the shortcomings of SWEM are due to the horizontal and vertical grid resolution, which was limited by the computing power that existed at the time the model was developed. Consequently, this study employs a model grid with a finer resolution than the SWEM grid. Features of the new LIS model grid are described below. This study's first objective is to analyze results from a baseline ROMS model that are comparable to results from the WY95 SWEM ECOM model and available data. For achieving this objective, the baseline ROMS model aims to use the same inputs as the SWEM ECOM model. The primary reason for this objective is to confirm that the ROMS model is functioning correctly. This study's second objective is to perform sensitivity analyses. That is, to generate results from adjusted ROMS models and compare those results to baseline ROMS model results. These comparisons will provide insight into what inputs should be changed as part of the CY05-06 pre-calibration modeling effort. The final objective is to summarize how the testing described above informs future pre-calibration and calibration work. It is not the intent of this study to reproduce the SWEM ECOM calibration with

ROMS using SWEM ECOM input. Differences in the model segmentation, inputs, and formulations will result in different output from ROMS using SWEM ECOM inputs.

2. Grid Refinement

2.1. Horizontal and Vertical Segmentation

Both ECOM and ROMS use a sigma-layer vertical coordinate system. This approach allows the model grid to fit the bottom bathymetry while keeping the same number of vertical segments. When there are steep changes in bathymetry, a shallow segment can be numerically connected with a deep segment (resulting in “upslope mixing”) which can artificially reduce vertical stratification. Finer horizontal segmentation can reduce upslope mixing and help maintain vertical stratification.

The new LIS model grid has finer resolution than the SWEM grid. The SWEM grid has 49 x 84 horizontal model segments with 10 sigma-layers. The new model grid has 307 x 170 horizontal model segments, and a sensitivity was conducted for up to 30 sigma-layers. The 10 sigma-layer setup was chosen as the baseline condition for comparing the effect of varied numbers of sigma-layers. In LIS, the SWEM grid has 3 to 9 segments across its width, from north to south, and the new model grid has approximately 20 to 50 segments across its width.

Figure 1 presents the spatial domain of the SWEM grid with color shading to indicate the depth of the individual model segments. Figure 2 presents the spatial domain and depths of the new LIS model grid. It is clear that the new LIS model better represents the shape of the coastline and bathymetric features such as the Hudson River Canyon. The improved LIS model segmentation and representation of bathymetry should allow the LIS model to better represent vertical and horizontal mixing as well as transport through the East River and LIS.

2.2. Bathymetry

2.2.1. SWEM Bathymetry

As mentioned previously, the SWEM model segmentation was relatively coarse making it difficult to accurately represent bathymetry in LIS. Figure 3 presents the SWEM model segmentation and bathymetry in LIS. It is clear that bathymetric features in the bottom of the sound, such as mounds or channels, have been smoothed out in SWEM. A similar observation can be made in the East River as presented in Figure 4. Features such as Rikers Island, which is not an island in the SWEM grid, are not always well represented. The main channel also shows a lot of variability in the depth.

2.2.2. LIS Model Bathymetry

Figure 5 presents the new LIS model segmentation and bathymetry in LIS. Deep channels and shallower mounds are evident and there is a smooth transition between depths. The shape of the channels in the Race at the eastern end of the sound are evident. SWEM had approximately 130 active horizontal model segments in LIS and the new model has more than 6,500 horizontal model segments.

The East River section of the new LIS model is presented in Figure 6. There is a smooth main channel with deeper sections that were not evident in the SWEM model bathymetry. Rikers Island is an island, and the East River tributaries are also now well represented.

Following are the sources of model bathymetry used to define the new LIS model depths:

- CUDEM (Continuously Updated Digital Elevation Model, NOAA) was used for most of the model domain.
- CRM (US Coastal Relief Model) was applied for the southern and eastern part of the model domain (Atlantic Ocean, and east of Nantucket area) where CUDEM cover is not available.
- CONED (Coastal National Elevation Database) was used for the Connecticut River but the upper Connecticut River (north of Hartford) was adjusted to a 3.5-meter depth. CONED bathymetry was first applied to the Raritan River, but then minimum depth of 3 meters was applied to most of Raritan River.
- Bathymetry used in the LTCP2 Open Waters Model was applied to the Upper Hudson River north of Cornwall-On-Hudson (about 5 miles north of West Point).
- Water depth from NOAA Nautical Chart (#12337, 1997 edition) was applied to the Hackensack River and Passaic River area.

3. Development of ROMS Inputs

3.1. Differences between SWEM ECOM and ROMS Input Requirements

For the ROMS hydrodynamic model testing, the WY95 inputs from SWEM ECOM were used whenever possible. However, there are differences in the model inputs and formulations beyond the coarse SWEM ECOM and fine ROMS model segmentation. Table 1 highlights differences relevant to this study. Some of these differences are discussed below. Later, tests are performed to assess ROMS sensitivity to some of the characteristics. Although ROMS has numerous options, only options relevant for modeling LIS are listed in Table 1.

Table 1. SWEM ECOM and ROMS Model Differences

Characteristic	SWEM ECOM	ROMS
Model Grid	49 x 84 Fewer inputs required	307x170 (Also requires Coriolis parameter, curvilinear coordinate metric, and derivative of inverse metric factor)
Boundary Condition Options	Clamped, Partially Clamped, Shulman, and Reid and Bodein	Closed, Clamped, Chapman-implicit, Chapman-explicit, Flather, Gradient, Nested, Nudging, Periodic, Radiation, Reduced Physics, and Shchepetkin
Boundary Condition Elevations	Elevations only	Elevations(1) and velocities
River Flow	Only rivers assigned as rivers	Rivers and point sources assigned as rivers(2)
Point Source Flow	Only a flow required	Added as rivers with a direction required
Bottom Friction	Quadratic formulation	Linear, logarithmic, and quadratic(3) options available
Generic Length Scale (Turbulence Closure Scheme)	k-kl (Mellor-Yamada 2.5)	k-kl, k-epsilon, k-w, and gen
Light Extinction/Adsorption	Extinction coefficient	Jerlov Water Type

Table 1. SWEM ECOM and ROMS Model Differences		
Characteristic	**SWEM ECOM**	**ROMS**
Tracer Advection Schemes	Central difference (2nd order), upwind difference, and MPDATA options	4th-order Akima, central difference (2nd Order), central difference (4th order), HSIMT with TVD limiter, MPDATA, SPLINES, split (3rd order) upstream, and upstream bias (3rd order) options
Heat Flux	Large and Pond (1982)	Fairall, et. al, 1996a,b; Liu, et al., 1979.
Constants	~10	~50

(1) Elevations calculated internally from ROMS with assigned tidal harmonic constituents
(2) At the time of testing, ROMS only allowed flows to be input as either rivers (originating from a connected land model grid) or point sources (assigned to a water model grid like an offshore outfall). Since the time of testing, the ROMS code has been modified to allow both river and point source flow inputs.
(3) The quadratic formulations in SWEM ECOM and ROMS differ.

3.2. Boundary Conditions

Salinity and temperature boundary conditions from SWEM ECOM were used at the south and east boundaries. Salinity and temperature at five locations along the open boundary were extracted from SWEM ECOM input and then linearly interpolated between the locations (by distance) to get the LIS ROMS inputs along the offshore boundary.

One difference between SWEM ECOM and ROMS is that SWEM ECOM only requires water elevation at the boundary and that is enough to drive currents into the model domain. ROMS requires both water elevation and current velocities at the boundary, so the ECOM water elevation boundary is not fully compatible with ROMS needed inputs. The ROMS required boundary data was gathered from a tidal database developed for the eastern coast of the United States (https://adcirc.org/products/adcirc-tidal-databases/) and data output from ADCIRC (Advanced Circulation Model) is used to supply both water elevations and velocities. ADCIRC (https://adcirc.org/products/adcirc-tidal-databases/) databases are available that can provide tidal constituents and current velocities for the desired location. Like ROMS, ADCIRC is an ocean circulation model that has been applied to different portions of the globe.

ROMS includes several options for specifying boundary condition inputs [Boundary Conditions - WikiROMS (myroms.org)]. Table 2 presents the chosen options for the baseline ROMS model. The western and northern boundaries are closed because they border land, New Jersey to the west and Connecticut and Rhode Island to the north.

Table 2. Offshore Boundary Condition Options*				
Boundary Condition	**West**	**South**	**East**	**North**
Free-surface	Closed	Clamped	Clamped	Closed

Table 2. Offshore Boundary Condition Options*				
Boundary Condition	**West**	**South**	**East**	**North**
2D U-momentum	Closed	Flather	Flather	Closed
2D V-momentum	Closed	Flather	Flather	Closed
3D U-momentum	Closed	Radiation	Radiation	Closed
3D V-momentum	Closed	Radiation	Radiation	Closed
Mixing TKE	Closed	Radiation	Radiation	Closed
Temperature	Closed	Radiation-Nudging	Radiation-Nudging	Closed
Salinity	Closed	Radiation-Nudging	Radiation-Nudging	Closed
* - See Attachment 1 for boundary condition option descriptions.				

3.3. Freshwater Flows

Freshwater flow inputs in ROMS are taken directly from SWEM ECOM inputs and applied to the finer resolution model grid. Freshwater flows include rivers, wastewater treatment plants, combined sewer overflows and stormwater. Currently, all freshwater flow inputs are assigned as river sources (Table 1) that require assignment of both magnitude and direction of flow. This type of input requires the flow to enter the model domain from an adjacent land cell, which is not appropriate for a number of outfalls located offshore (e.g., Oakwood Beach WRRF). Further model code evaluation is required to allow these offshore discharges to be assigned correctly. Although all freshwater flows were assigned as river sources, the impact on the calculation of salinity is considered small.

3.4. Meteorology

The meteorological inputs from SWEM ECOM were applied in ROMS. The inputs included spatially constant air temperature, relative humidity, and barometric pressure. Two wind fields (speed and direction) were applied in SWEM ECOM and in ROMS. One was local to New York City area waters based on data from Central Park and Newark Airport, and another was based on a buoy in the vicinity of the apex of NY Bight (ALSN6A8) that was applied to the remaining open water areas in the model (including LIS). Figure 7 shows where the two wind fields were applied.

3.5. Baseline ROMS Model Options

ROMS requires the modeler to choose from a number of options to control calculations such as horizontal and vertical advection schemes, boundary condition type, and vertical turbulence closure scheme. The model documentation provides some information as to the preferred or typical options. Table 3 shows some of the options used for the baseline ROMS model.

In SWEM ECOM, vertical light attenuation is controlled by assigning a light extinction coefficient and using the following equation which reduces surface light with depth:

$$I_Z = I_0 e^{K_e \times Z}$$

where: I_Z – Light at depth Z (W/m^2)
I_0 – Light at the surface (W/m^2)
K_e – Light extinction coefficient (1/m)
Z – Depth (m)

Additionally, 10% of the incoming short wave solar radiation was assumed to be reflected at the water surface (i.e., albedo). ROMS uses a Jerlov Water Type to control vertical light extinction through upper and lower layers of the water column. There are nine water type options available in ROMS, each with specific coefficients that define light penetration through the water column. The following equation is used in ROMS to represent light attenuation in the water column (Paulson and Simpson, 1977):

$$I_Z = I_0 \times \left[R \times e^{Z/\mu 1} + (1 - R) \times e^{Z/\mu 2}\right]$$

where: R – Fraction of surface light absorbed over top 5 meters
μ_1 – absorption coefficient for solar wavelength band 1 for selected Jerlov water type (m)
μ_2 – absorption coefficient for solar wavelength band 2 for selected Jerlov water type (m)

Table 3. ROMS Model Options

Input	Option
Vertical Layers	10
Horizontal Advection	3rd-Order Upstream Bias (U3)
Vertical Advection	2nd-Order Centered Difference (C4)
Harmonic/Biharmonic Horizontal Diffusion	10 m^2/s (TNU2)
Background Vertical Mixing Coefficient	5E-06 m^2/s (AKT_BAK)
Upper Threshold Value for Computed Vertical Viscosity Coefficient	1E-03 m^2/s
Generic Length Scale Turbulent Closure Parameters (Turbulent Closure Scheme)	Default parameters (k-epsilon)
Quadratic Bottom Drag Coefficient	3.0E-03
Bottom Roughness	0.001 m
Surface Roughness	0.005 m
Jerlov Water Type	5 (Type III)

4. Approach and Data for Testing ROMS

A baseline ROMS model was set up as a starting point for testing the model. To the extent possible, inputs for the baseline ROMS model matched inputs from the original WY95 SWEM ECOM simulation. ROMS and ECOM differ, so modifications to the ECOM input supplied to ROMS were necessary (Table 1). Baseline ROMS model results are compared to SWEM ECOM output, and data from WY95. Comparisons are made for time series of water elevation, temperature, and salinity, vertical profiles of temperature and salinity. Additionally, East River fluxes were calculated for a north-south transect along the river. Station locations where model versus data comparisons were made are presented in Figures 8 (water elevation), 9 and 10 (temperature and salinity). When model results are compared to temperature and salinity data the station names are indicated in the upper right corner of each panel. Results from the baseline model run comparisons are used to determine if ROMS is reasonably reproducing previous SWEM ECOM output and available data. That is, the baseline runs serve to ensure that the ROMS model is working properly. Also, the baseline model results provide insight into what inputs should be modified during future calibration efforts.

The next level of testing involves changes to options or features within ROMS. These changes include adjustments to the vertical mixing option, number of vertical layers, Jerlov Water Type (which defines light extinction/absorption), and bottom friction options. To assess the adjustments, output from each adjusted ROMS model is compared to output from the baseline ROMS model, data, or SWEM ECOM results. As is done for testing the baseline ROMS model, adjusted ROMS models are evaluated by reviewing time series of water elevation, temperature, and salinity; vertical profiles of temperature and salinity; and East River fluxes. Results from the adjusted ROMS models will guide future calibration efforts by demonstrating the relationship between inputs and outputs.

5. Baseline ROMS Model Results

5.1. Water Elevation

Figure 11 presents a model versus data comparison of water elevation at NOAA tide gage locations in Bridgeport, CT and near Bergen Point, NJ on the south side of Kill Van Kull. ROMS reasonably reproduces the timing and magnitude of the data. On occasion, the model and data diverge during periods that appear to be driven by meteorological events. During the original SWEM ECOM calibration, two wind fields were assigned as was also used in the ROMS model setup. The ROMS comparison to data suggests that more spatially varying meteorological input, primarily wind speed and direction, could improve the model comparisons to water elevation data. Additional water elevation comparisons can be found in Attachment 2.

5.2. Temperature

Time-series comparisons of ROMS model temperature output, SWEM ECOM model temperature output, and temperature data are presented in Figure 12 at three locations in western LIS. The darker red and blue lines represent the surface and bottom ROMS model output, respectively. The SWEM model output is represented by the lighter red (surface) and blue (bottom) lines. Available data are represented by triangles, upward pointing for the surface and downward pointing for the bottom. The ROMS model output tend to match the data fairly well for most of the year but tends to overestimate the temperature during the warmer spring/summer months. The ROMS model output tend to have lower temperature levels in the winter as compared to SWEM ECOM and generally fits these cooler period data better. During the spring/summertime period, SWEM ECOM does a better job reproducing the data. ROMS and SWEM ECOM have different heat flux formulations, so part of the model calibration will involve improving the model comparison to the summer temperature data. Additional time-series figures are presented in Attachments 3 and 4.

5.3. Salinity

Figure 13 shows time-series model-data comparisons for salinity at three locations in the western LIS. There is not much temporal variability in the salinity data and both SWEM ECOM and ROMS reproduce the observed data well. Figure 14 presents model-data salinity comparisons at three stations in the

Hudson River where the temporal variability is more dynamic. Both the SWEM ECOM and ROMS results show stratification and destratification patterns that fit the data. The ROMS bottom salinity is higher than SWEM ECOM bottom salinity. This is likely due to the more contemporary bathymetry used in the ROMS input, which includes deeper navigation channels than existed during the WY95 time period. More testing is needed to verify this, but this result suggests for the Hudson River it is important to use bathymetry data that are representative of the period being modeled. Additional time-series figures of salinity are included in Attachments 3 and 4.

5.4. Vertical Profiles of Temperature and Salinity

One of the important features that needs to be modeled accurately is the vertical stratification of temperature and salinity, or overall density stratification. Figure 15 presents comparisons of vertical profiles of temperature and salinity between ROMS baseline condition output and data. The salinity data does not show much of a difference vertically in the water column and the model reproduces the lack of salinity stratification. Temperature stratification is more obvious, especially during the warmer spring/summer months. The model does reproduce temperature during cooler months but predicts warmer temperatures in the spring/summer months throughout the water column. The model does reproduce some of the structure of the temperature stratification. Tests were performed to assess whether changes to some of the model inputs would alter temperature calculations. These tests and test results are discussed in Section 6. Additional vertical profile figures are presented in Attachment 5.

5.5. Flux through the East River

East River fluxes are an important factor in the transport of nitrogen into and out of LIS. Fluxes are a result of the net direction of the currents, which are controlled by geomorphological features, freshwater flows, tides, meteorology, and density gradients. However, as noted in HydroQual (2001), there are vertical eddies in the East River that make the choice of the transect along which to calculate fluxes important. The HydroQual memorandum compared the results of three models of Long Island Sound: the East River Model (ERM) (Blumberg and Pritchard, 1997), LIS3.0 (Smaltz, 1994), and SWEM. Since these models were compared for the water year 1989 conditions, the results are not directly comparable to WY95, but general comparisons can be made. Transect 78 (Figure 16) was chosen to assess East River flux estimates (additional testing will be conducted as part of the model calibration). Net fluxes are calculated by adding the positive and negative flows in all horizontal and vertical segments across a transect for a 30-day period.

Figure 17 presents the calculated monthly surface layer, bottom layer and net flux through Transect 78 as calculated using ROMS. ROMS calculated a net flux (blue bars) towards the west, as has been calculated by previous models, i.e., ERM, LIS3.0, and SWEM (HydroQual, 2001). The net flux magnitude calculated by ROMS is somewhat smaller than was calculated by previous models; this discrepancy will be investigated during model calibration. ROMS is calculating a flux to the east in the surface layer (orange bars) and a smaller flux to the west in the bottom layer (green bars). In general, the top three layers in ROMS typically flow to the east and the bottom seven layers flow to the west. Net surface flows to the east and bottom flows to the west are consistent with previous studies (Blumberg and Pritchard, 1997). ROMS testing (see below) considers how computed East River fluxes are affected by turbulence closure schemes, vertical segmentation, water type, and bottom friction.

6. Adjusted ROMS Model Results

6.1. Vertical Mixing

One of the advantages that ROMS has over ECOM is the availability of four vertical mixing turbulence closure schemes (k-epsilon, k-kl, k-omega and gen) versus the Mellor-Yamada Level 2.5 closure scheme (k-kl) used in ECOM. Since there are concerns about SWEM ECOM's ability to reproduce the vertical structure of dissolved oxygen (O'Donnell et al. 2010), which is impacted by vertical mixing, the four vertical mixing schemes available in ROMS were tested.

In ROMS, temperature and salinity estimates were generated using each of the turbulence closure schemes. Then, using estimates derived from the k-epsilon scheme as a baseline, differences in the temperature and salinity estimates were derived. In addition, due to the importance of transport between the East River and LIS, fluxes in this area were analyzed for differences between mixing schemes. Testing focused on changes within the LIS. The four closure-schemes available in ROMS yielded similar temperatures and salinity levels with minor differences in magnitude and degree of stratification. Likewise, changing closure schemes resulted in only minor changes to East River fluxes.

6.1.1. Temperature

With k-epsilon as the baseline condition, the application of k-kl results in the largest differences in temperature (Figure 18). Calculated temperatures with k-kl are generally cooler with more noticeable differences in deeper water during the warmer months. The k-omega scheme (Figure 19) follows the same trends as k-kl. The gen scheme (Figure 20) follows the same general pattern as k-kl when compared to the baseline condition but to a lesser extent and gen is the least different from k-epsilon. In general, the temperature differences between the schemes are small with a noisy pattern. Additional figures are included in Attachments 6a, 6b and 6c for the different vertical closure scheme sensitivities.

6.1.2. Salinity

How salinity responded to changes in the turbulence closure schemes was similar to temperature except the different schemes generally made LIS saltier than the baseline condition. The k-kl approach (Figure 21) made the largest difference, and the k-omega scheme (Figure 22) had the smallest change from the baseline condition. Figure 23 shows that the gen scheme falls between the other two schemes. The salinities seem to gradually reach a higher salinity concentration, above the baseline condition, as the simulation progresses. Station K2, near the Connecticut River, shows a great deal more variability in salinity than the other locations (see p. 8 in Attachments 6a, 6b and 6c). This may be due to how the different turbulence closure schemes affect the plume of the river. Figures showing salinity estimates for additional stations are included in Attachments 6a, 6b and 6c.

6.1.3. Flux through the East River

Compared to the baseline condition, the k-kl scheme results in a smaller net flux to the west and a larger surface flux to the east (Figure 24). Net flux estimates derived using the k-omega scheme (Figure 25) are more similar to the baseline condition than estimates derived using the k-kl scheme. Figure 26 indicates that fluxes derived using the gen scheme are the most similar to flux estimates derived under the baseline condition. A quick review of the flux in each individual layer during December indicated the top three layers had a next flux to the east and the bottom seven layers had a net flux to the west.

6.2. Additional Vertical Segmentation

SWEM ECOM used 10 vertical-layers because the available computing power at the time limited the use of more vertical layers and this is the standard convention in circulation modeling. Additional vertical layers can affect vertical mixing in the model. To assess how adding vertical layers affects vertical mixing in ROMS, a sensitivity run was completed using 30 vertical-layers. Model calculated temperature, salinity, and East River fluxes from the sensitivity run were compared to results from a baseline run in which there were 10 vertical layers. Results from the comparisons are described below.

6.2.1. Water Elevation

Additional vertical layers resulted in moderate changes to the water elevation. Figure 27 compares water elevations at Bridgeport, CT and Bergen Point, NY for the baseline condition and the 30-layer run. The figure also shows the difference in water elevation for the baseline condition and the 30-layer run. At Bridgeport, the amplitude increases about 10-15 cm while at Bergen Point it increases about 2-5 cm.

6.2.2. Temperature and Salinity

Due to the complexities of comparing surface and bottom model output in runs that have a different number of layers, which affects the thickness of the layers, comparisons will be made in a different way for the layer testing runs. For Station C1, Figure 28 presents vertical profile comparisons of temperature and salinity data as well as temperature and salinity model output from the baseline condition and the 30-layer run. The example shown is for CTDEEP station C1 for sample dates in February, May, and July. The events represent non-stratified (February) to vertically stratified (July) periods. The temperature results are subtlety different. At station C1, 30-layer results tend to be slightly closer to the measured temperature, but that is not the case at all stations. At some stations the gradients in the temperature profile tend to be slightly sharper with the 30-layer scenario. The salinity results from the 30-layer scenario have slightly higher concentrations than the baseline condition. The baseline condition comparison to the salinity data is a better fit than the 30-layer scenario. Additional figures are presented in Attachment 7.

The results from the 30-layer scenario indicate that slightly more stratification can be achieved than with the 10-layer baseline condition, but testing will need to be done with the water quality model to see if the additional layers are worth the extra computational time burden. This will be done by assessing if appreciably more DO vertical stratification can be achieved with more vertical layers.

6.2.3. Flux through the East River

Figure 29 presents (a) monthly fluxes through the East River as computed in the -30-layer scenario and (b) differences in monthly fluxes through the East River as computed under the baseline condition and the 30-layer scenario. For the comparison to the surface and bottom fluxes in the baseline condition, the top three and bottom three layers of the 30-layer run were summed so the same cross-sectional area as the 10-layer run was compared. The addition of vertical layers results in slightly greater net flux to the west.

6.3. Water Type

In the initial testing of the model to create the baseline condition, it was observed that surface temperatures calculated by ROMS overestimated measured temperatures. ROMS uses the Jerlov Water Type array index to model light absorption. Classifications range from clear open ocean (Type I) to dark coastal waters (Type 7). The baseline condition used coastal waters (Type III). Testing was completed to assess how water type could be used to improve future calibration efforts for temperature. Jerlov Water Types I and 7 were applied to test the two extremes of the available water types.

6.3.1. Temperature

The clearest water condition, Type I, results in the least light absorption at the surface. As would be expected this results in greater light penetration and causes greater heating at depth, which reduces temperature stratification. Figure 30 shows that most of the temperature change occurred at depth during the warmer months of the year. The temperature increases at depth as would be expected. The use of Jerlov Water Type 7 (dark coastal water) results in slight cooling at depth with respect to the baseline condition as shown in Figure 31. Even using the condition with the most near-surface light absorption (Type 7), the model overestimates bottom temperatures during warmer months. Additional figures comparing Water Type I and baseline (Type III) results can be found in Attachment 8.

6.3.2. Salinity

The temperature changes from using both Jerlov Water Type I and Type 7 caused very little change in the salinity as would be expected.

6.3.3. Flux through the East River

The choice of Jerlov Water Type has almost no effect on fluxes through the East River.

6.4. Bottom Friction

From the baseline ROMS model results, it was apparent that the water elevation comparison to data could be improved in some areas. In SWEM ECOM, spatially variable bottom friction was applied (the default value was 0.003). For the baseline ROMS model, the same spatial variable bottom friction was applied (Figure 32). Testing was completed to assess how removing the spatial variability and applying constant bottom friction impacted ROMS model results. Note that sites referred to in figures cited below (e.g., New London, Bridgeport, A4, C2, and C1), with the exception of Transect 78, are located in areas where the default bottom friction was applied.

Also noteworthy is that it is possible that the coarser resolution of SWEM ECOM required additional bottom friction to offset the coarseness of the East River model geometry. Better resolution of LIS and the East River may eliminate or reduce the need to spatially vary bottom friction to improve the hydrodynamic model calibration. The SWEM ECOM documentation did not provide justification for the spatially variable bottom friction other than reporting that it improved the calibration. Spatially variable bottom friction could be warranted, and if used, will have proper justification.

6.4.1. Water Elevation

Applying a spatially uniform bottom friction resulted in reduced tidal ranges at New London and Montauk (not shown) and an increased tidal range at Bridgeport (Figure 33). The changes did not improve the model comparison to the available data, but the sensitivity shows that adjusting the bottom friction can be a tool that can potentially benefit the model calibration.

6.4.2. Temperature

The decrease in bottom friction in the East River resulted in lower summertime temperatures in LIS that improved the model comparison to data as shown in Figure 34. There was also an increase in temperature stratification during the warmer months. In some areas, small increases in temperature were calculated during the cooler months. Adjustments to the bottom friction can be used to improve the temperature calibration. Additional figures can be found in Attachment 9.

The lower bottom friction in the East River likely reduces bottom turbulence thereby reducing vertical mixing. Additionally, it is likely that cooler ocean water can enter the LIS from the east as a result of the bottom friction change.

6.4.3. Salinity

The removal of spatially variable bottom friction resulted in higher salinity with more vertical stratification than the baseline condition as shown in Figure 35. However, the baseline condition compared more favorably to the salinity data than the bottom friction sensitivity.

6.4.4. Flux through the East River

Figure 36 shows the comparison between the East River fluxes in the baseline condition run (bottom panel) and the bottom friction sensitivity (top panel). Compared to baseline, surface fluxes in the bottom friction sensitivity increase to the east and the bottom fluxes increase to the west. Net flux to the west decreased except in December and March.

7. Conclusions and Implications for CY05-06 Preliminary Calibration

The ROMS hydrodynamic model was set up using WY95 inputs from the SWEM ECOM model. Not all of the SWEM ECOM inputs were compatible with ROMS, and ROMS required some additional inputs to be specified (e.g., offshore boundary condition velocity). Since the time of testing, the ROMS code has been modified to allow for assigning two types of freshwater inputs: sources originating along the shoreline (e.g., rivers, CSOs) and sources associated with offshore outfalls (e.g., Oakwood Beach WRRF). Until the modified ROMS code can be implemented, all freshwater inputs are assigned as shoreline inputs. There are also differences between the ROMS and SWEM ECOM atmospheric heat exchange and light absorption/extinction formulations that impact the calculation of temperature. Nonetheless, the ROMS model output did generally reproduce the WY95 water elevation, current speed, temperature, and salinity data and SWEM ECOM model output. The higher spatial resolution ROMS model grid is likely part of the reason for some of the differences noted between the two models.

The following conclusions are presented based on the ROMS model testing using the SWEM ECOM WY95 model inputs.

- ROMS calculated water elevations reproduced the data fairly well using the SWEM ECOM model inputs. Currently identified areas for model-data comparison improvements during model calibration include using increased spatial variation of meteorological inputs, representation of meteorological effects in the offshore boundary condition inputs, and spatially varying bottom friction adjustments.
- ROMS calculated water temperatures reproduced the general seasonal pattern fairly well using the SWEM ECOM model inputs but ROMS over-calculated temperatures during the spring and summer as compared to the SWEM model output and data, particularly in the bottom layer. Currently identified areas for model-data comparison improvements during model calibration include reviewing the ROMS atmospheric heat exchange and light absorption/extinction formulations, using site-specific light extinction data, using increased spatial variation of meteorological inputs, and closely evaluate water transport into LIS from the ocean near The Race, particularly near the bottom layer.

- ROMS calculated salinity reproduced the data well using the SWEM ECOM model inputs from the vertically mixed conditions in LIS to the vertically stratified conditions in the Hudson River. Currently identified areas for model-data comparison improvements during model calibration include reviewing when and where dredging activities occurred as the deepening can affect salinity intrusion in the bottom layer.
- ROMS calculated volume fluxes in the East River are consistent with previous studies but additional work is needed to evaluate transport processes in the East River and elsewhere in the study area. Currently identified areas for model-data comparison improvements during model calibration include further model-data comparisons to available ADCP data and model bathymetry/geometry adjustments.
- It is clear that additional calibration of the ROMS hydrodynamic model is required and will be addressed during model calibration to the CY05-14 time period. Additionally, groundwater flows and increased spatial variation of meteorological inputs will also be added to ROMS as part of model calibration.

Several model tests were conducted using the ROMS hydrodynamic model with WY95 SWEM ECOM inputs as baseline conditions. Testing included sensitivities to available ROMS turbulence closure schemes, the number of vertical layers, Jerlov Water Type (i.e., light attenuation/extinction), and bottom friction. Conclusions from the model testing are presented below.

- Four turbulence-closure-schemes were tested: k-epsilon; k-kl (Mellor-Yamada 2.5, which is used in SWEM ECOM); k-omega; and general (gen). The turbulence closure schemes all resulted in similar model output (i.e., water elevations, temperature, salinity and East River volume fluxes, and levels of vertical stratification). The greatest differences were observed between the k-epsilon and k-kl schemes. The different options for turbulence closure schemes did not provide conclusive results, so no option has been eliminated from future use in model calibration. Further testing will be done with the water quality portion of the model to see how dissolved oxygen is affected by the different schemes.
- Adding more vertical layers (increasing from 10 to 30) produced minor changes to the calculated vertical temperature and salinity stratification. Additional testing with the water quality model will be necessary to ascertain if these changes are important to calculated DO levels. Adding vertical layers noticeably changed water elevations in portions of Long Island Sound and affected the East River net volume flux at Transect 78. Due to significantly increased model run times when using more vertical layers, it may be better to complete routine calibration runs with 10 layers and use more layers for final testing if the decision is made that more vertical layers improve the accuracy of the model output.
- The Jerlov Water Type sensitivity behaved as would be expected. Clearer water (Type I) resulted in deeper penetration of light and warmer water at depth with less stratification. Darker water (Type 7) resulted in more heat being absorbed in the surface water and more stratification. Neither type fully rectified the overheating of water in LIS during the summer in ROMS. The ROMS water type (light absorption/existing) will be based on site-specific data and will be used to improve model-data comparisons for temperature during model calibration.
- The bottom friction sensitivity impacted water elevation and temperature and when reasonably adjusted spatially can help improve the water elevation, temperature, and salinity calibration of the model.
- As the preliminary ROMS hydrodynamic model calibration effort begins with the CY05-06 data, additional testing of model inputs will be completed as part of the calibration process. Improved information available to develop model inputs will be used to aid in the model calibration. Factors such as spatially variable meteorology, better ocean boundary conditions, and an understanding

of groundwater flows can be used to improve the model calibration beyond the factors explored in the model testing.

8. References

Blumberg, A.F., & Pritchard, D.W., 1997. Estimates of the transport through the East River, New York. *Journal of Geophysical Research: Oceans, 102*, 5685-5703. doi:https://doi.org/10.1029/96JC03416

Defne, Z., F. Spitz, V. DePaul, and T.A. Wool, 2017. Toward a Comprehensive Water-Quality Modeling of Barnegat Bay: Development of ROMS to WASP Coupler, *Journal of Coastal Research*, 78(sp1), 34-45, https://doi.org/10.2112/SI78-004.1

Fairall, C.W., E.F. Bradley, D.P. Rogers, J.B. Edson and G.S. Young, 1996a. Bulk parameterization of air-sea fluxes for tropical ocean-global atmosphere Coupled-Ocean Atmosphere Response Experiment, *JGR*, 101, 3747-3764.

Fairall, C.W., E.F. Bradley, J.S. Godfrey, G.A. Wick, J.B. Edson, and G.S. Young, 1996b. Cool-skin and warm-layer effects on sea surface temperature, *JGR*, 101, 1295-1308.

HDR, 2021. Hydrodynamic & Water Quality Model Selection and Setup. For the New York City Department of Environmental Protection DEP LIS-HWQMS Project. Contract: BEPA-LIS-HWQMS; PIN: 82619BEPALIS.

HydroQual, 2001. Technical Memorandum. Response to “Report on the Calibration and Validation of the System-Wide Eutrophication Model Hydrodynamic Model.” By Connecticut Department of Environmental Protection. Prepared under subcontract to Greeley and Hansen.

Large, W.G. and S. Pond, 1982. Sensible and Latent Heat Flux Measurements over the Ocean. *J. Phys. Oceanogr.*, 12, 464-482.

Levin, J., J. Wilkin, N. Fleming, and J. Zavala-Garay, 2018. Mean circulation of the Mid-Atlantic Bight from a climatological data assimilative model, *Ocean Modelling*, 128, 1-14.

Liu, W.T., K.B. Katsaros, and J.A. Businger, 1979. Bulk parameterization of the air-sea exchange of heat and water vapor including the molecular constraints at the interface, *J. Atmos. Sci.*, 36, 1722-1735.

O’Donnell, J., H. Dam, G. McCardell and T. Fake, 2010. Simulation of Long Island Sound with the System-Wide Eutrophication Model (SWEM): Inter-annual Variability and Sensitivity. Long Island Sound Study EPA Assistance Award Final Report. LI-97127101.

O'Donnell, J., J. J. Fitzpatrick, G. McCardell, T. Fake and R. Horwitz, September 2014. Final Report: The Development of a Community Model of Nutrient Transport and Cycling for Long Island Sound. Prepared for New England Interstate Water Pollution Control Commission.

Paulson, C.A. and J.J. Simpson, 1977. Irradiance Measurements in the Upper Ocean. *J. Phys. Oceanogr.*, 7, 952-956.

Schmidt, S.R. and M.M. Whitney, 2018. A Model Study on the Summertime Distribution of River Waters in Long Island Sound. Estuaries and Coasts 41:1002-1020.

Smaltz, R.A., 1994. Application and documentation of the Long Island Sound three-dimensional circulation model. Summary Report, Vol. 1, Long Island Sound Oceanography Report. NOAA Technical Report NOS OES 003, 77 pp.

Whitney, M. M., and D. L. Codiga, 2011: Response of a large stratified estuary to wind events: Observations, simulations, and theory for Long Island Sound. *J. Phys. Oceanogr.*, 41, 1308-1327.

Whitney, M.M., Y. Jia, P.M. McManus, and C.J. Kunz, 2014. Sill effects on physical dynamics in eastern Long Island Sound. *Ocean Dyn.*, 64, 443–458, doi:10.1007/s10236-013-0681-6.

Whitney, M.M., D.S. Ullman, and D.L. Codiga, 2016. Subtidal exchange in eastern Long Island Sound. *J. Phys. Oceanogr.*, 46 (8), 2351–2371. https://doi.org/10.1175/JPO-D-15-0107.

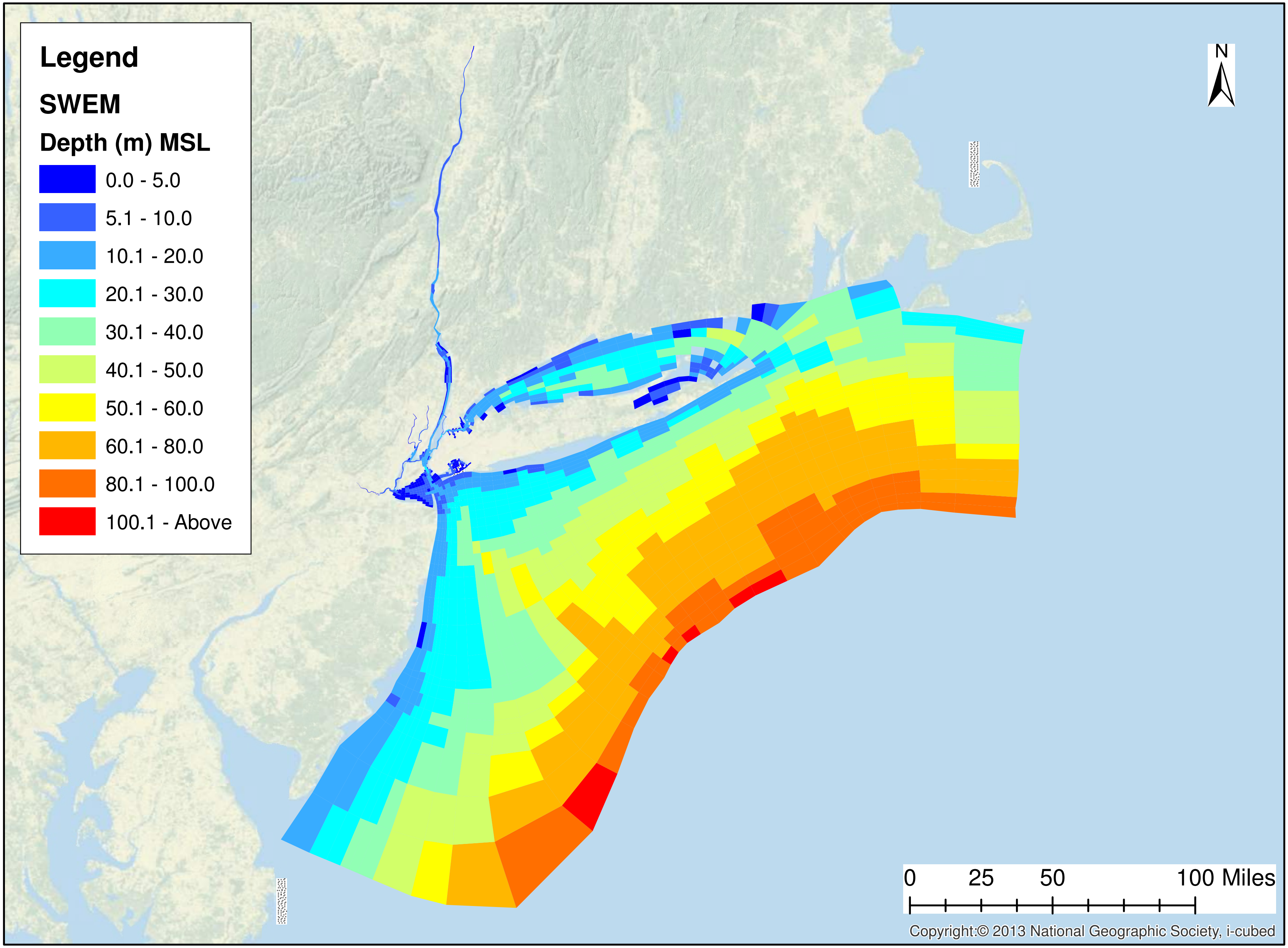


Figure 1. SWEM Model Grid

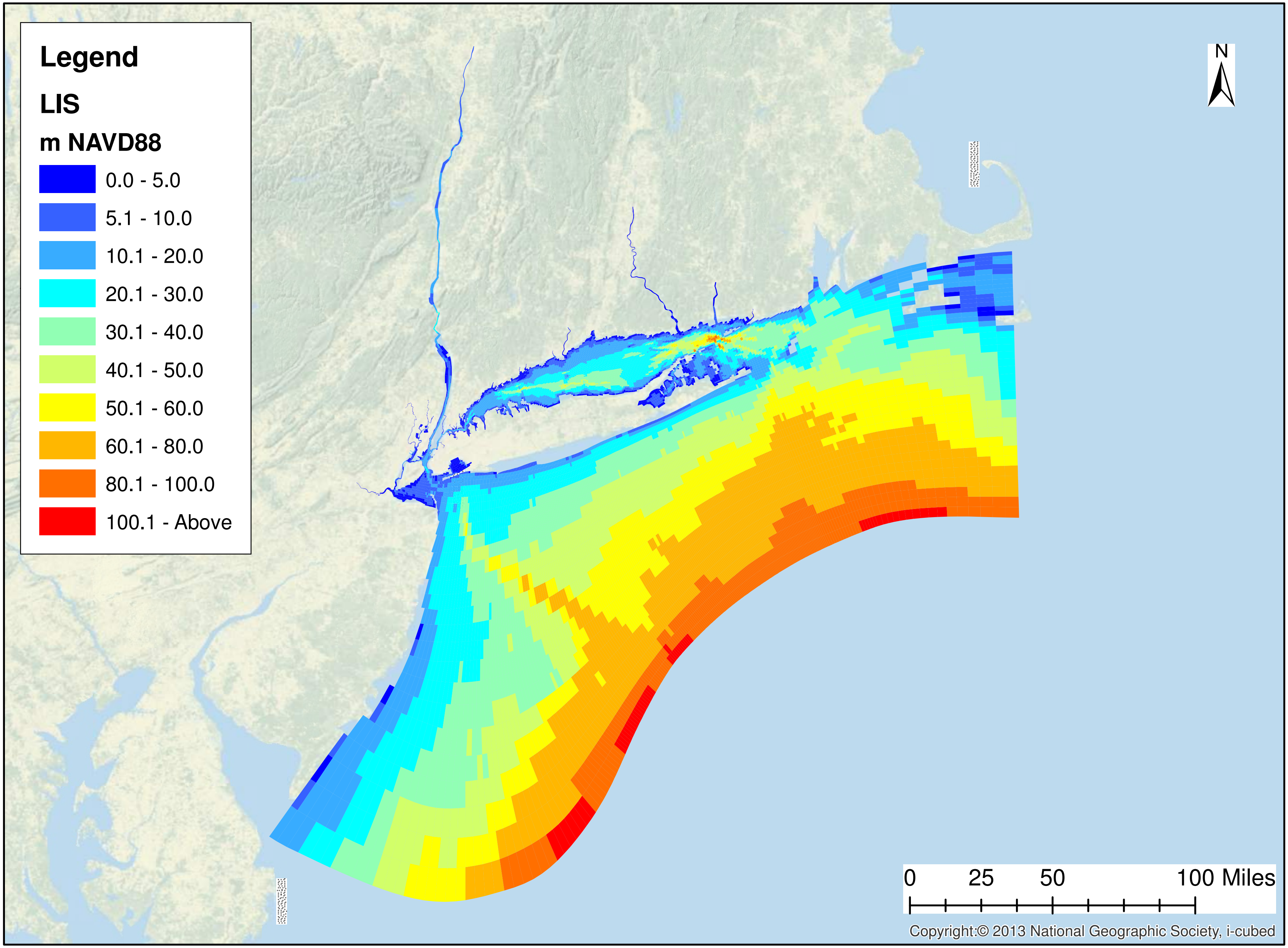


Figure 2. ROMS-RCA Model Grid

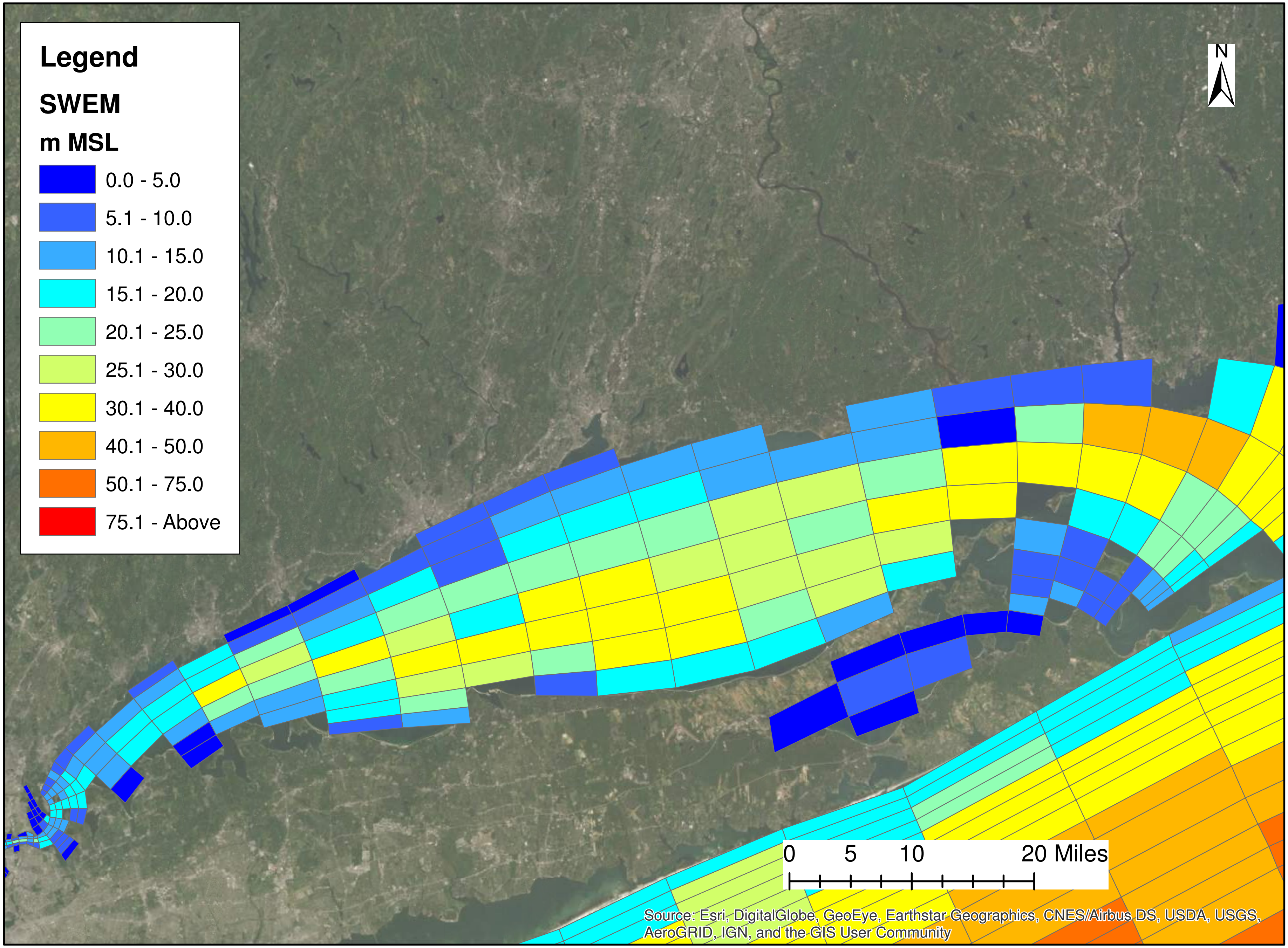


Figure 3. SWEM Model Grid of Long Island Sound

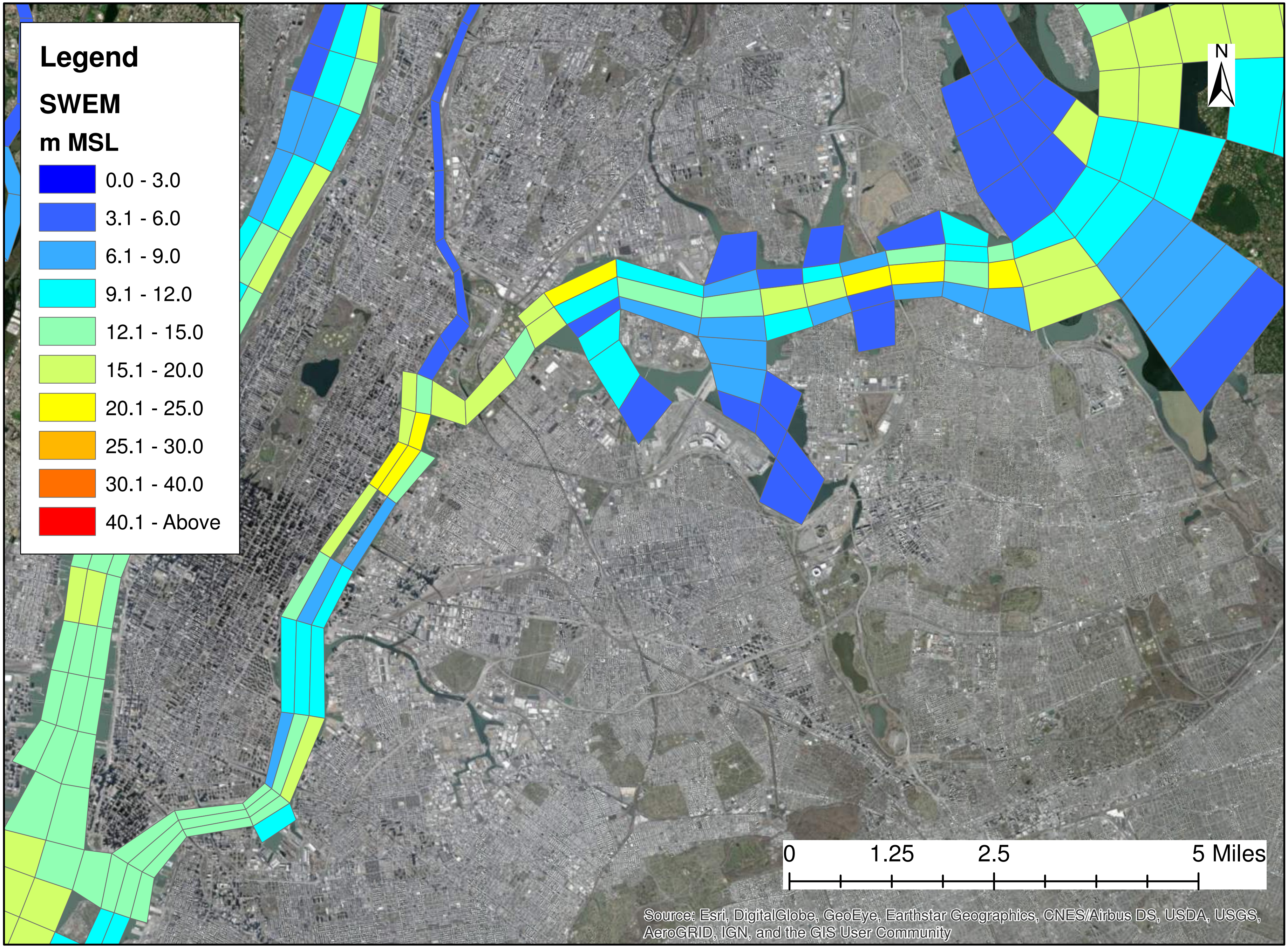


Figure 4. SWEM Model Grid of the East River

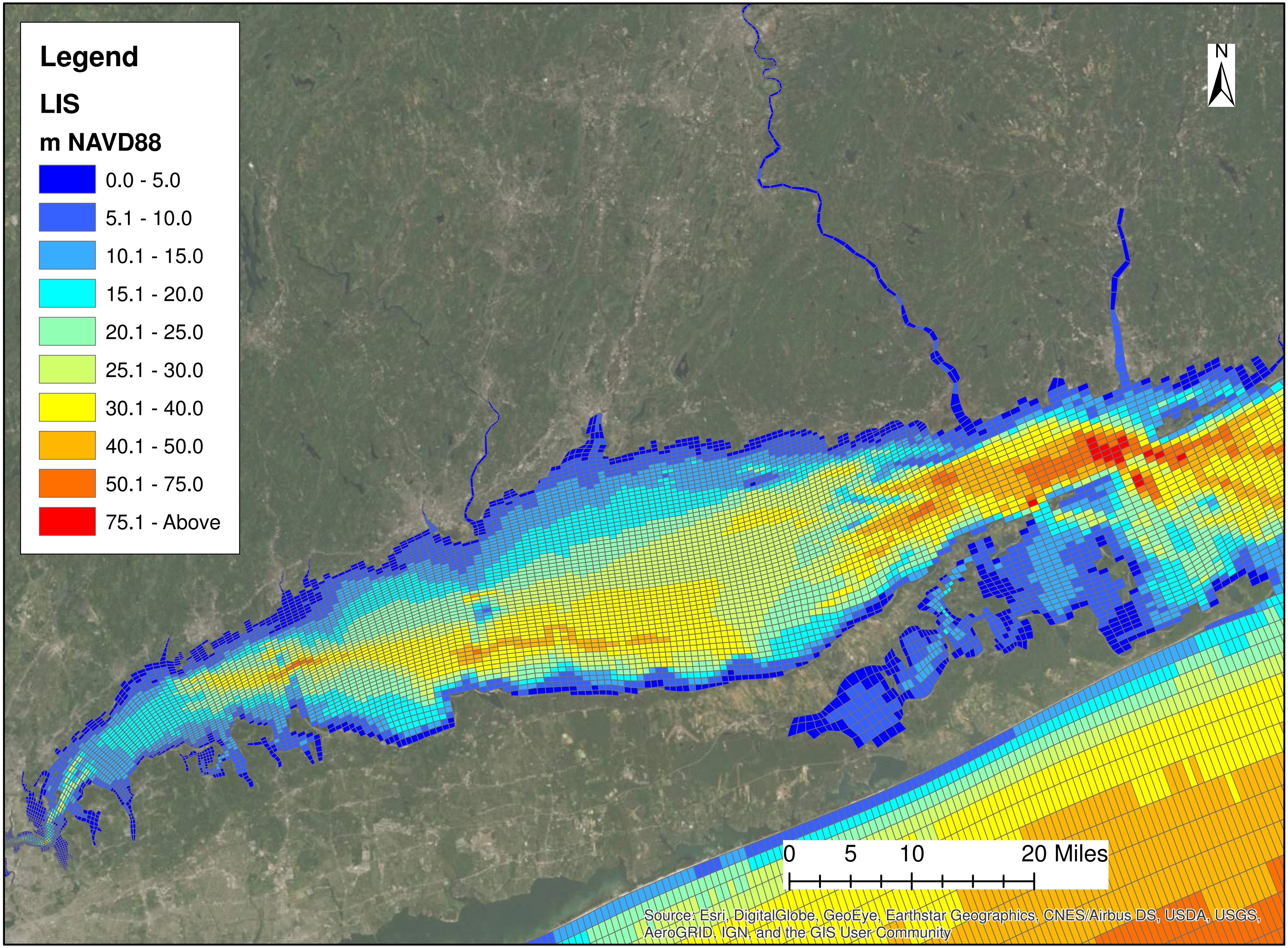


Figure 5. ROMS-RCA Model Grid of Long Island Sound

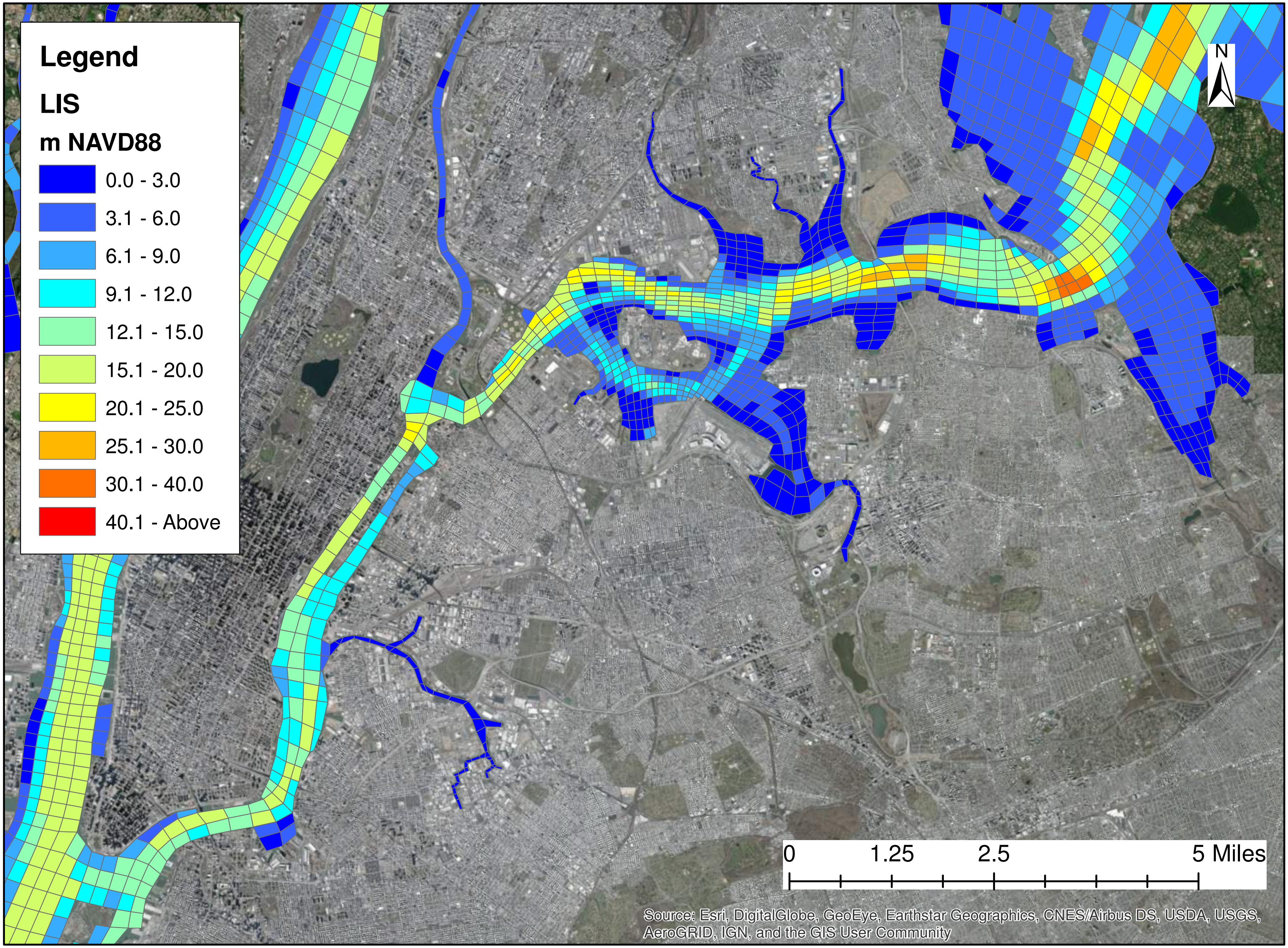


Figure 6. ROMS-RCA Model Grid of the East River

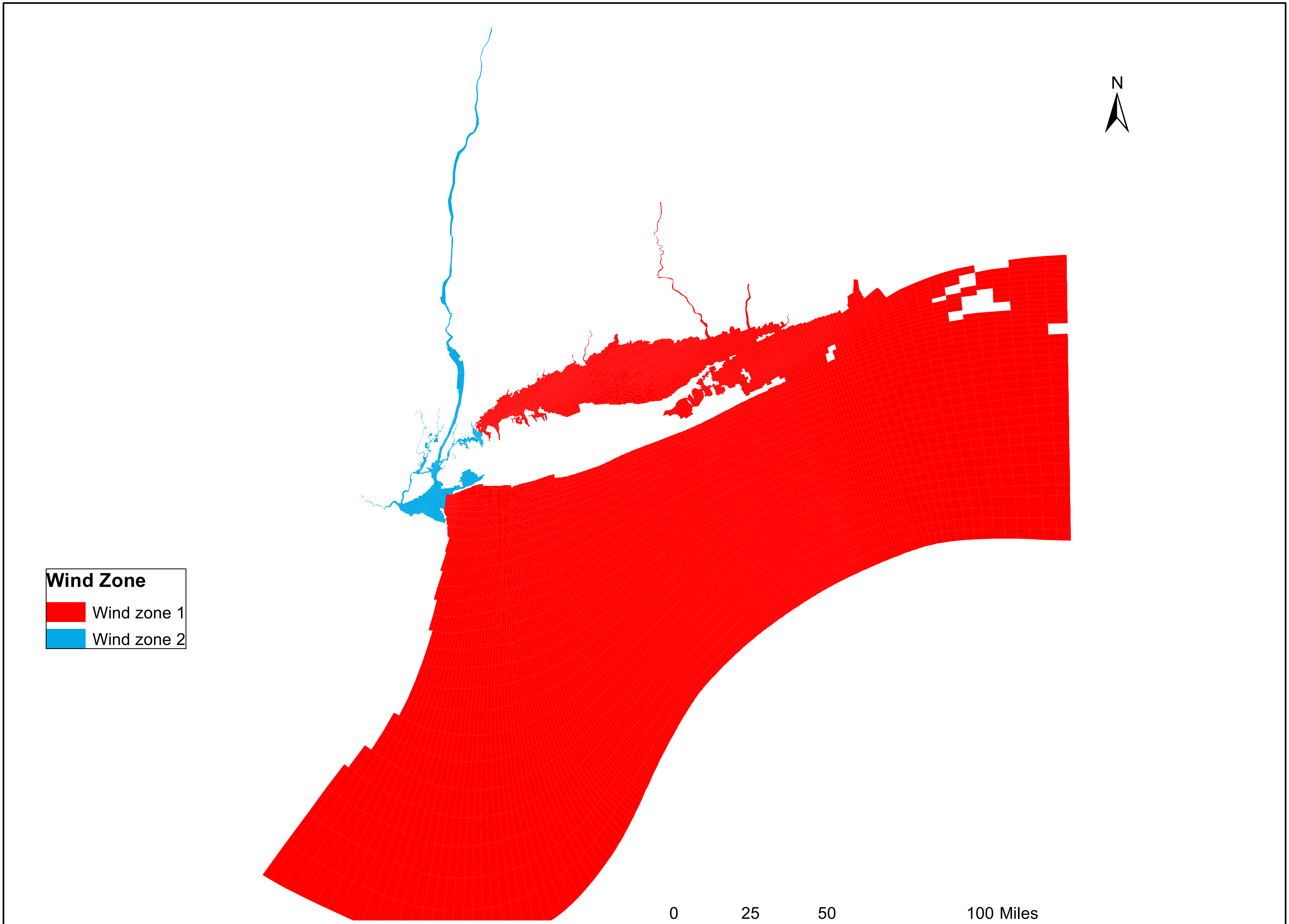


Figure 7. Wind Zones Applied in the Models

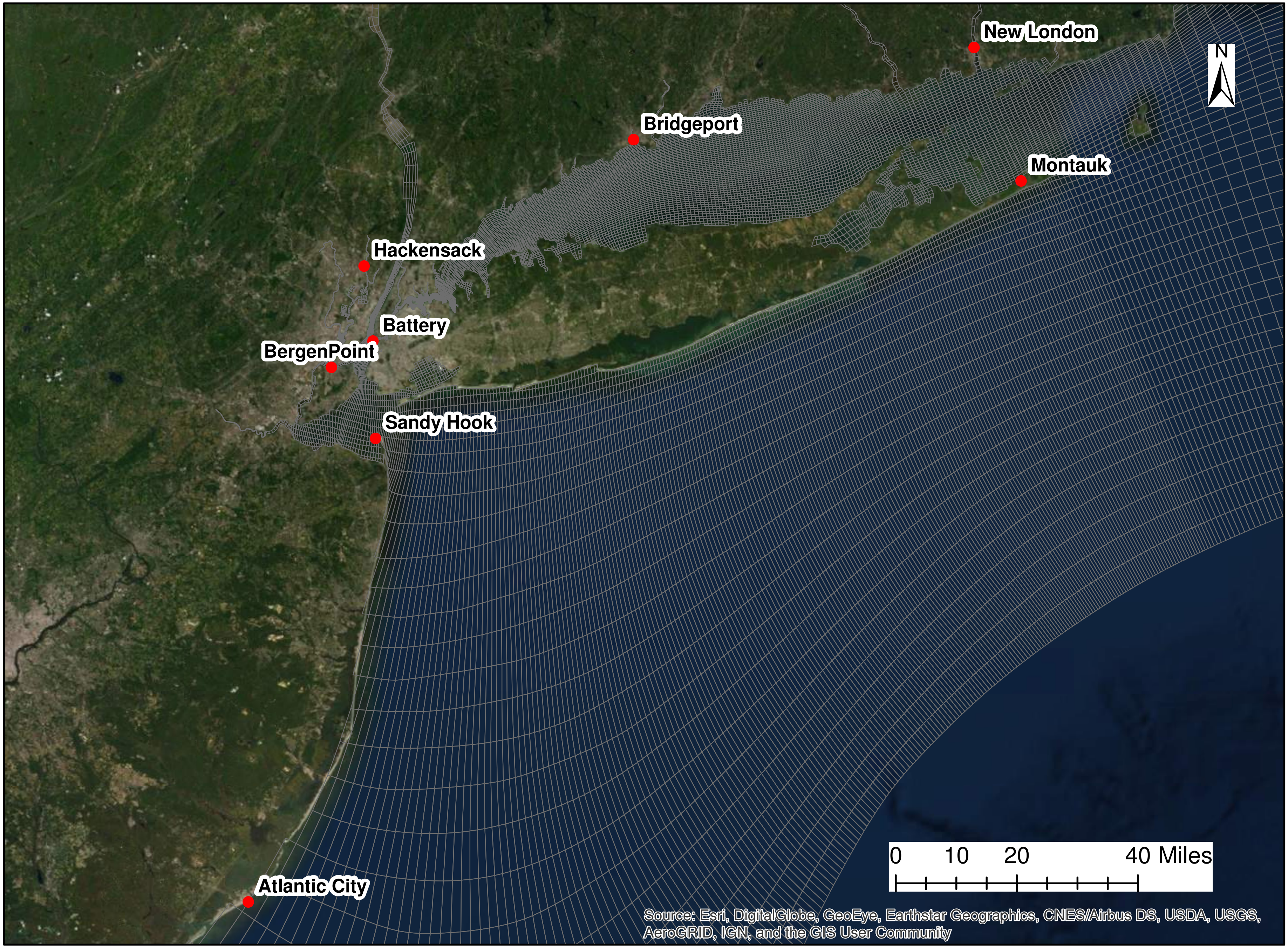


Figure 8. NOAA Water Elevation Station Locations

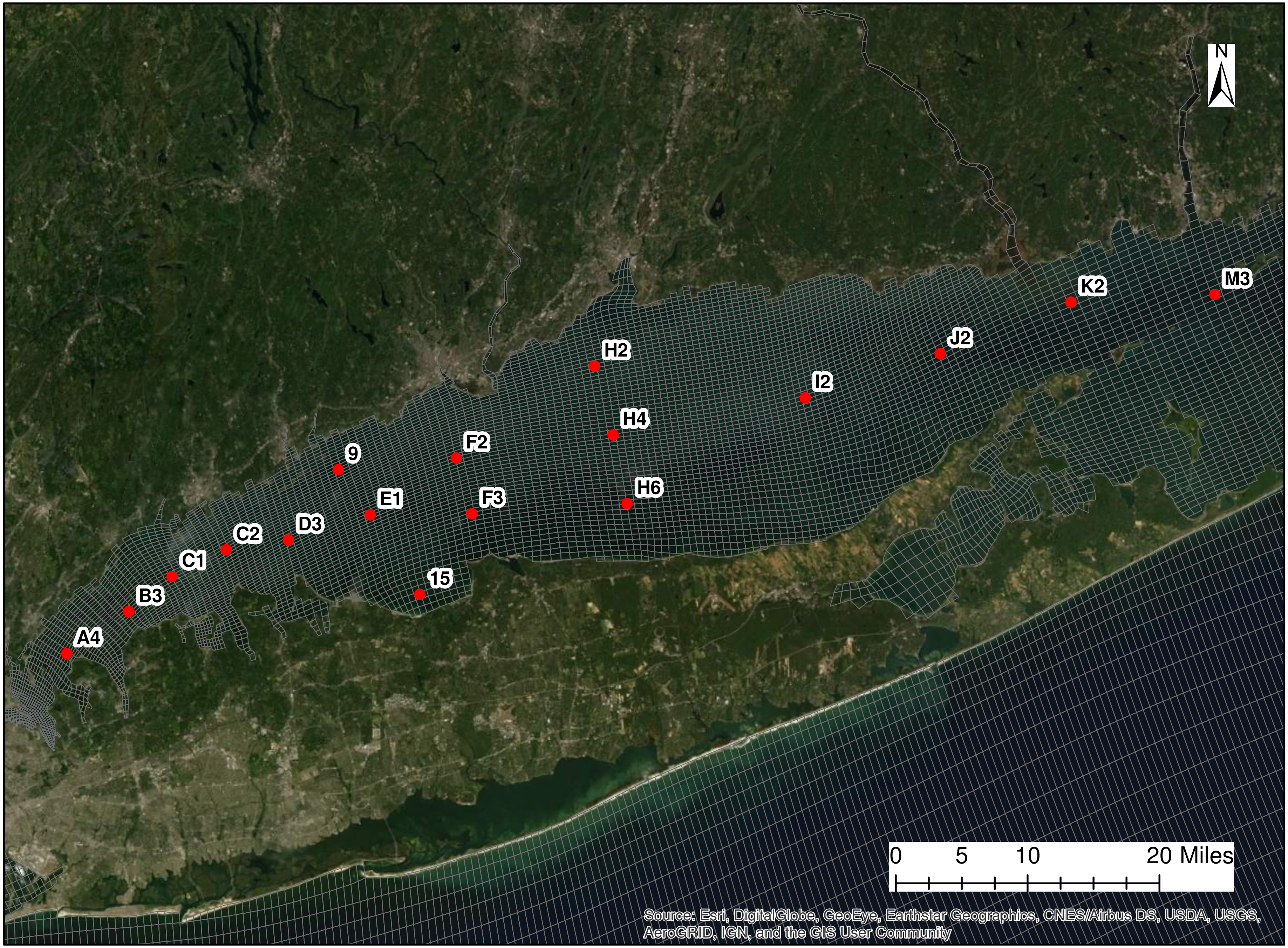


Figure 9. CTDEEP Monitoring Station Locations

New York City Harbor Water Quality Survey Stations 2016

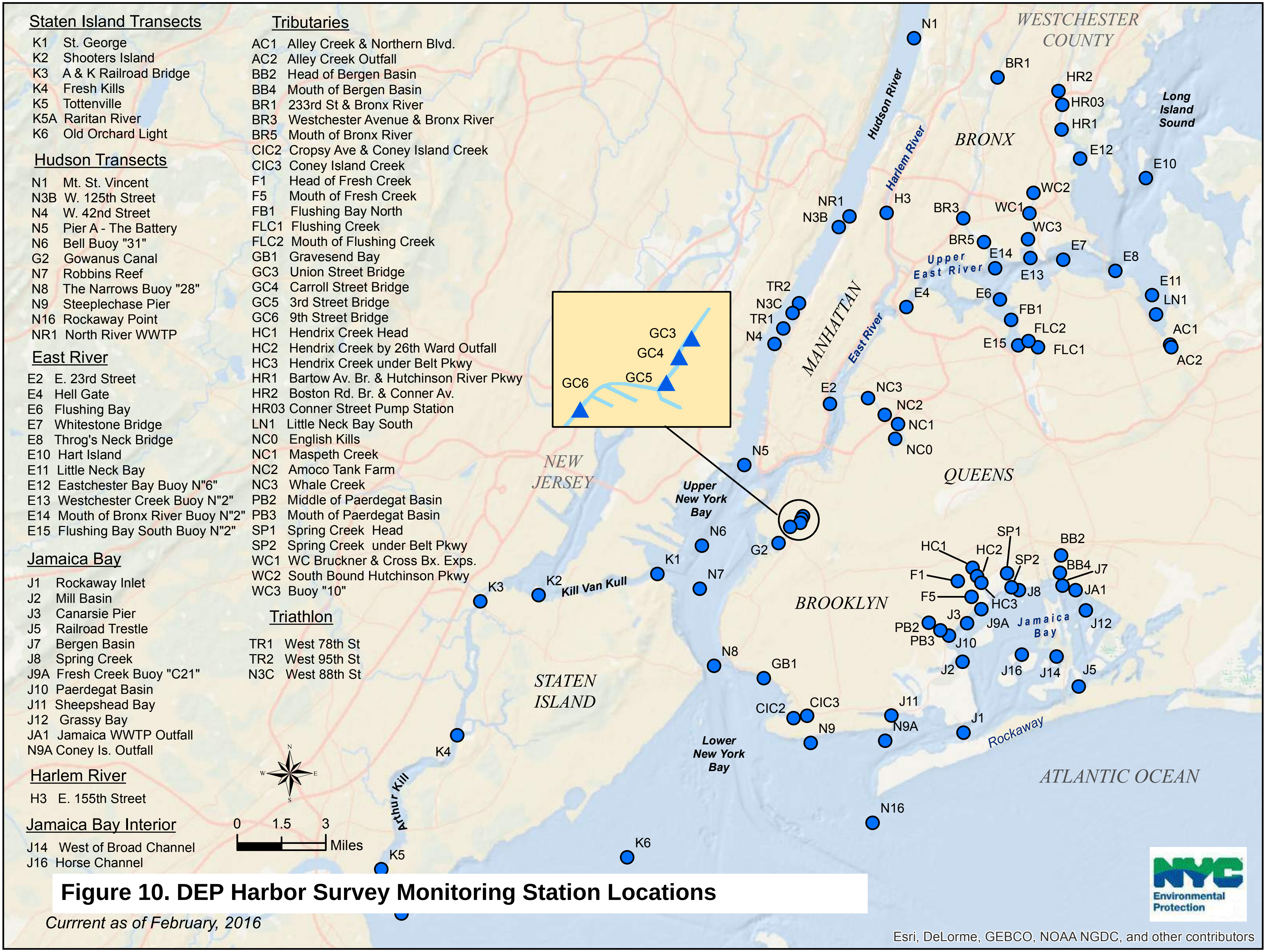


Figure 10. DEP Harbor Survey Monitoring Station Locations

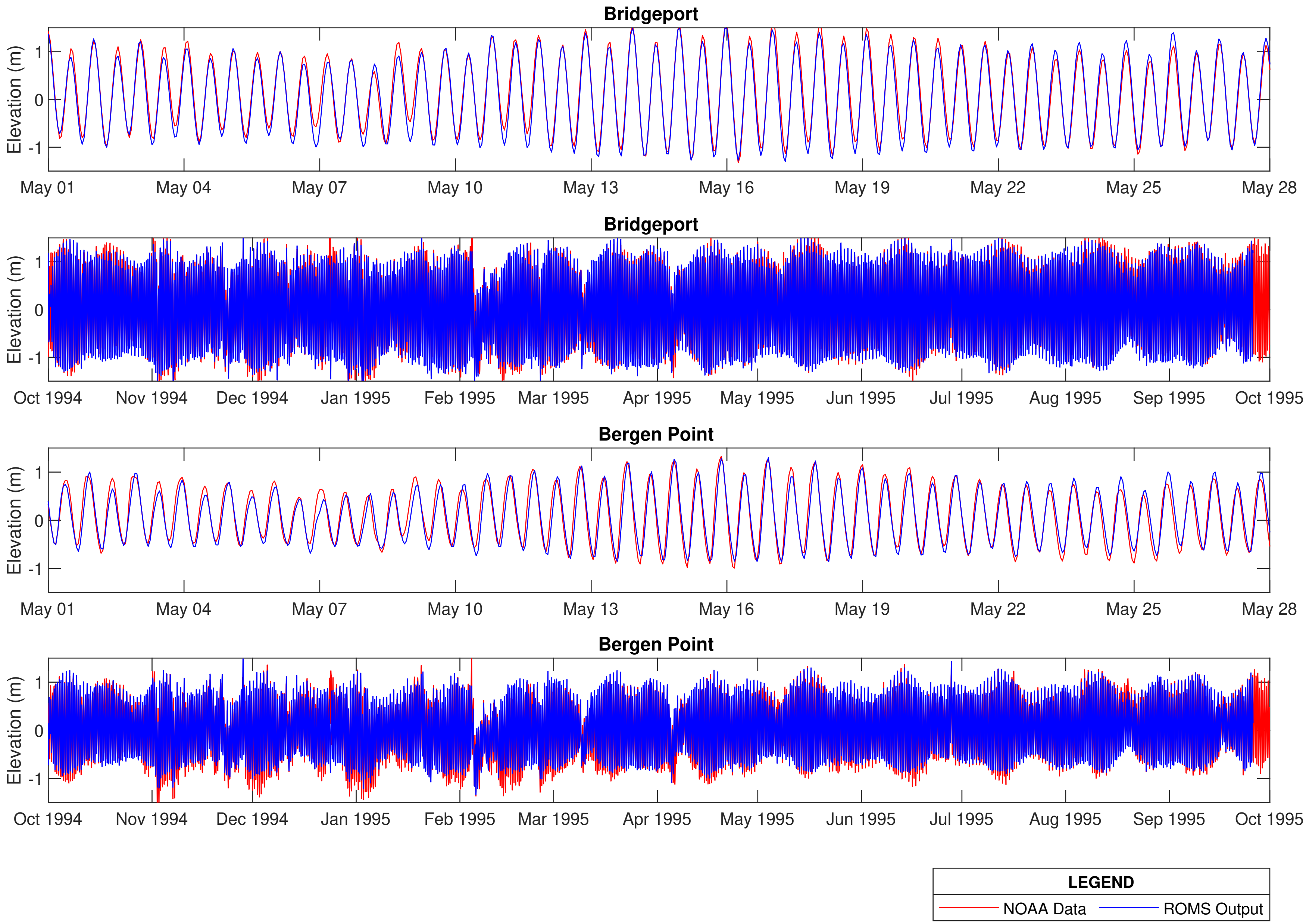


Figure 11. Comparison of Baseline Water Elevation to NOAA data at Bridgeport, CT and Bergen Point, NY (27-day and 365-day periods shown, red line - NOAA data, blue line - model output)

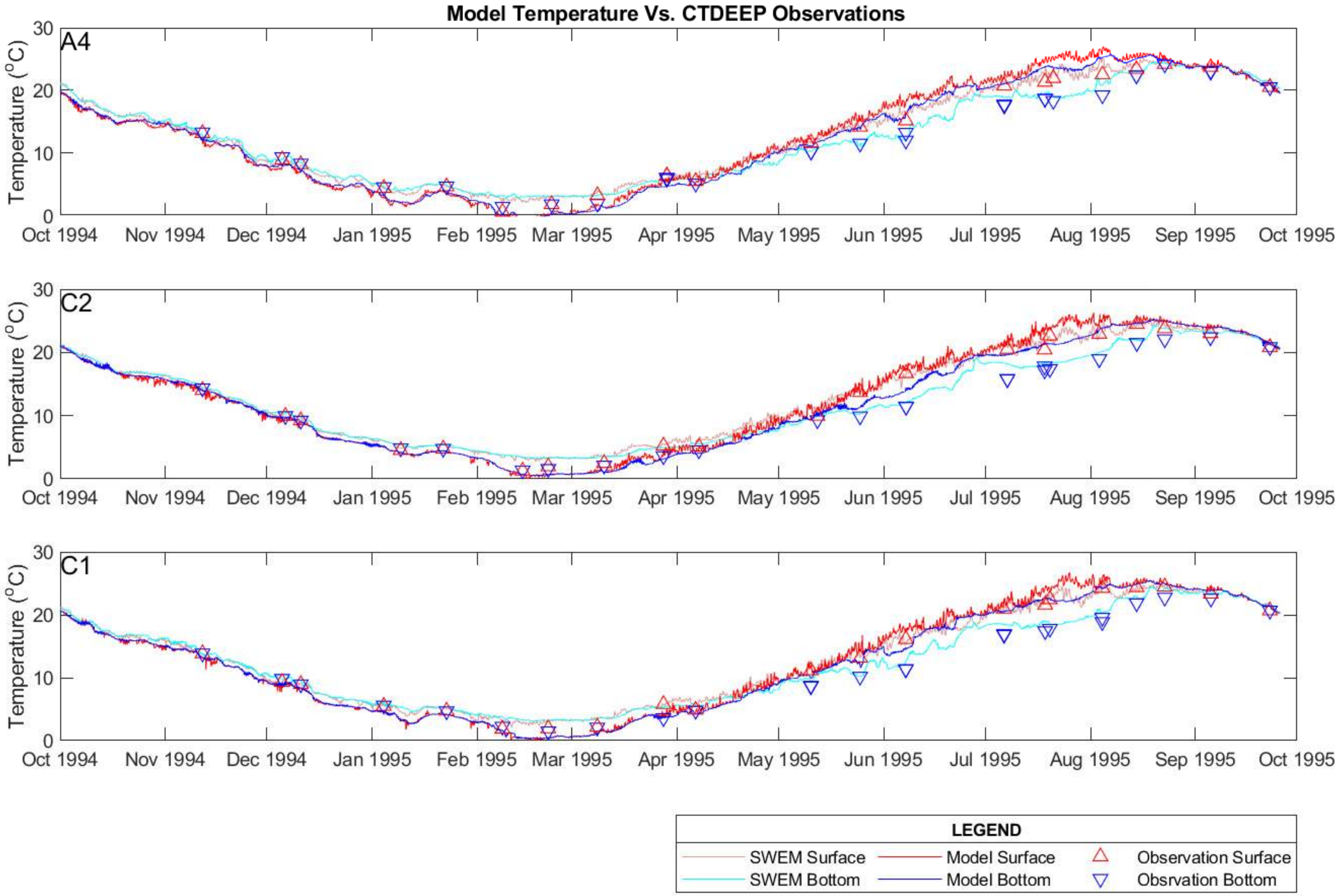


Figure 12. Baseline Temperature Results Compared with Temperature Data and SWEM Results at three CTDEEP Stations in Western Long Island Sound

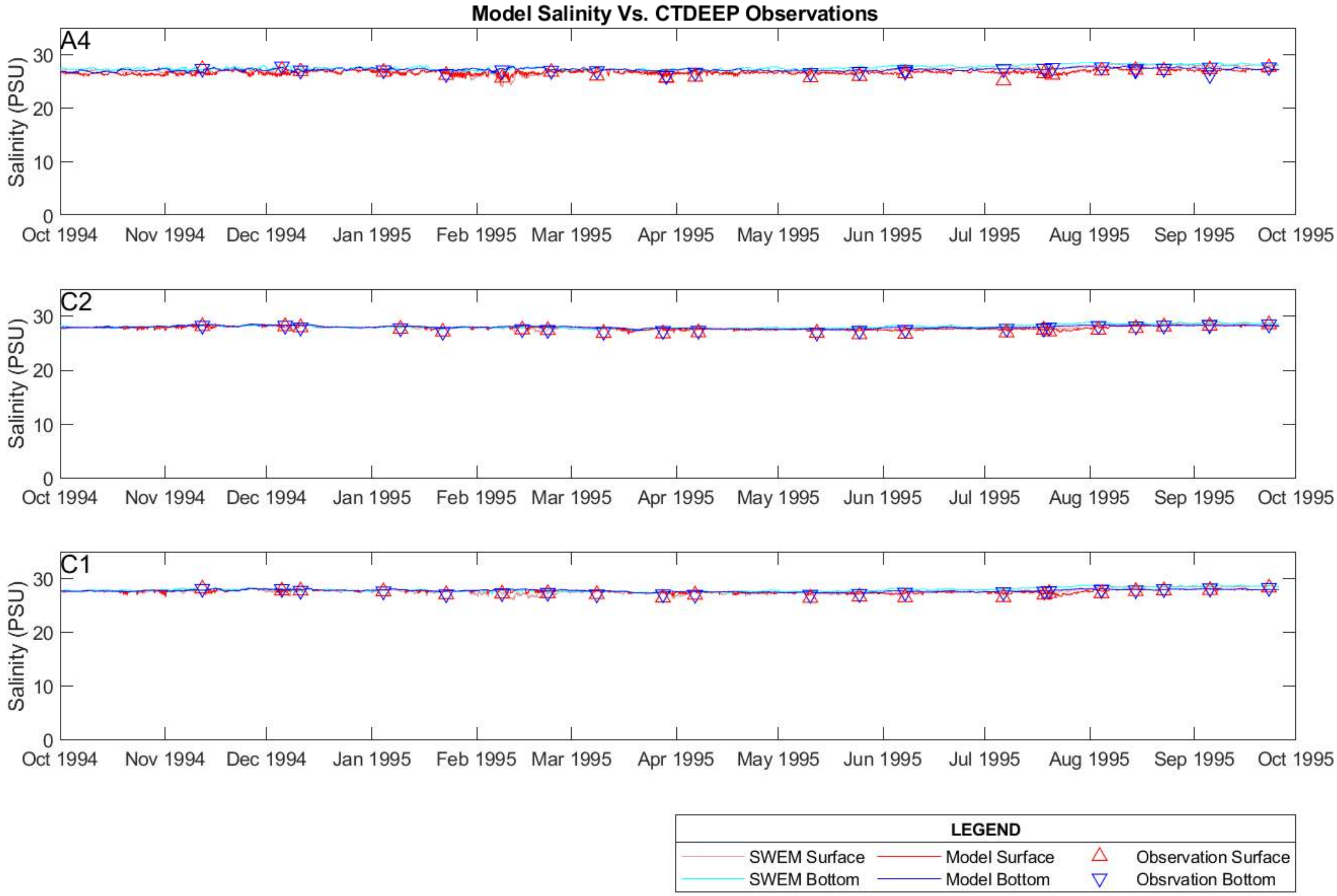


Figure 13. Baseline Salinity Results Compared with Salinity Data and SWEM Results at three CTDEEP Stations in Western Long Island Sound

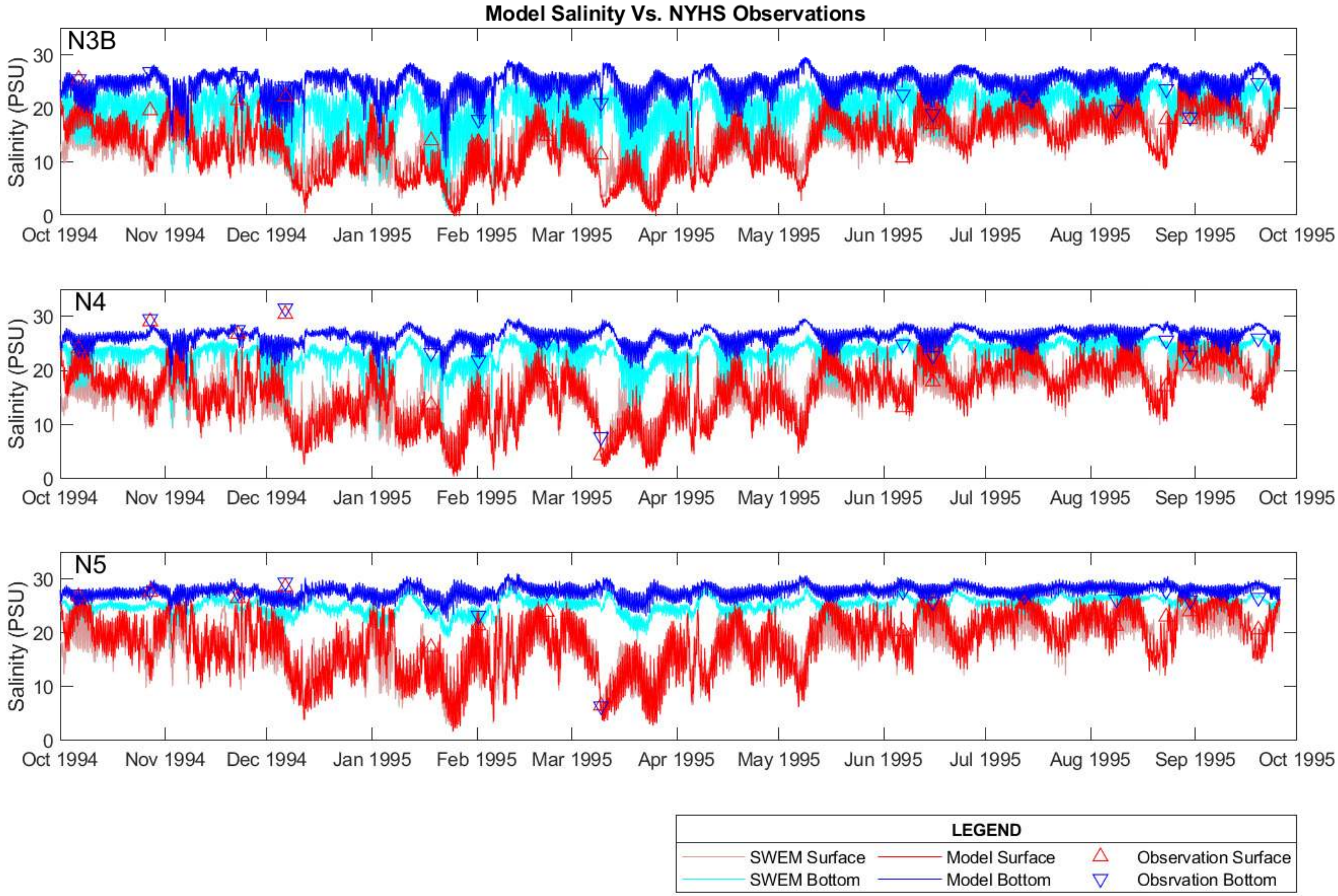


Figure 14. Baseline Salinity Results Compared with Salinity Data and SWEM Results at three DEP Hudson River Stations

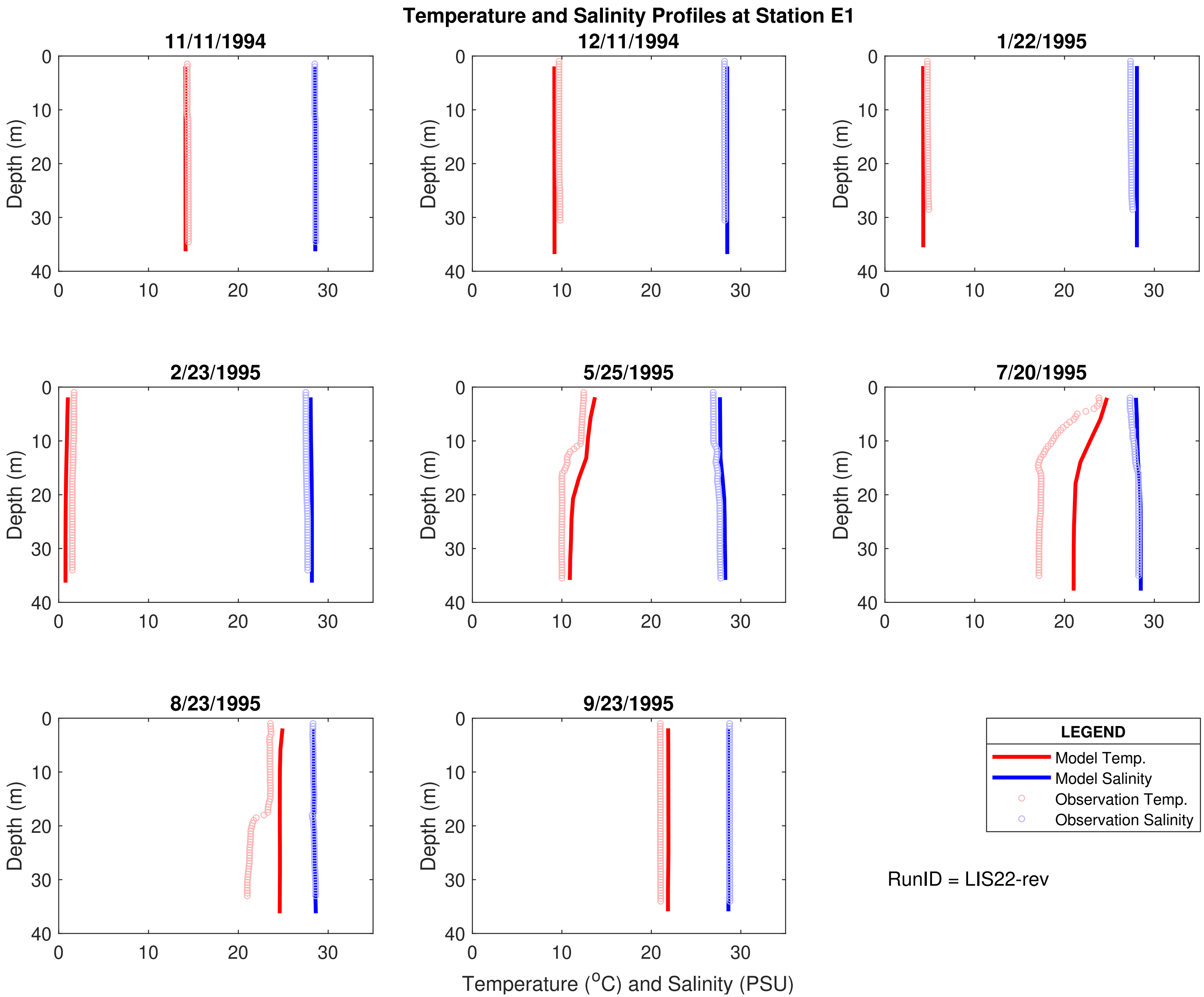


Figure 15. Baseline Model vs. Temperature and Salinity Profiles at CTDEEP Station E1

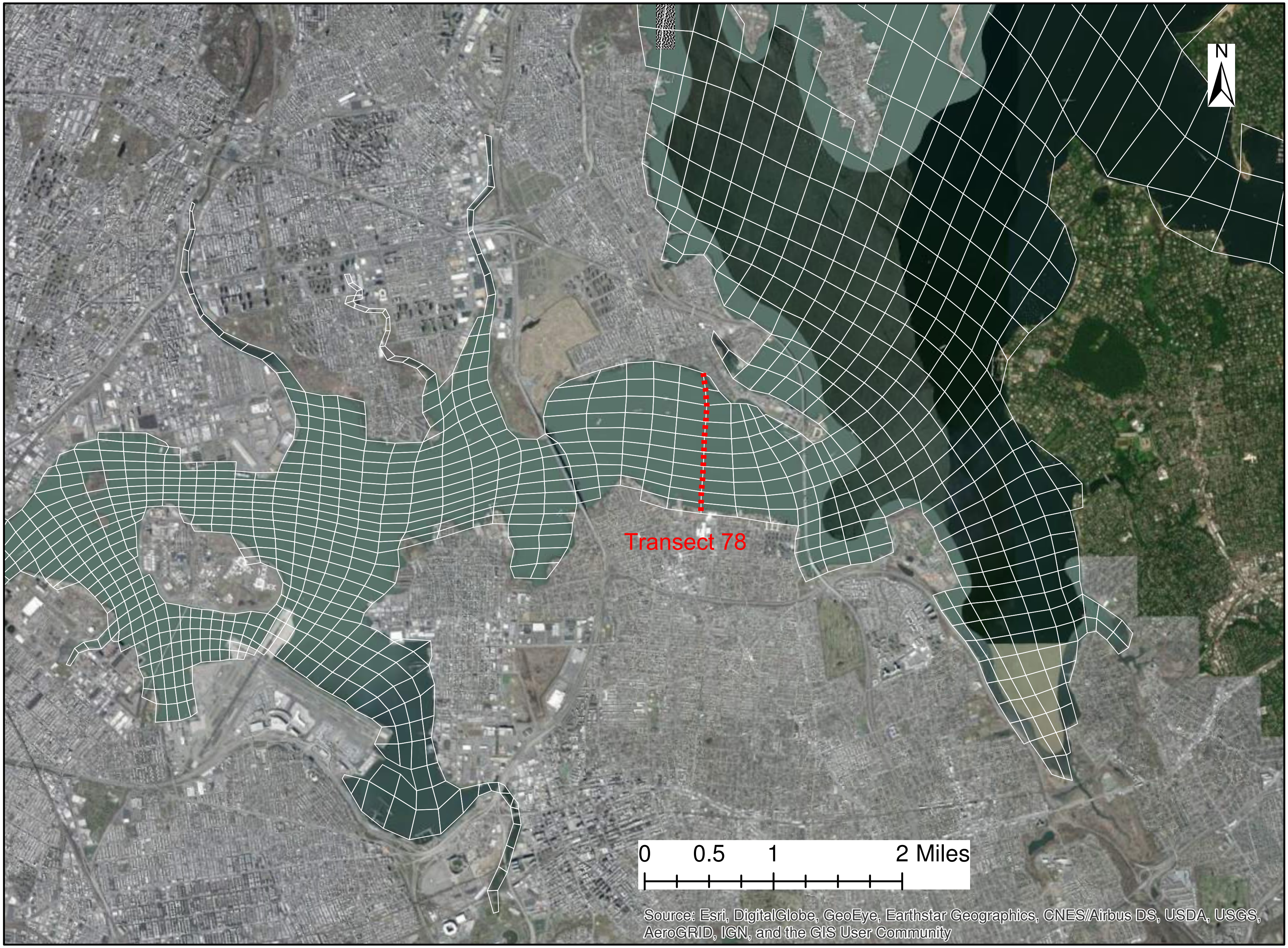


Figure 16. Model Transect Location Chosen for East River Flux Calculations

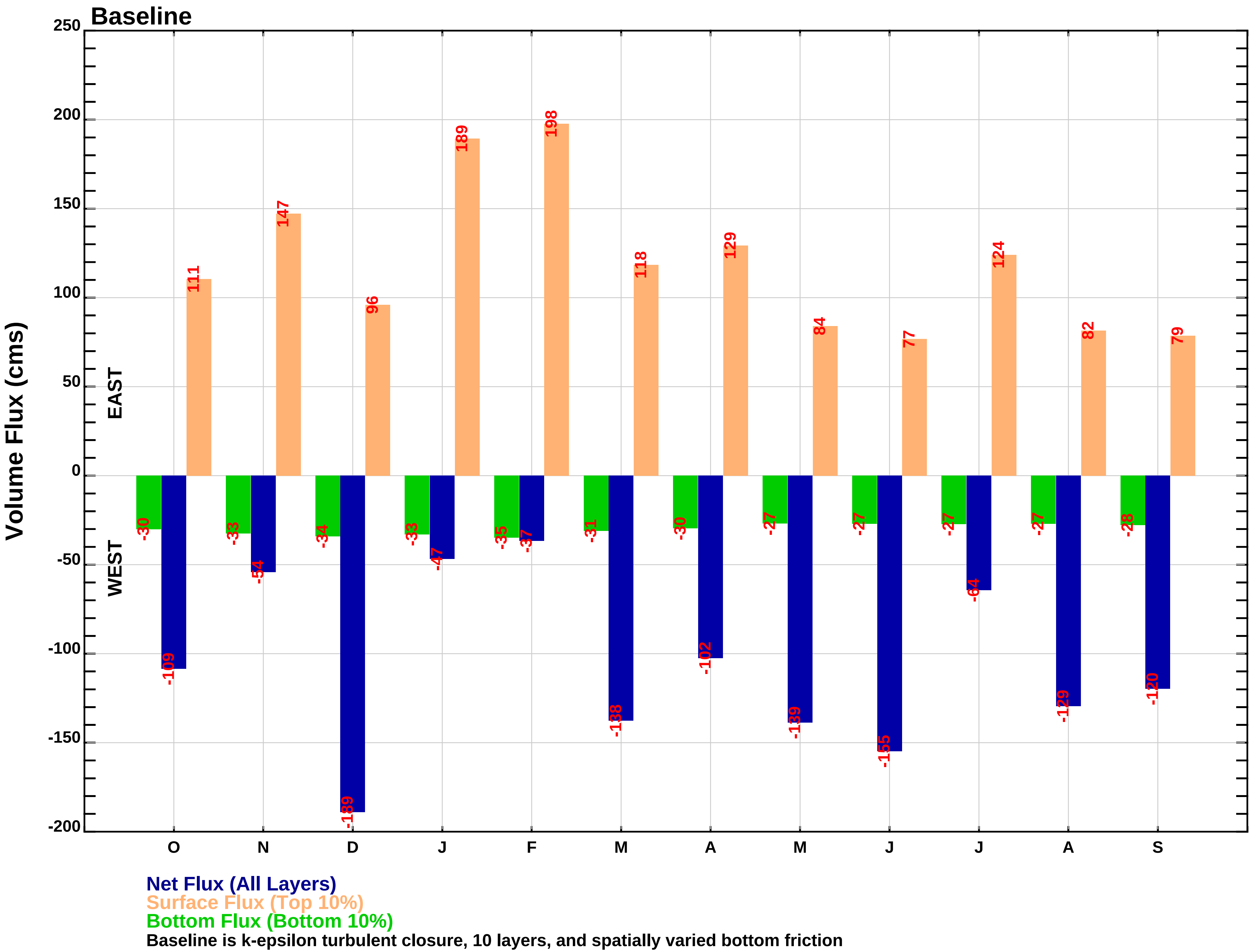


Figure 17. Calculated Monthly Surface, Bottom, and Net Fluxes through the East River at Transect 78.

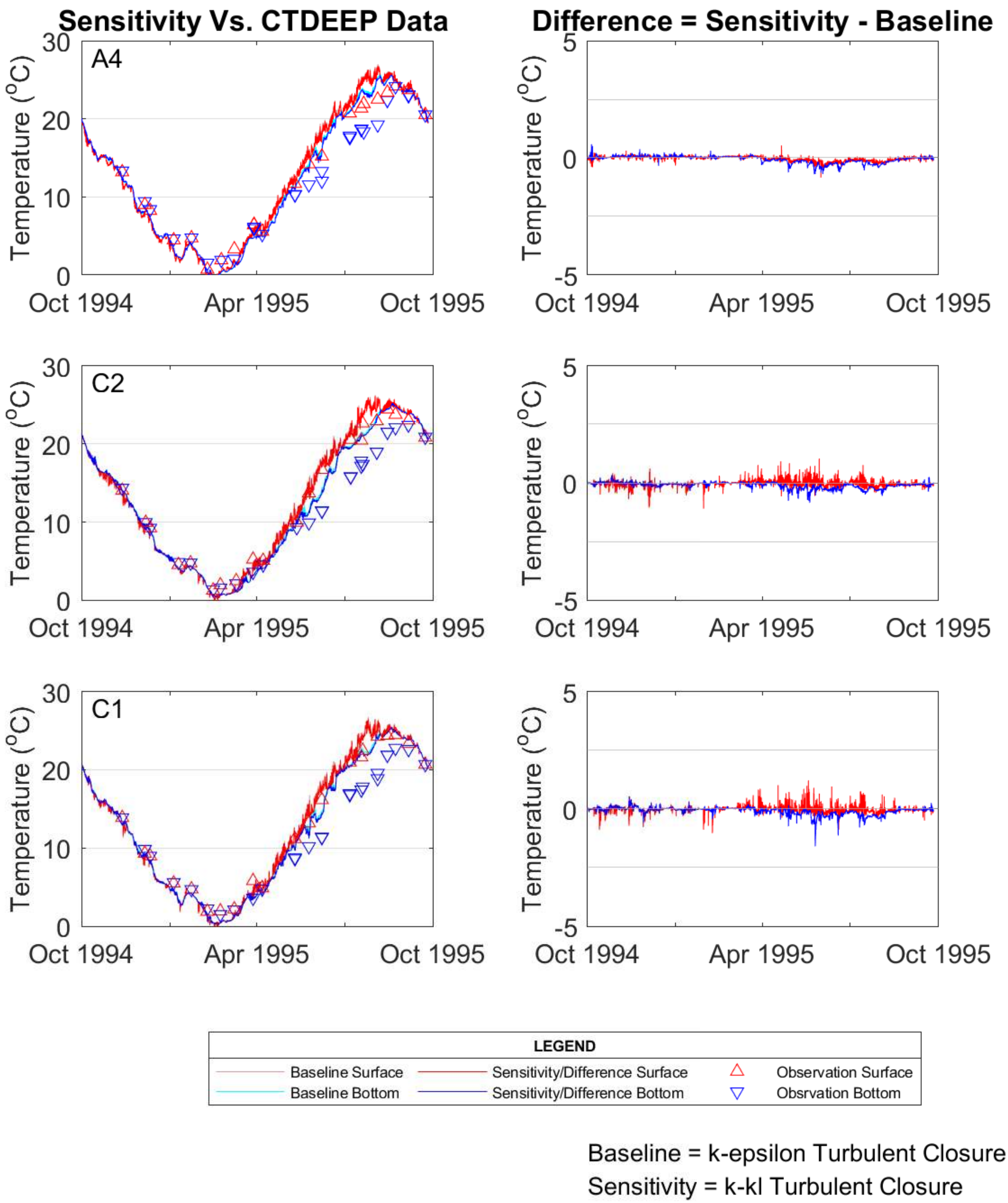
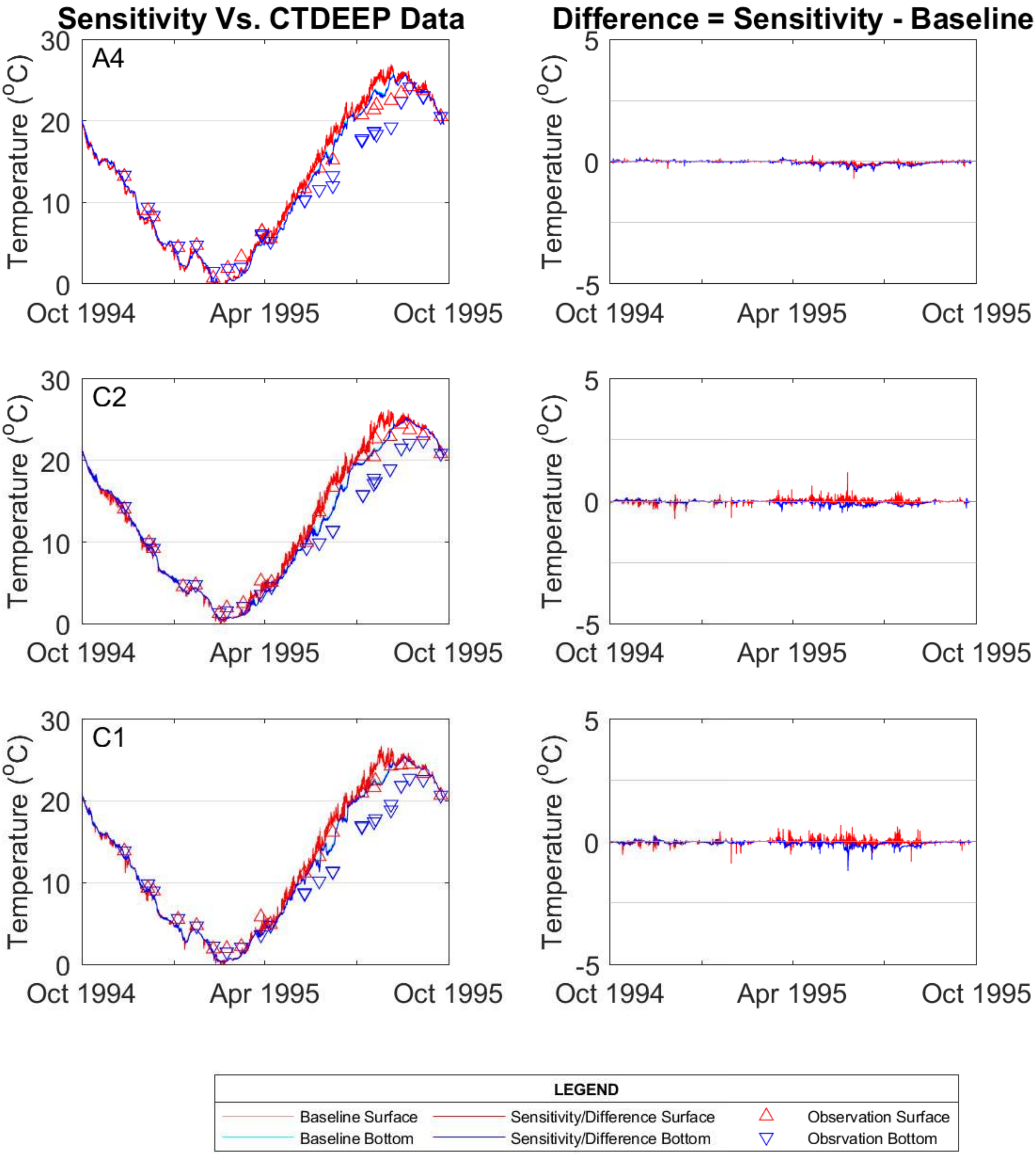
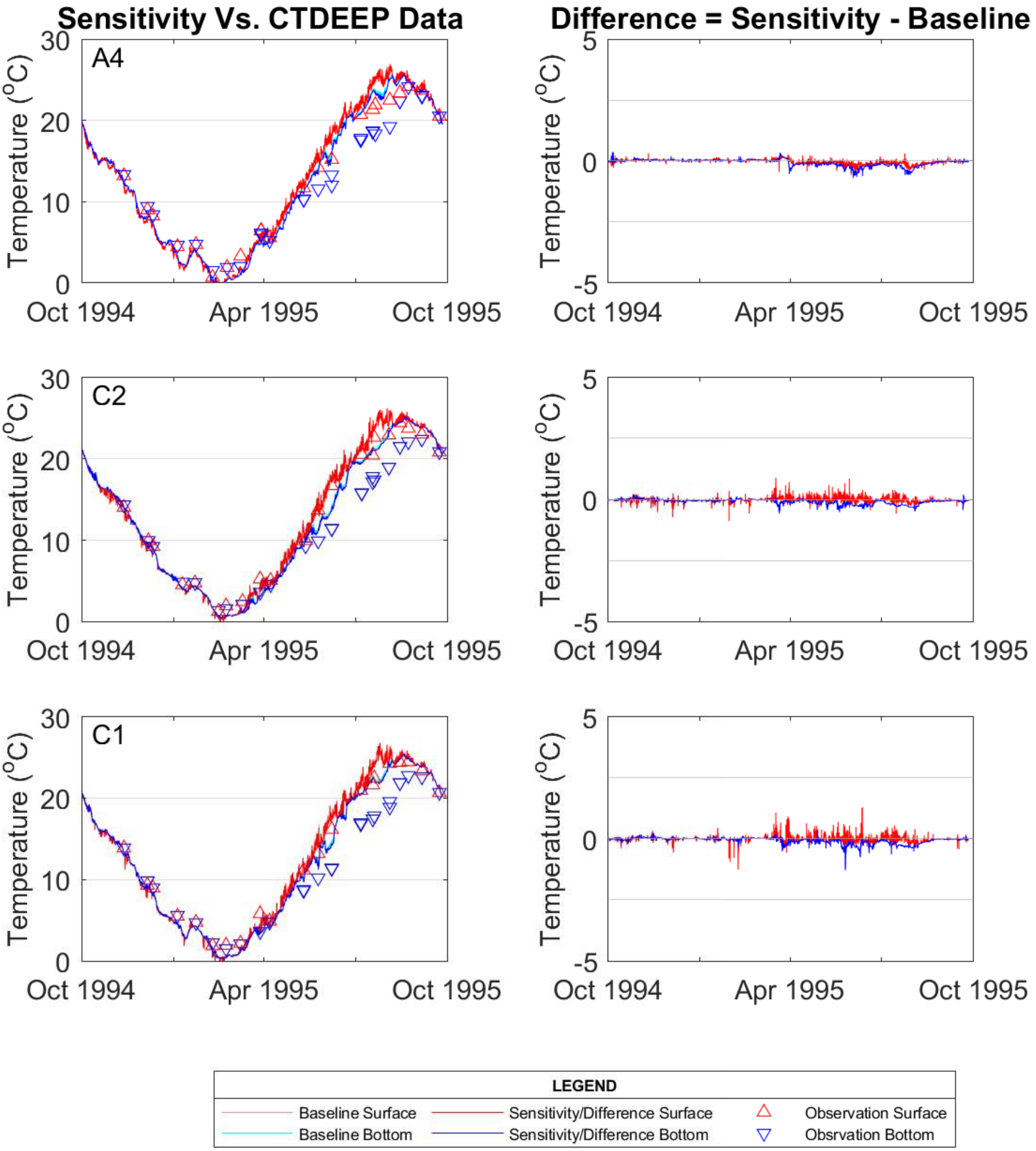


Figure 18. Comparison of Model Temperature Results using the k-kl Turbulence Closure Scheme to Temperature Data and Baseline Temperature



Baseline = k-epsilon Turbulent Closure
Sensitivity = k-omega Turbulent Closure

Figure 19. Comparison of Model Temperature Results using the k-omega Turbulence Closure Scheme to Temperature Data and Baseline Temperature



Baseline = k-epsilon Turbulent Closure
Sensitivity = Gen Turbulent Closure

Figure 20. Comparison of Model Temperature Results using the gen Turbulence Closure Scheme to Temperature Data and Baseline Temperature

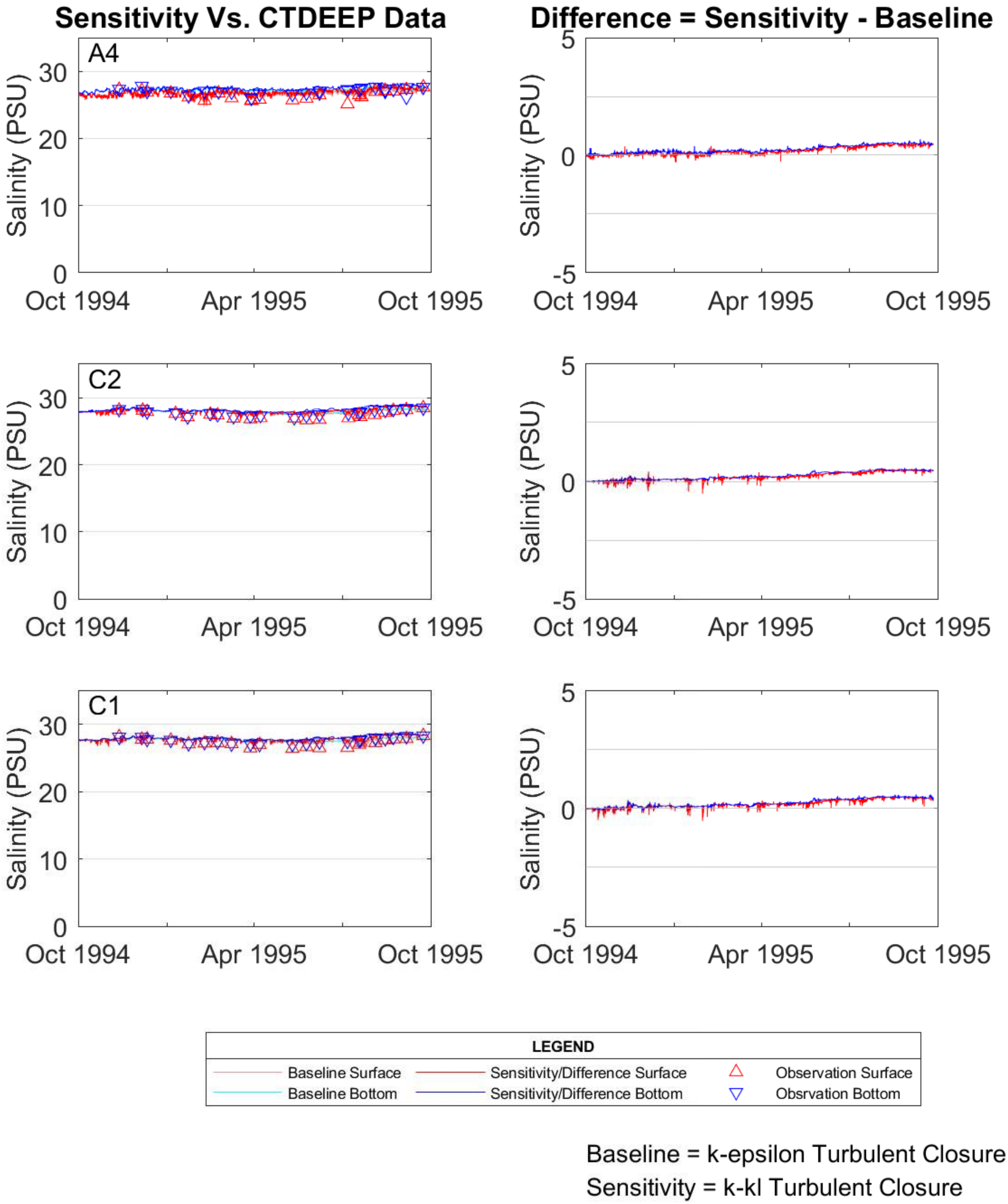
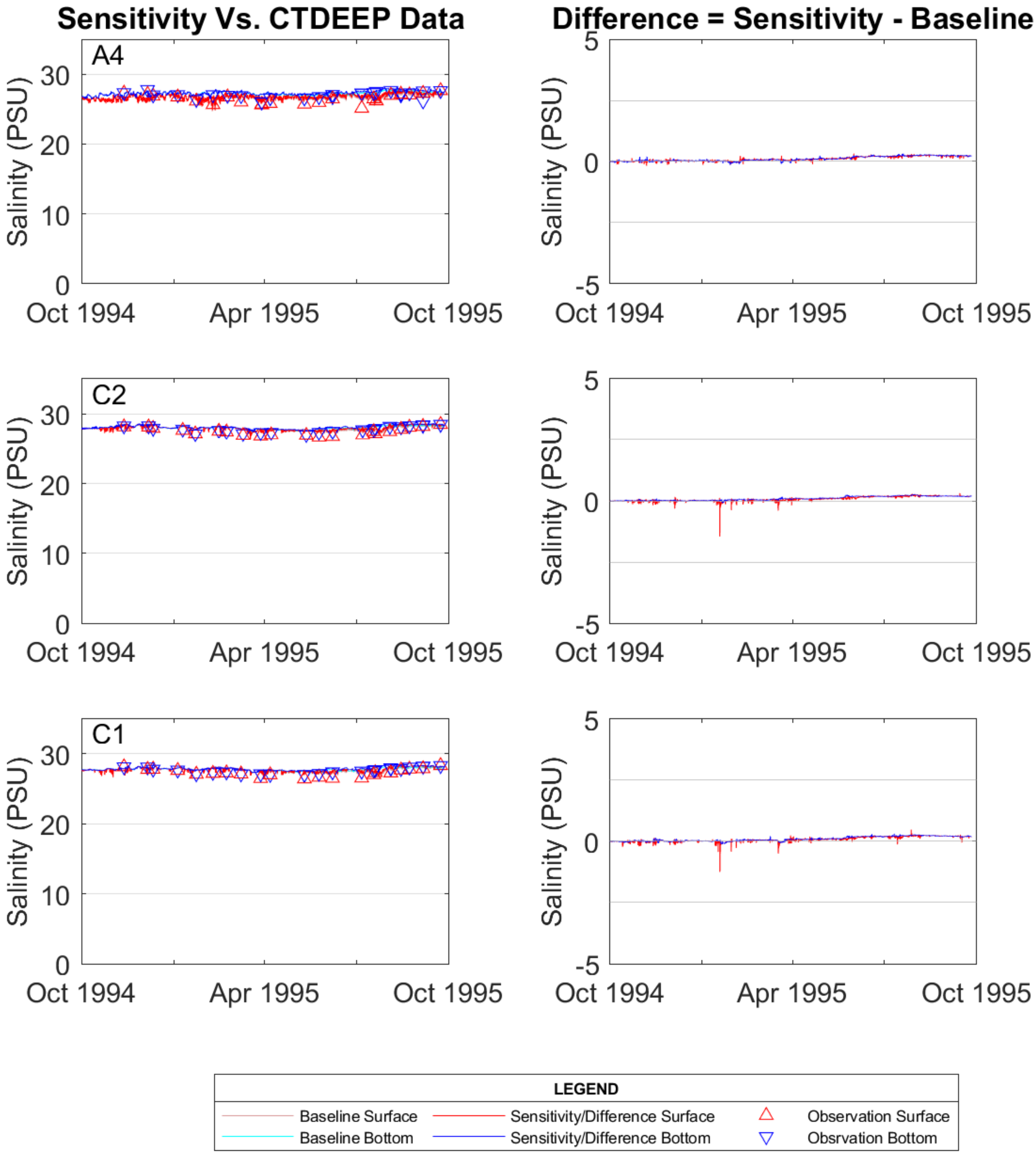


Figure 21. Comparison of Model Salinity Results using the k-kl Turbulence Closure Scheme to Salinity Data and Baseline Salinity



Baseline = k-epsilon Turbulent Closure
Sensitivity = k-omega Turbulent Closure

Figure 22. Comparison of Model Salinity Results using the k-omega Turbulence Closure Scheme to Salinity Data and Baseline Salinity

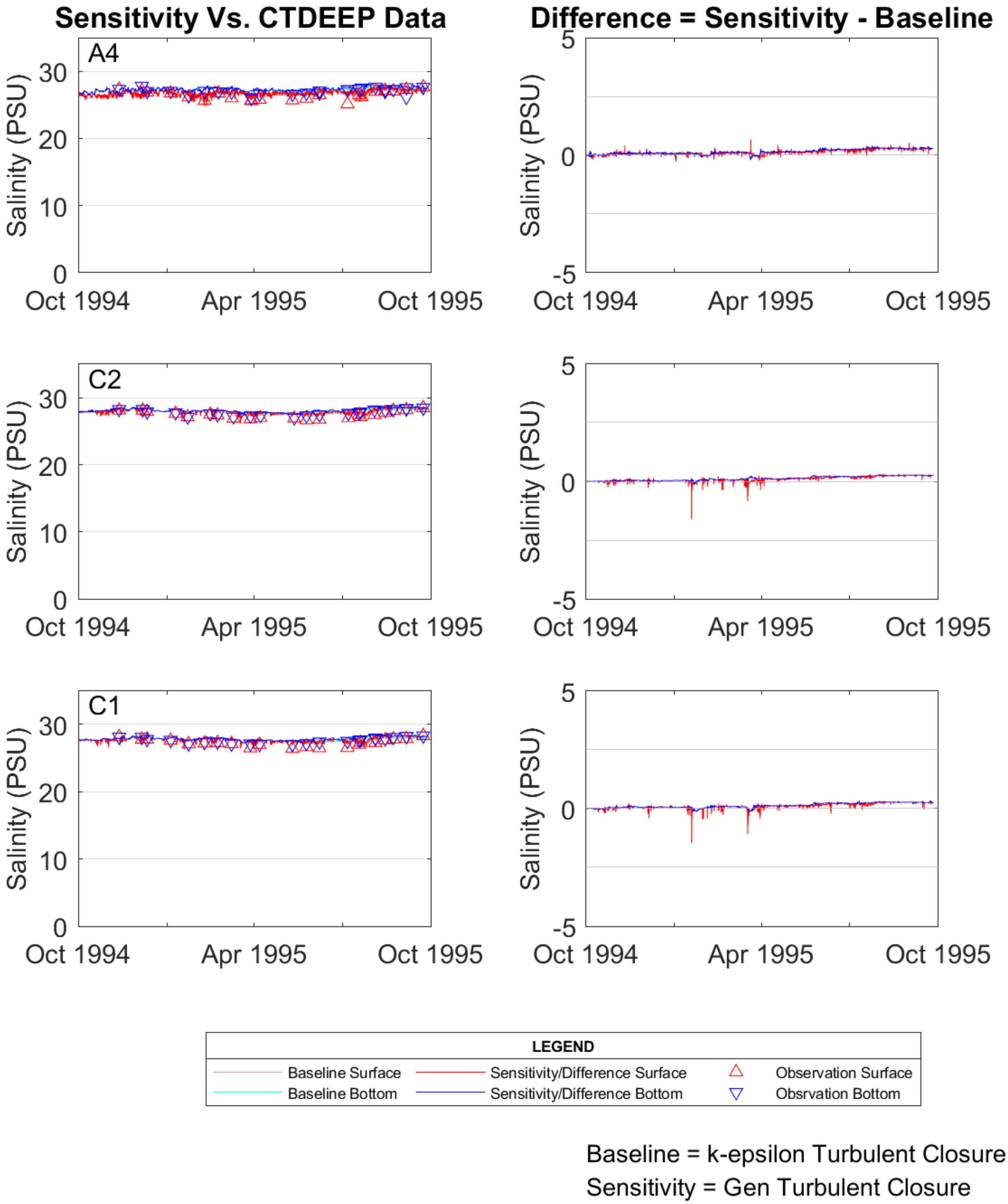


Figure 23. Comparison of Model Salinity Results using the gen Turbulence Closure Scheme to Salinity Data and Baseline Salinity

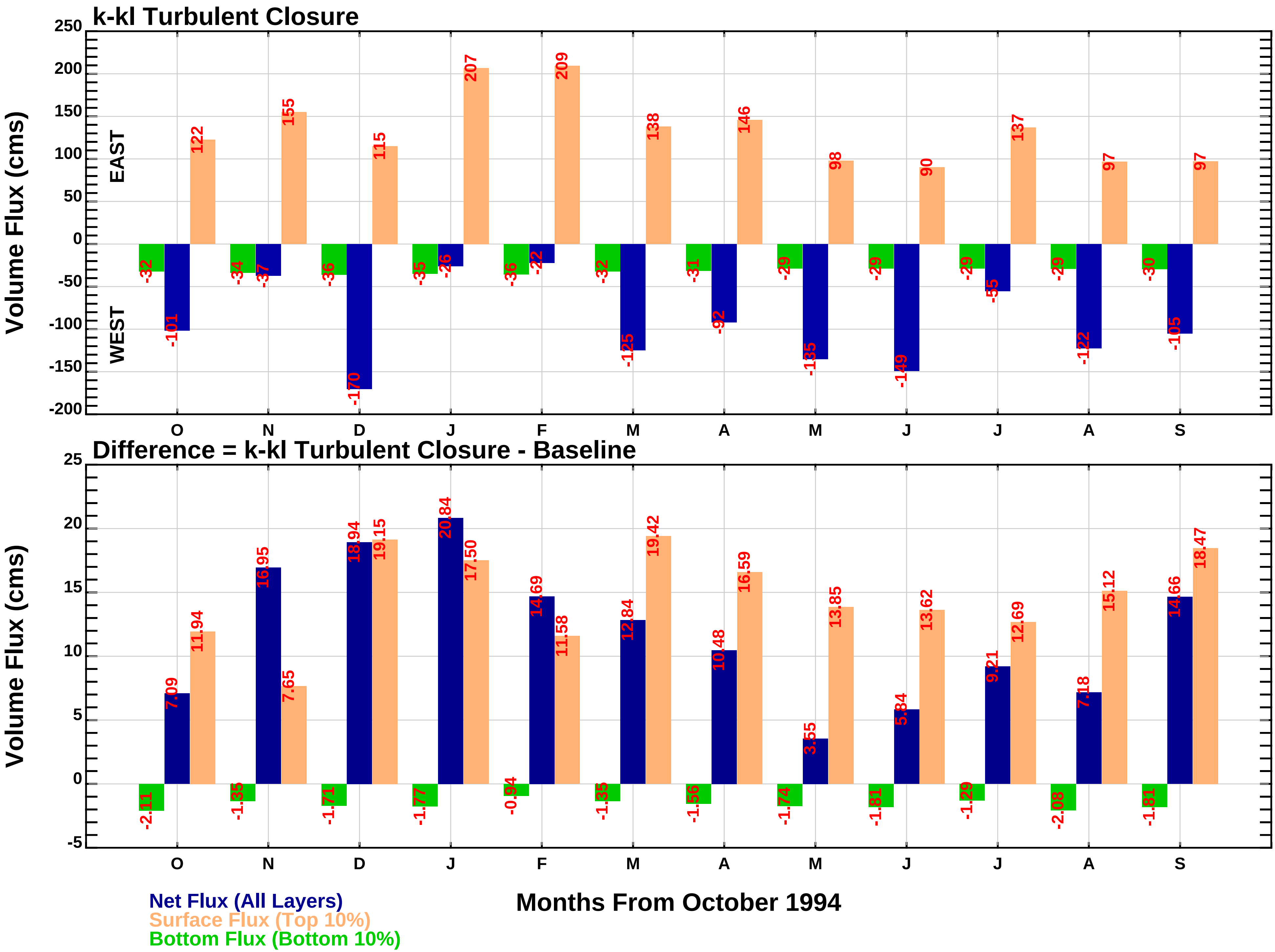


Figure 24. Comparison of Model East River Monthly Fluxes using the k-kl Turbulence Closure Scheme to the Baseline Monthly East River Fluxes at Transect 78

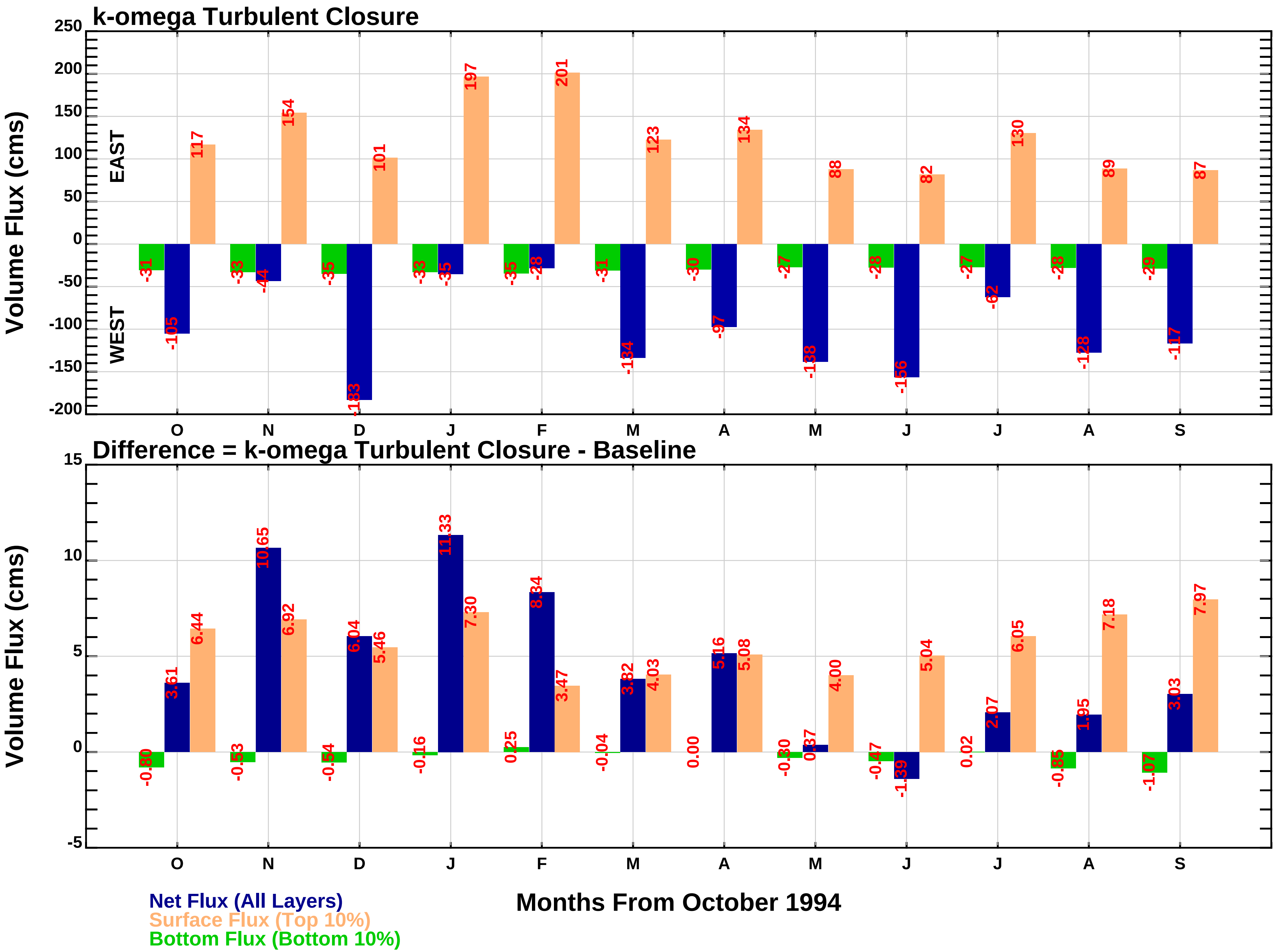


Figure 25. Comparison of Model East River Monthly Fluxes using the k-omega Turbulence Closure Scheme to the Baseline Monthly East River Fluxes at Transect 78

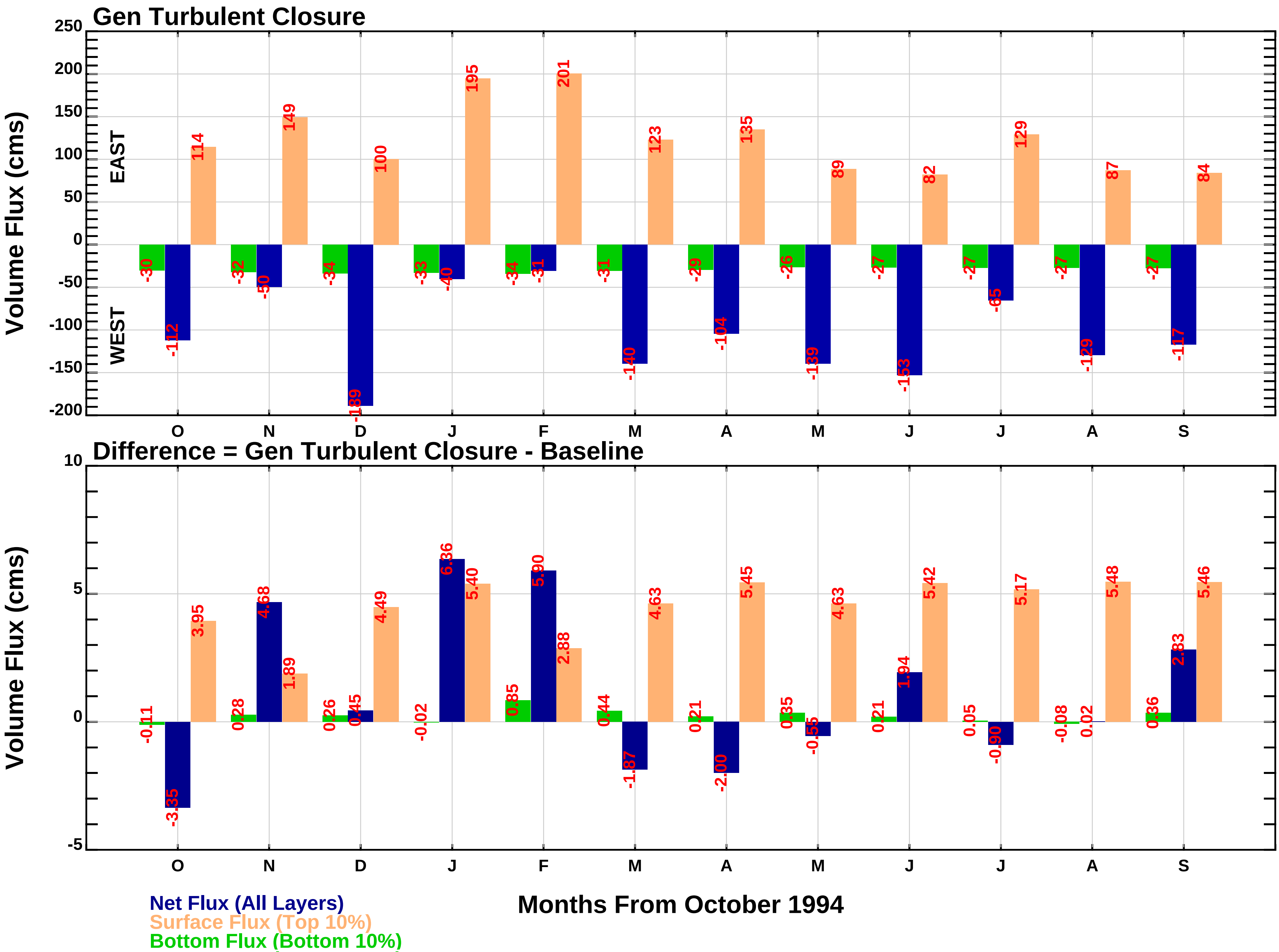


Figure 26. Comparison of Model East River Monthly Fluxes using the gen Turbulence Closure Scheme to the Baseline Monthly East River Fluxes at Transect 78

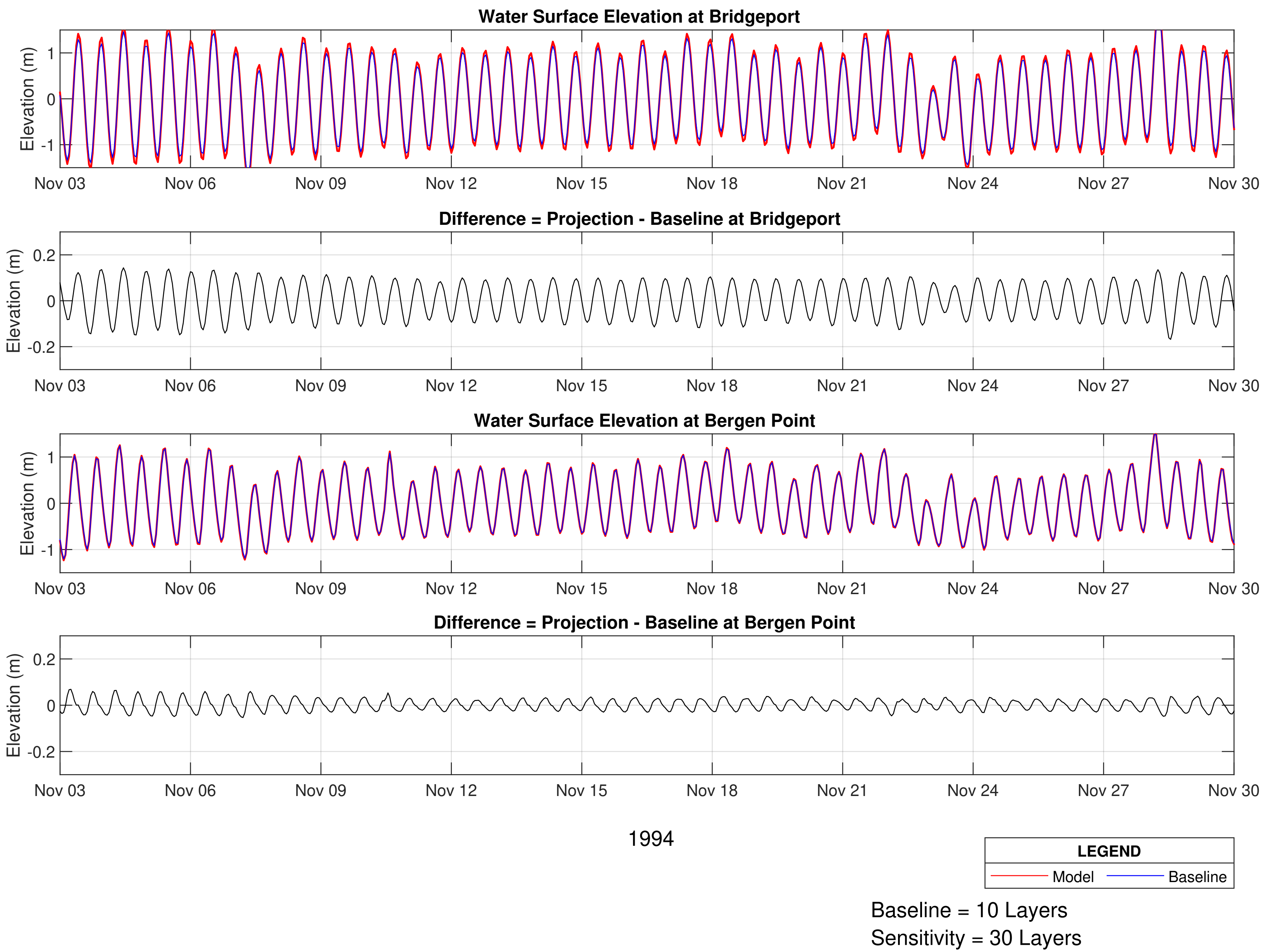


Figure 27. Comparison of Water Elevation at Bridgeport, CT and Bergen Point, NY using 30-Layers to Baseline Water Elevation

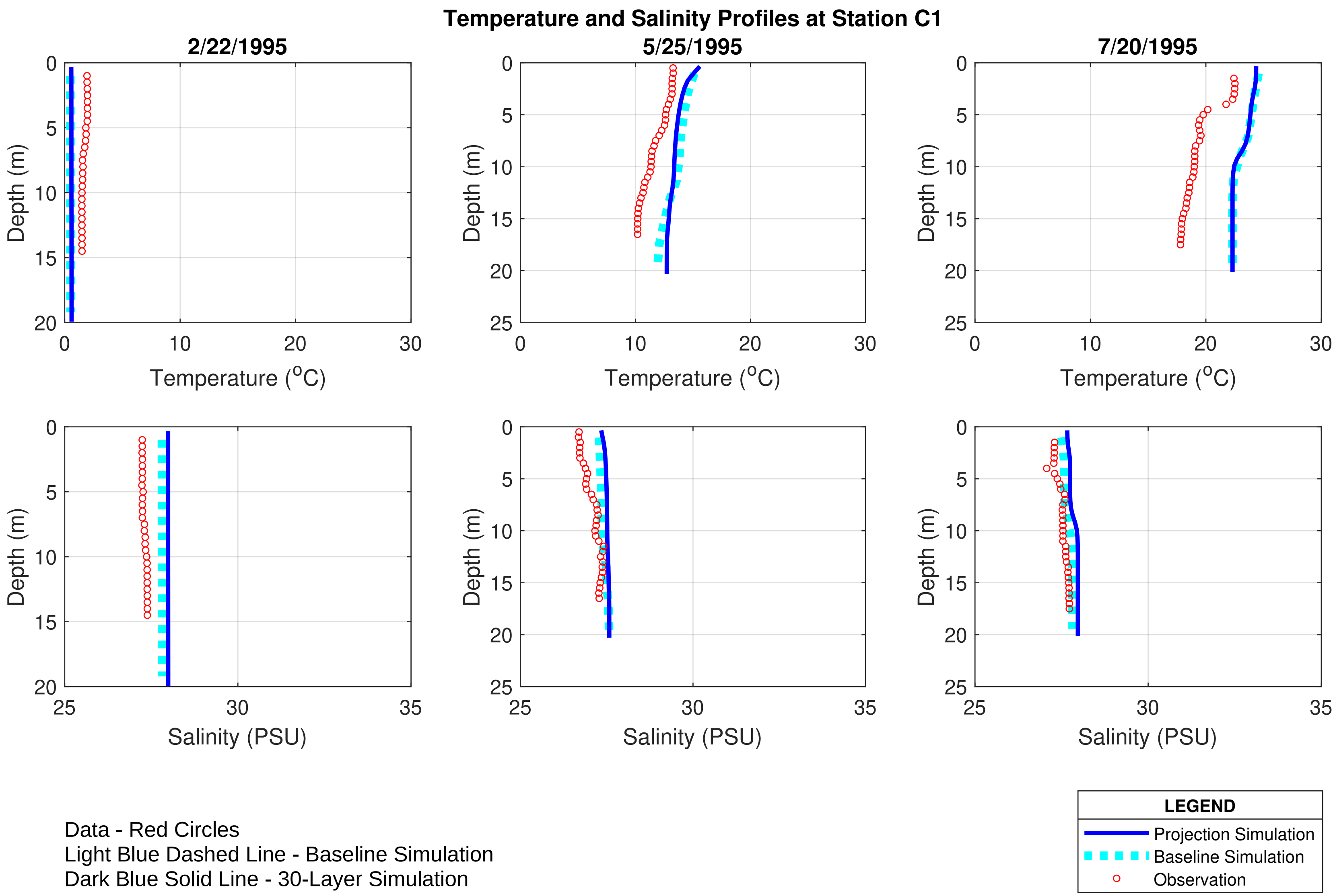


Figure 28. Baseline Model vs. 30-Layer Model Profiles at CTDEEP Station C1

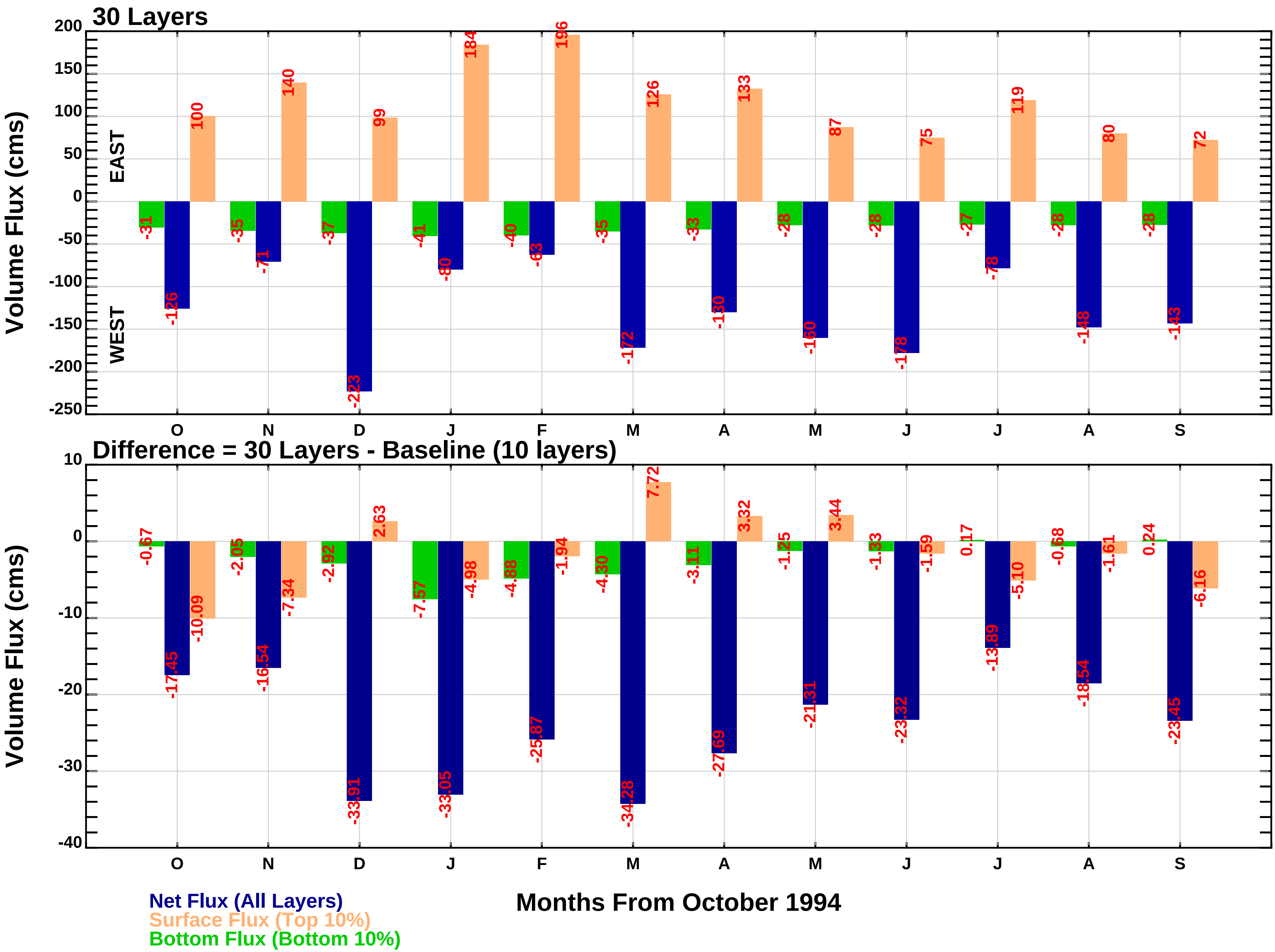


Figure 29. Comparison of Model East River Monthly Fluxes using 30-Layers to the Baseline Monthly East River Fluxes at Transect 78

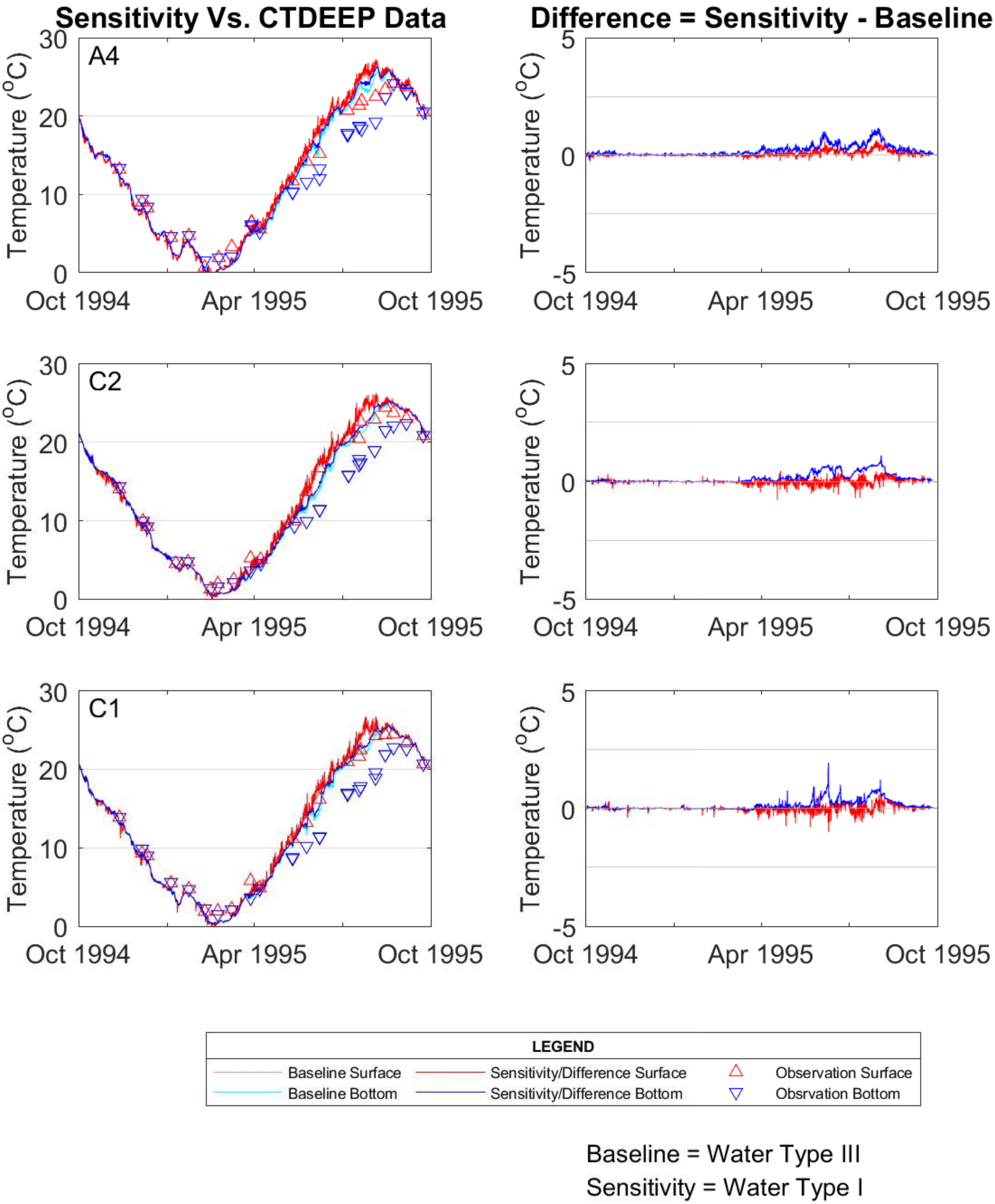


Figure 30. Comparison of Model Temperature Results using Jerlov Water Type I to Temperature Data and Baseline Temperature

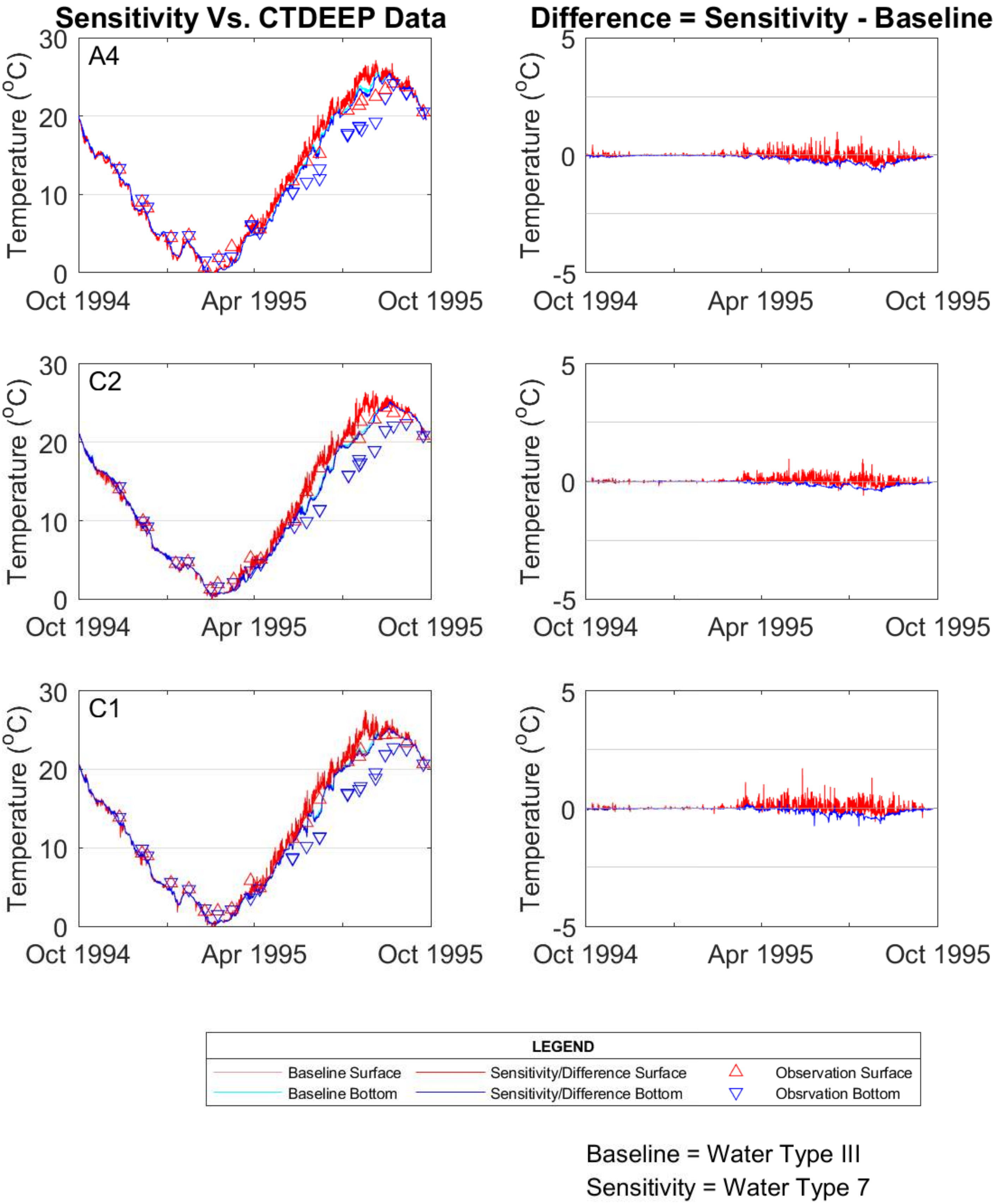


Figure 31. Comparison of Model Temperature Results using Jerlov Water Type 7 to Temperature Data and Baseline Temperature

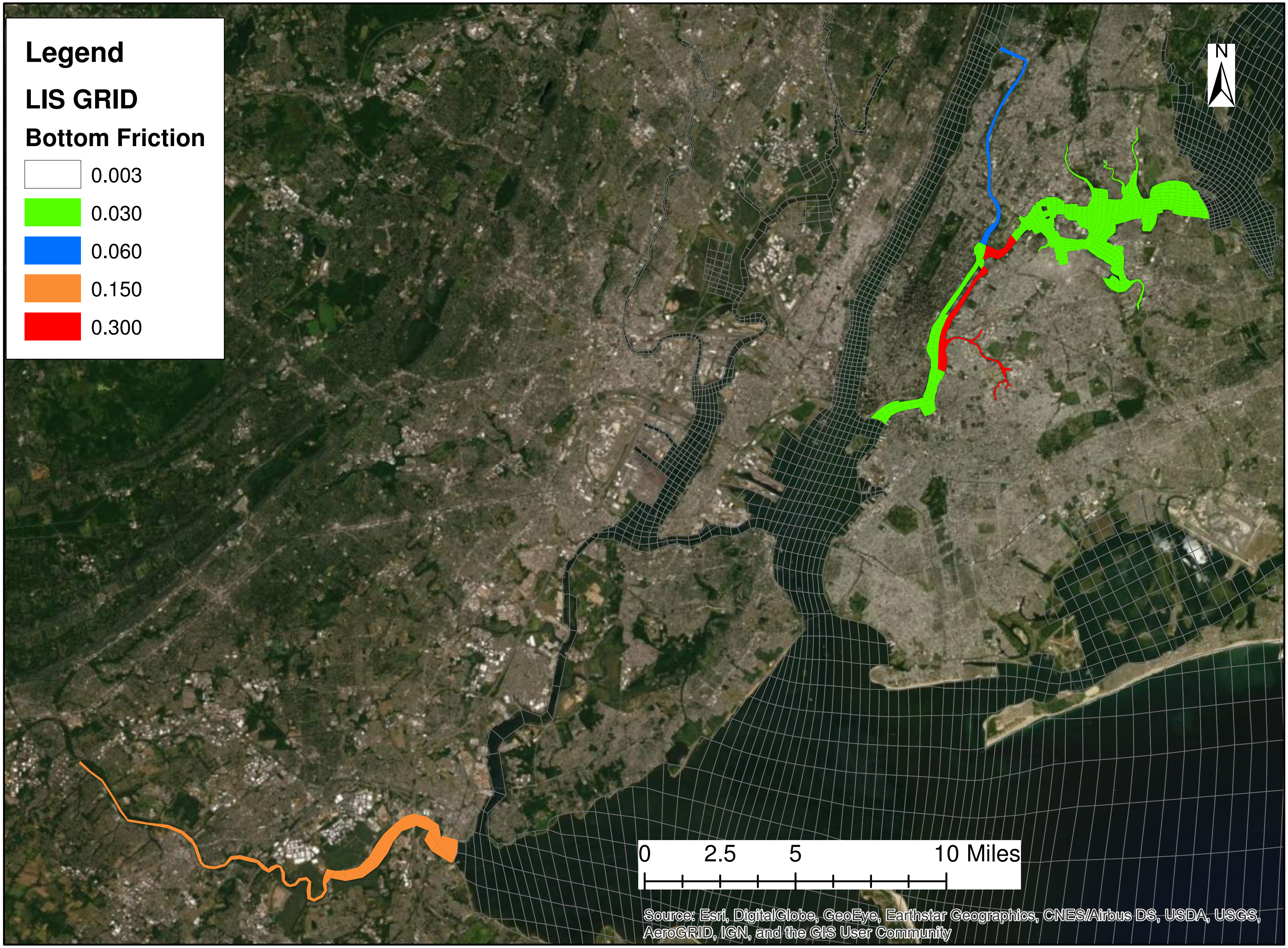


Figure 32. Map of Spatially Variable Bottom Friction used in Baseline
(Areas not highlighted use bottom friction of 0.003)

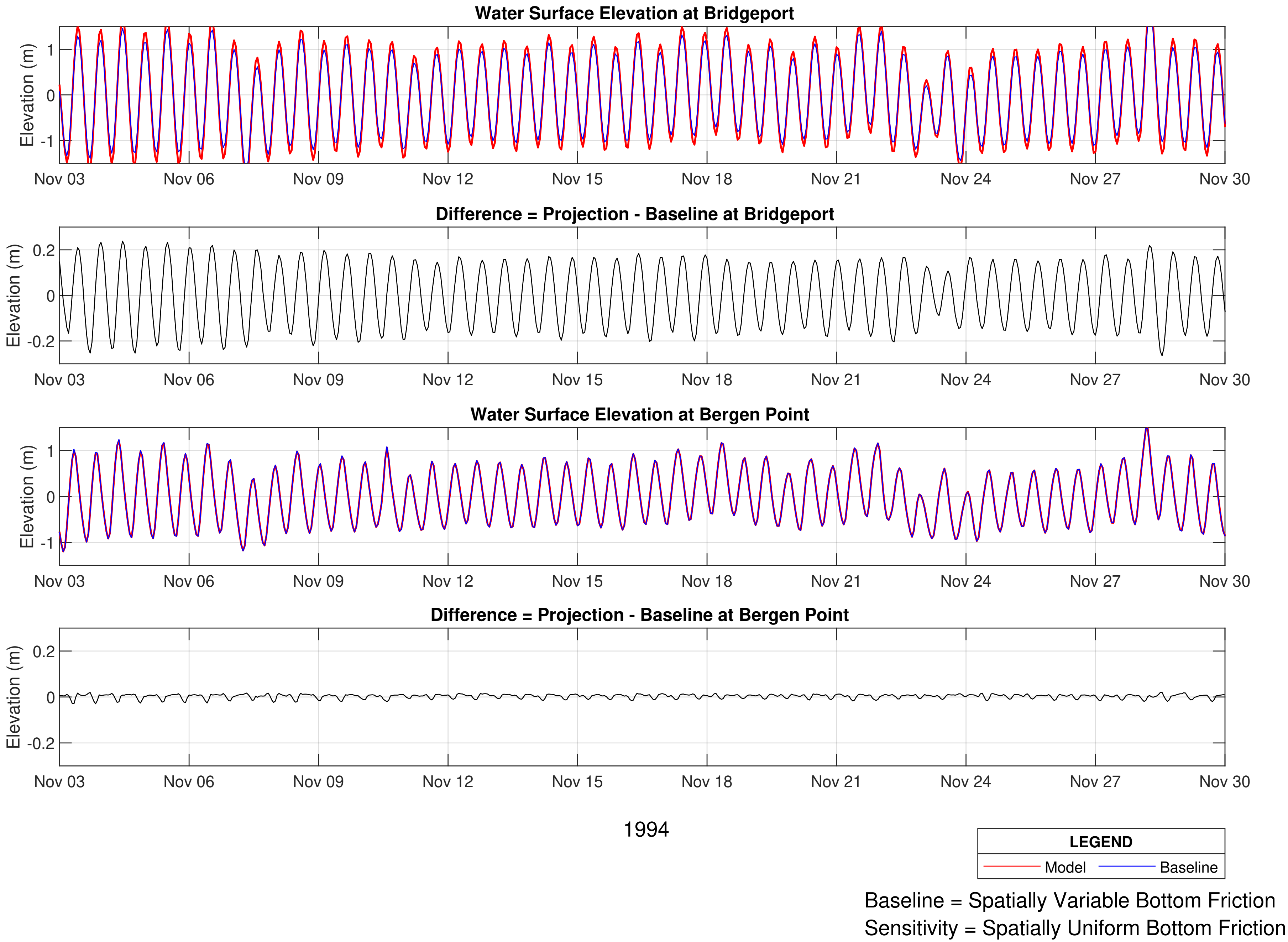


Figure 33. Comparison of Water Elevation at Bridgeport, CT and Bergen Point, NY using Uniform Bottom Friction to Baseline Water Elevation

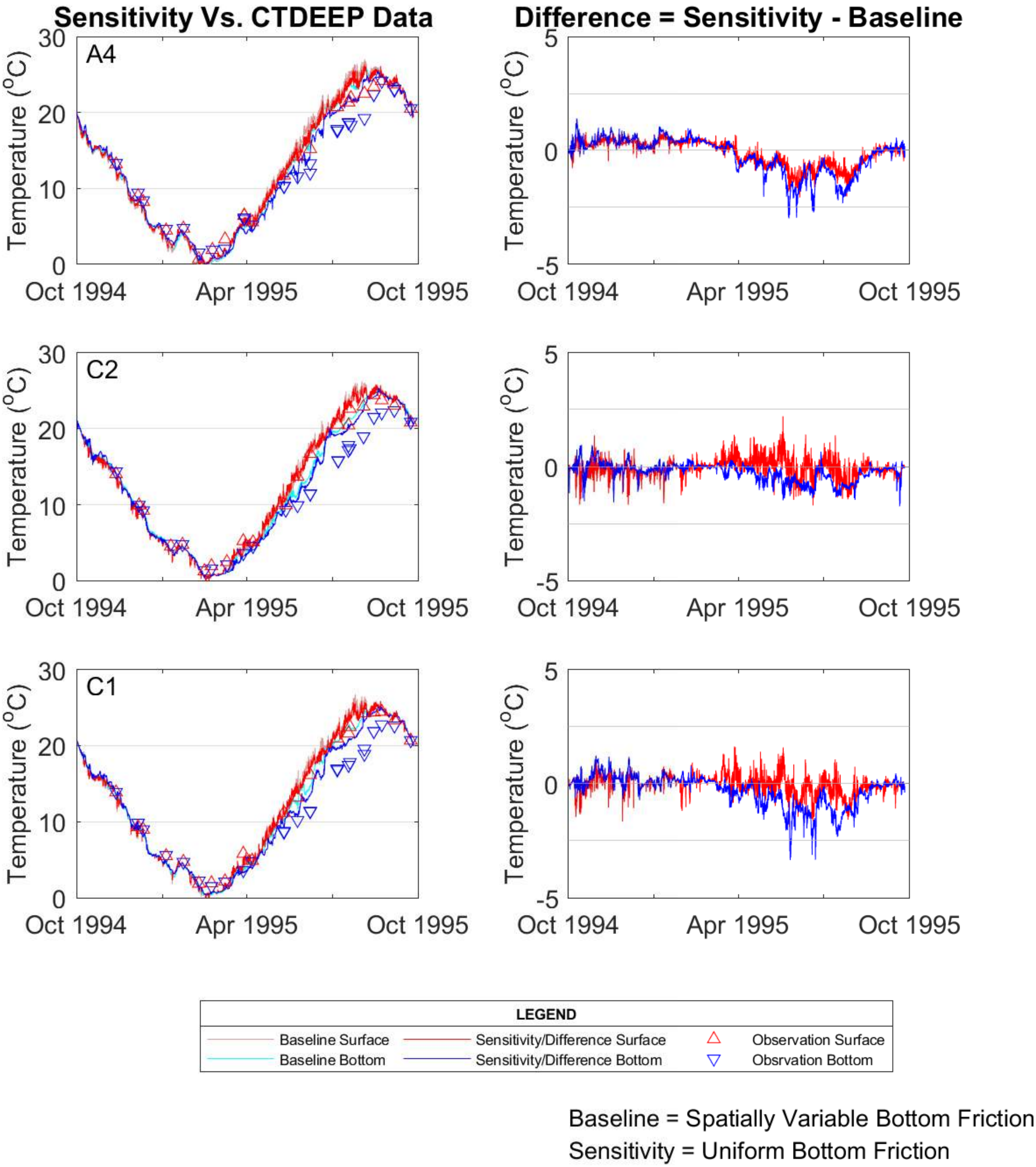
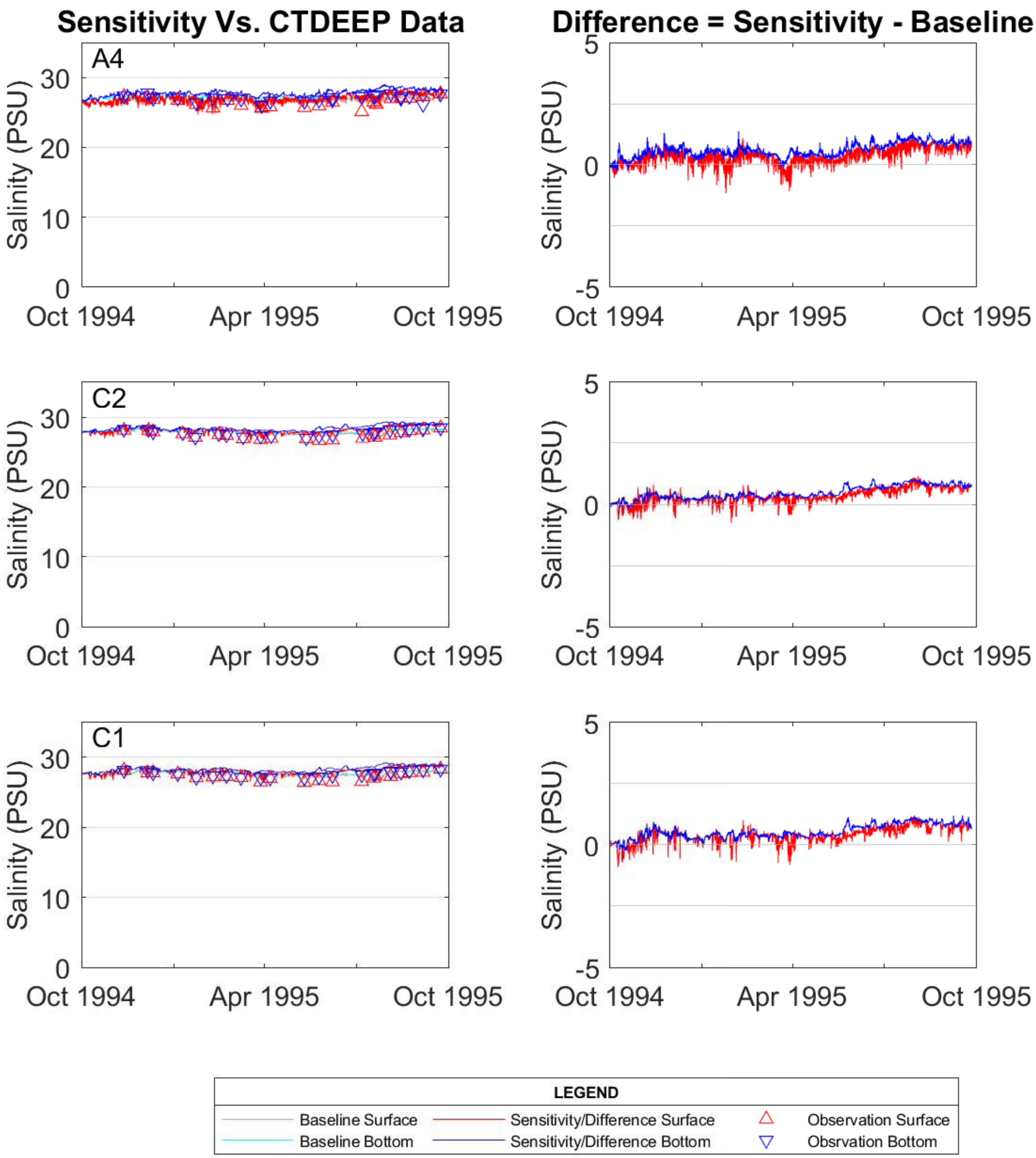


Figure 34. Comparison of Model Temperature Results using Uniform Bottom Friction to Temperature Data and Baseline Temperature



Baseline = Spatially Variable Bottom Friction
Sensitivity = Uniform Bottom Friction

Figure 35. Comparison of Model Salinity Results using Uniform Bottom Friction to Salinity Data and Baseline Salinity

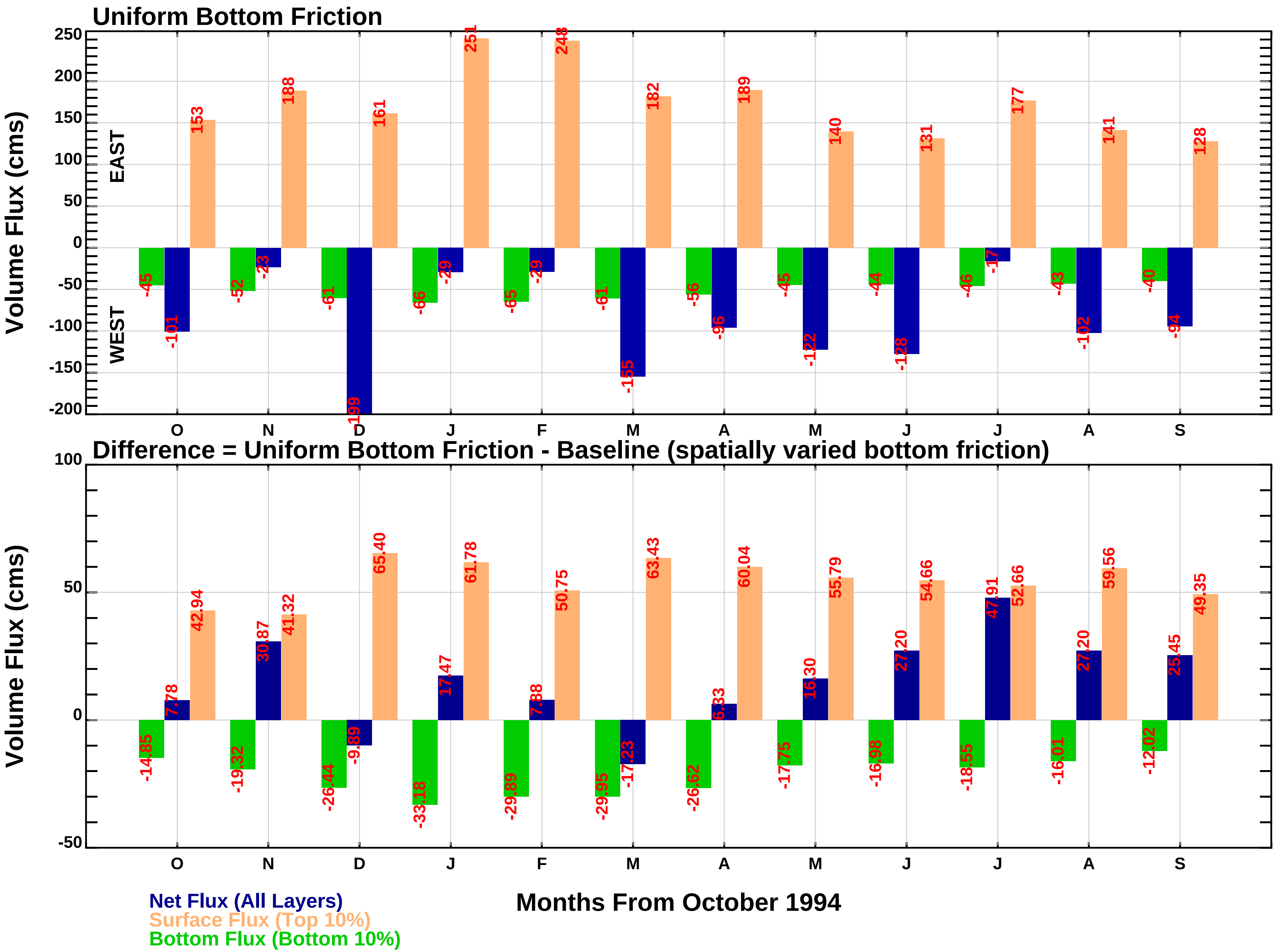


Figure 36. Comparison of Model East River Monthly Fluxes using Uniform Bottom Friction to the Base Condition Monthly East River Fluxes at Transect 78

1

ROMS Boundary Condition Type Descriptions

Clamped boundary condition

Almost as simple as setting the boundary value to a known exterior value.

Flather boundary condition

For the normal component of the barotropic velocity, one option is to radiate out deviations from exterior values at the speed of the external gravity waves (Flather, 1976).

Chapman boundary condition

The corresponding condition for surface elevation was investigated by Chapman (1985) assuming all outgoing signals leave at the shallow-water wave speed of $(gD)^{1/2}$.

Radiation boundary condition

In realistic domains, open boundary conditions can be extremely difficult to get right. There are situations in which incoming flow and outgoing flow happen along the same boundary or even at different depths at the same horizontal location. Orlanski (1976) proposed a radiation scheme in which a local normal phase velocity is computed and used to radiate things out (if it is indeed going out). This works well for a wave propagating normal to the boundary, but has problems when waves approach the boundary at an angle. Raymond and Kuo (1984) have modified the scheme to account for propagation in all three directions. In ROMS, only the two horizontal directions are accounted for (with the recommended RADIATION_2D option).

The radiation approach is appropriate for waves leaving the domain. A check is made to see which way the phase velocity is headed. If it is entering the domain, a zero gradient condition is applied unless the next option is also specified.

Mixed radiation-nudging boundary condition

As described in Marchesiello *et al.* (2001), ROMS has an option for providing radiation conditions on outflow and nudging to a known exterior value on inflow. This is implemented as a variation on the radiation condition, requiring two timescales: the inflow nudging timescale and the outflow nudging timescale. These timescales are provided in the input to ROMS (roms.in).

All descriptions are from https://www.myroms.org/wiki/Boundary_Conditions/.

References

Chapman, D. C., 1985: Numerical treatment of cross-shelf open boundaries in a barotropic coastal ocean model, *J. Phys. Oceanogr.*, 15, 1060--1075.

Flather, R. A., 1976: A tidal model of the northwest European continental shelf. *Memoires de la Societe Royale de Sciences de Liege*, 6, 141-164.

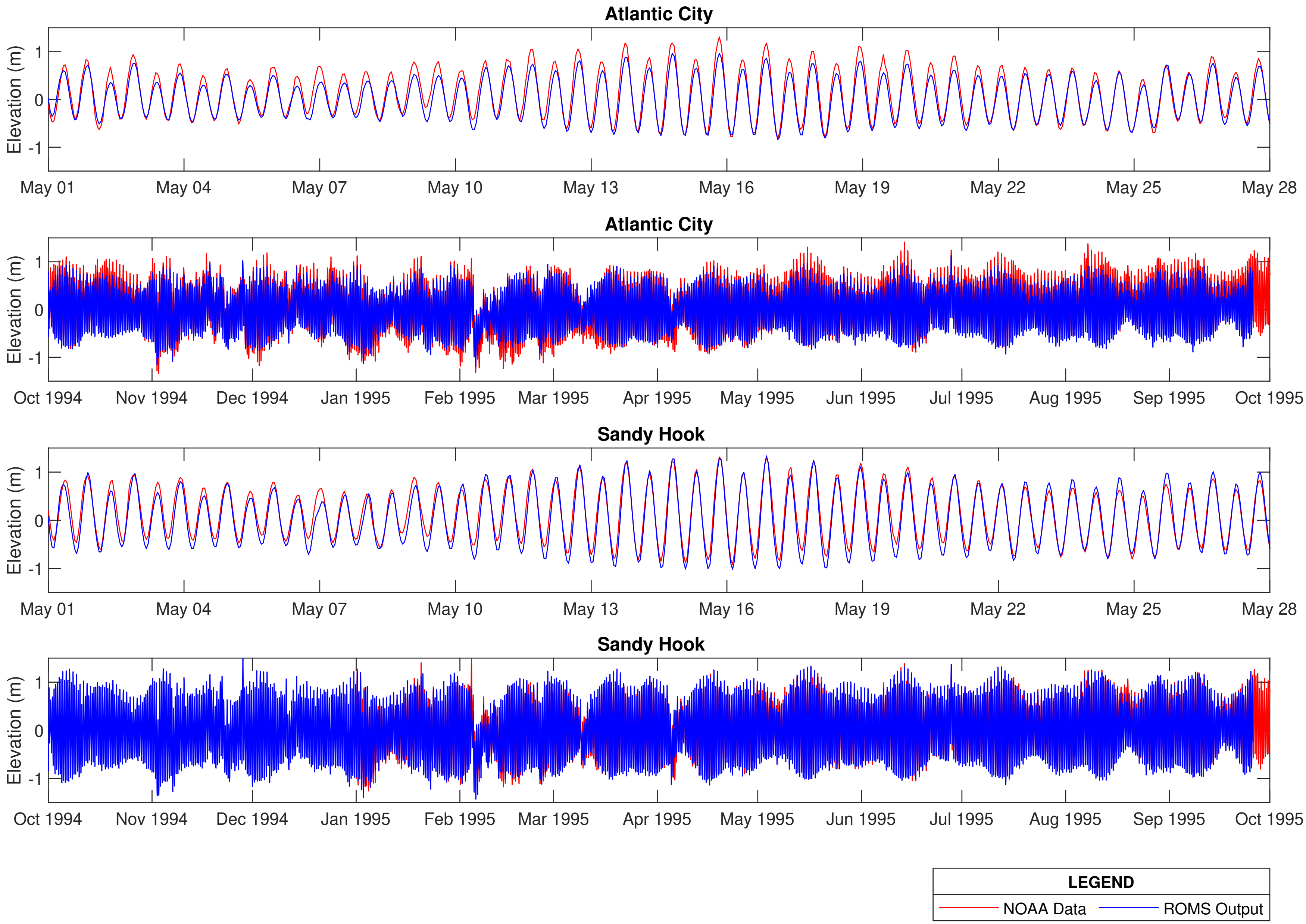
Marchesiello, P., J. C. McWilliams, A. F. Shchepetkin, 2001: Open boundary conditions for long-term integration of regional ocean models, *Ocean Modelling*, **3**, 1-20.

Orlanski, I., 1976: A simple boundary condition for unbounded hyperbolic flows. *J. Comp. Sci.*, **21**(3), 251-269.

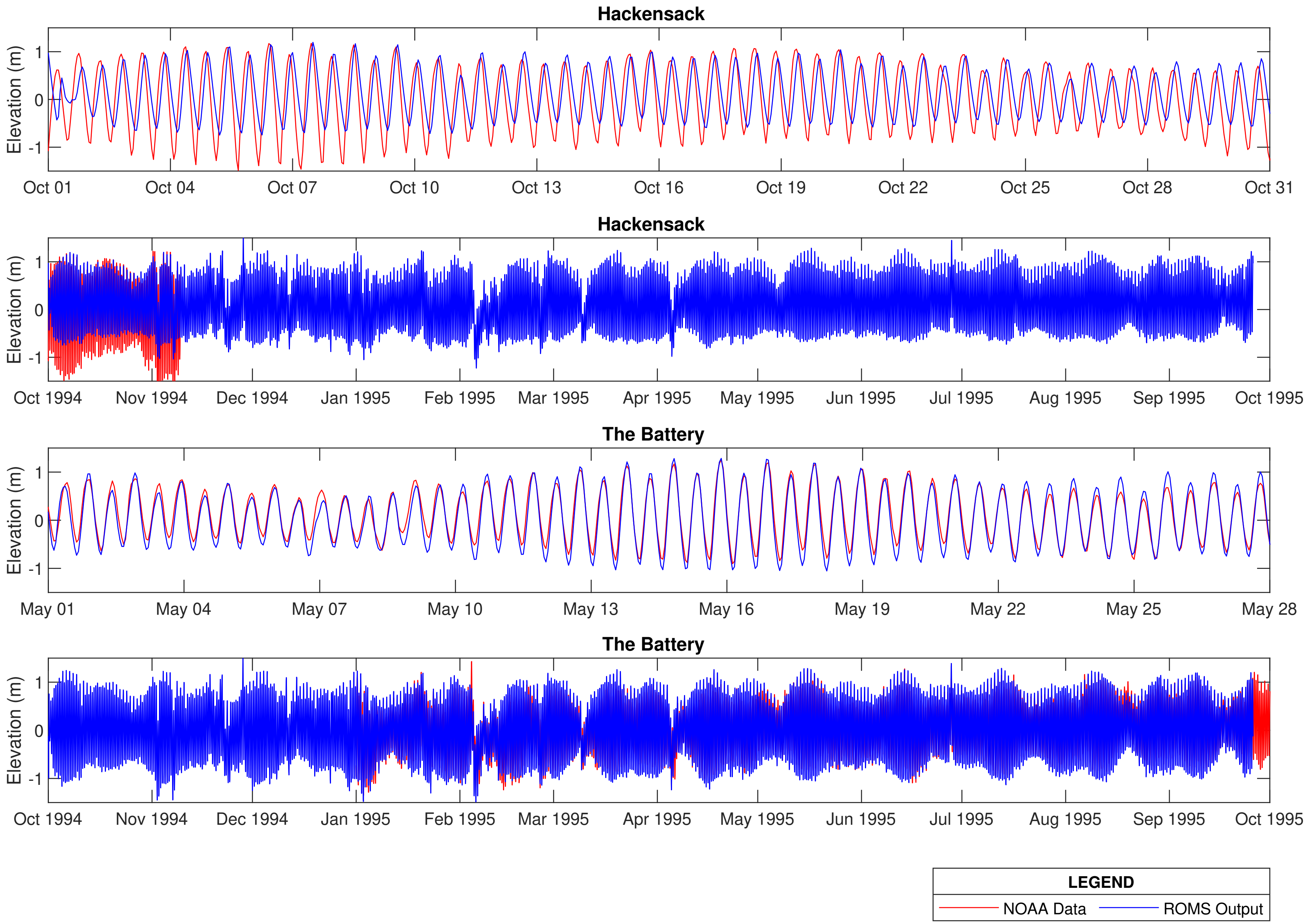
Raymond, W. H. and H. L. Kuo, 1984. A radiation boundary condition for multi-dimensional flows, *Quart. J. R. Met. Soc.*, 110, 535-551.

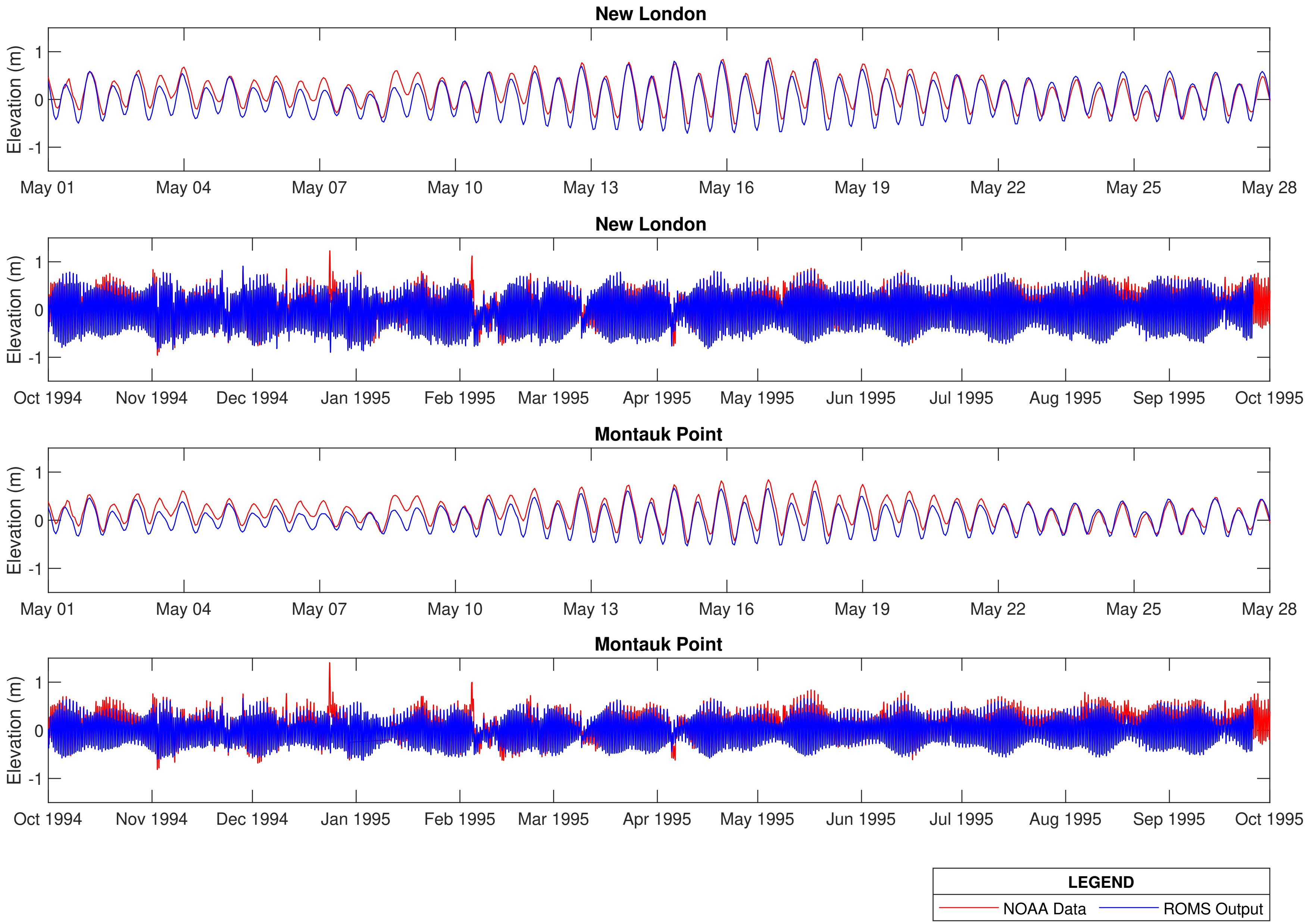
2

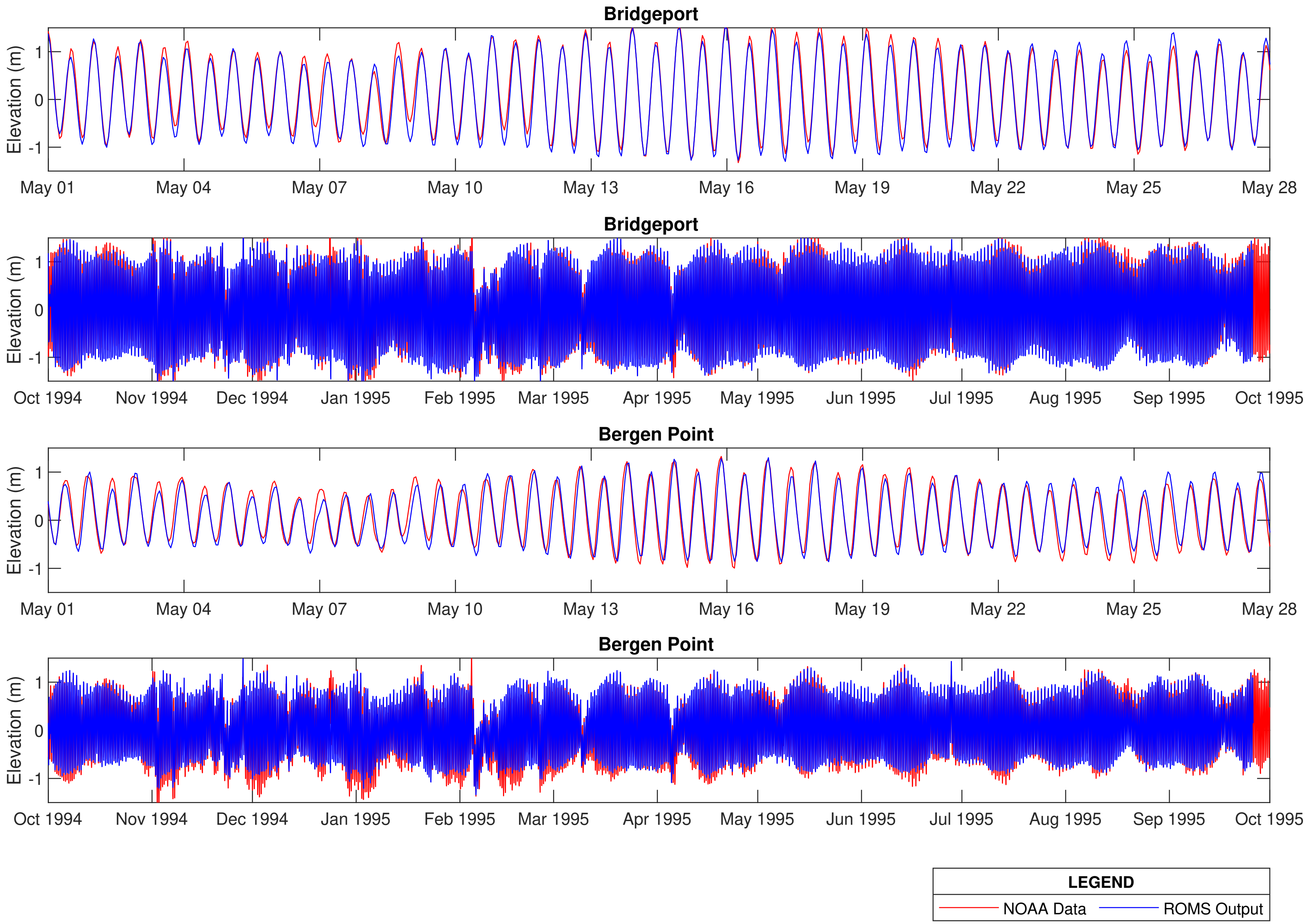
WY95 ROMS Baseline Water Elevation Time-Series Comparisons



Atlantic City
Elevation (m)
1
0
-1
May 01
May 04
May 07
May 10
May 13
May 16
May 19
May 22
May 25
May 28
Atlantic City
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
Sandy Hook
Sandy Hook
LEGEND
NOAA Data
ROMS Output


Hackensack
Elevation (m)
Oct 01
Oct 04
Oct 07
Oct 10
Oct 13
Oct 16
Oct 19
Oct 22
Oct 25
Oct 28
Oct 31
Hackensack
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
The Battery
May 01
May 04
May 07
May 10
May 13
May 16
May 19
May 22
May 25
May 28
The Battery
LEGEND
NOAA Data
ROMS Output

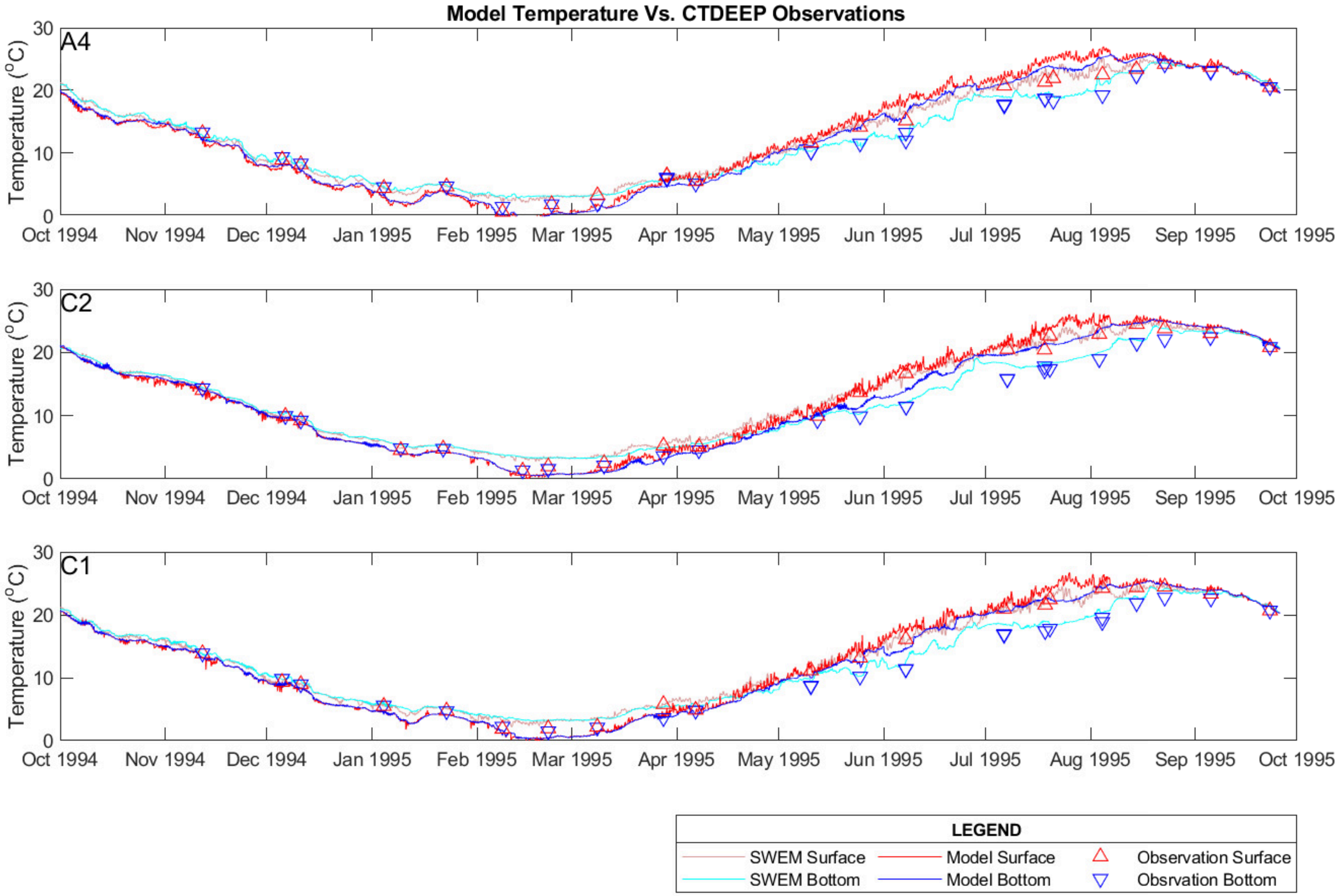

New London
Elevation (m)
1
0
-1
May 01
May 04
May 07
May 10
May 13
May 16
May 19
May 22
May 25
May 28
New London
Elevation (m)
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
Montauk Point
Elevation (m)
Montauk Point
Elevation (m)
LEGEND
NOAA Data
ROMS Output

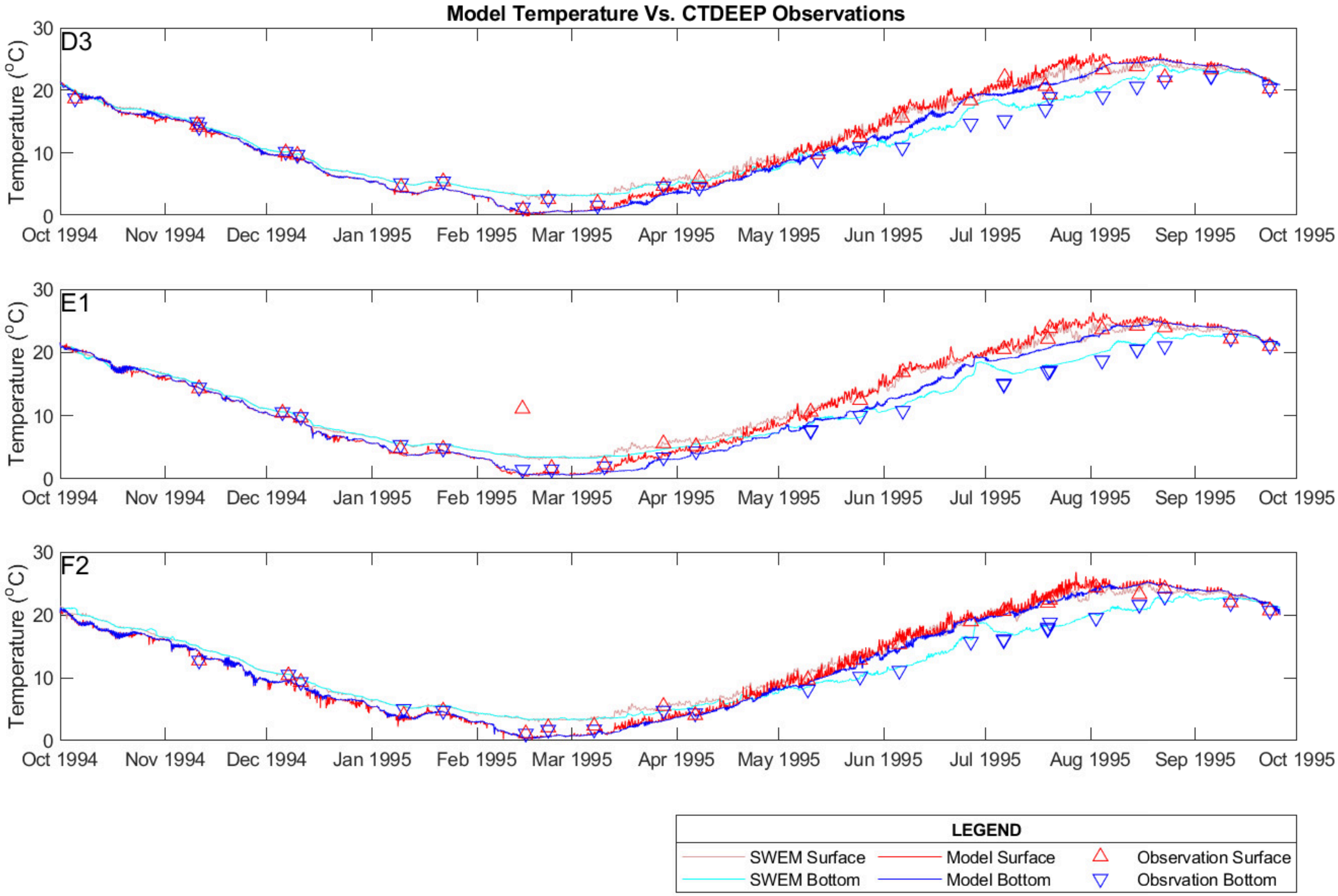


Bridgeport
Elevation (m)
1
0
-1
May 01
May 04
May 07
May 10
May 13
May 16
May 19
May 22
May 25
May 28
Bridgeport
Elevation (m)
1
0
-1
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
Bergen Point
Elevation (m)
1
0
-1
May 01
May 04
May 07
May 10
May 13
May 16
May 19
May 22
May 25
May 28
Bergen Point
Elevation (m)
1
0
-1
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
NOAA Data
ROMS Output

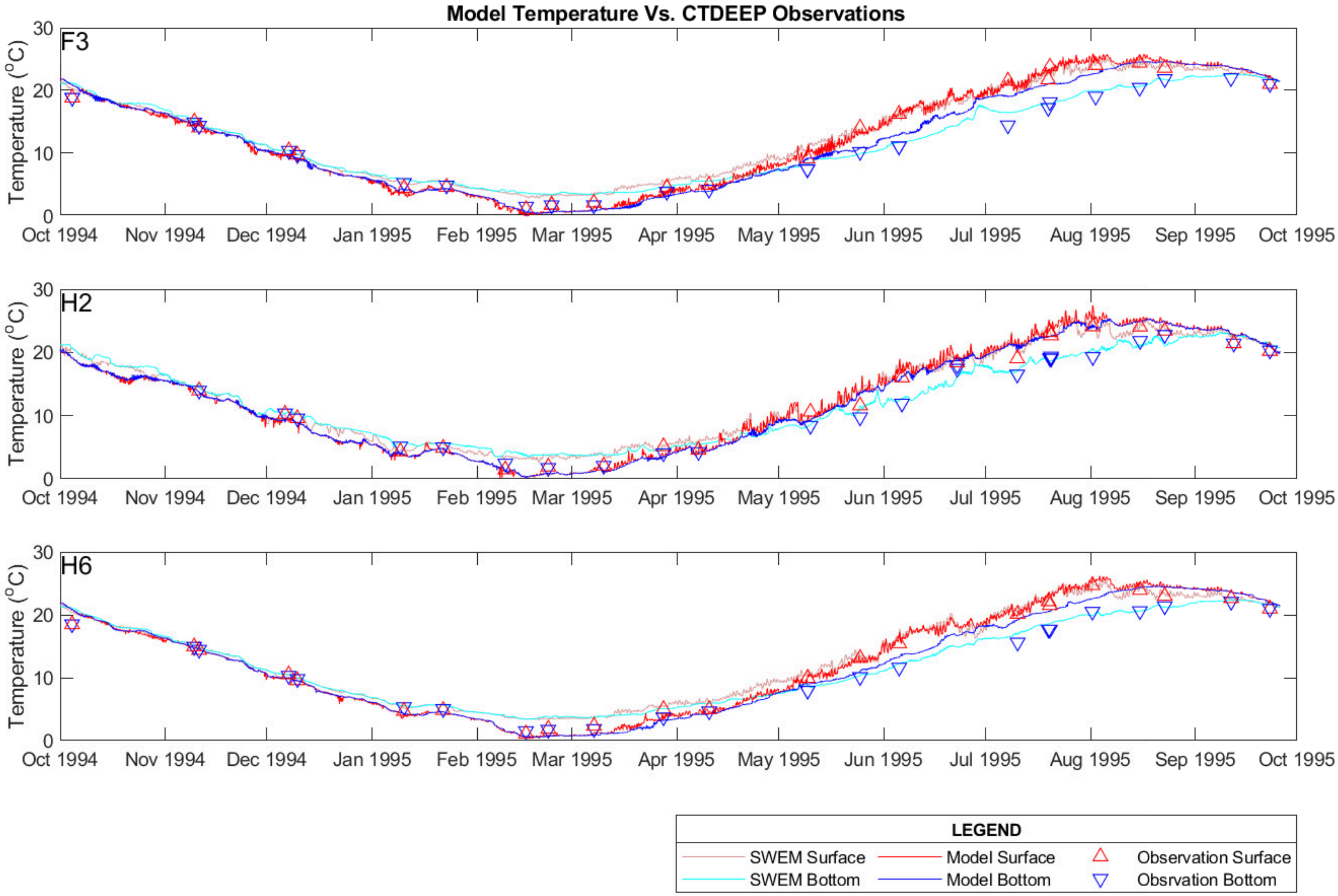
3

WY95 ROMS Baseline Temperature and Salinity Time-Series Comparisons at CTDEEP Stations

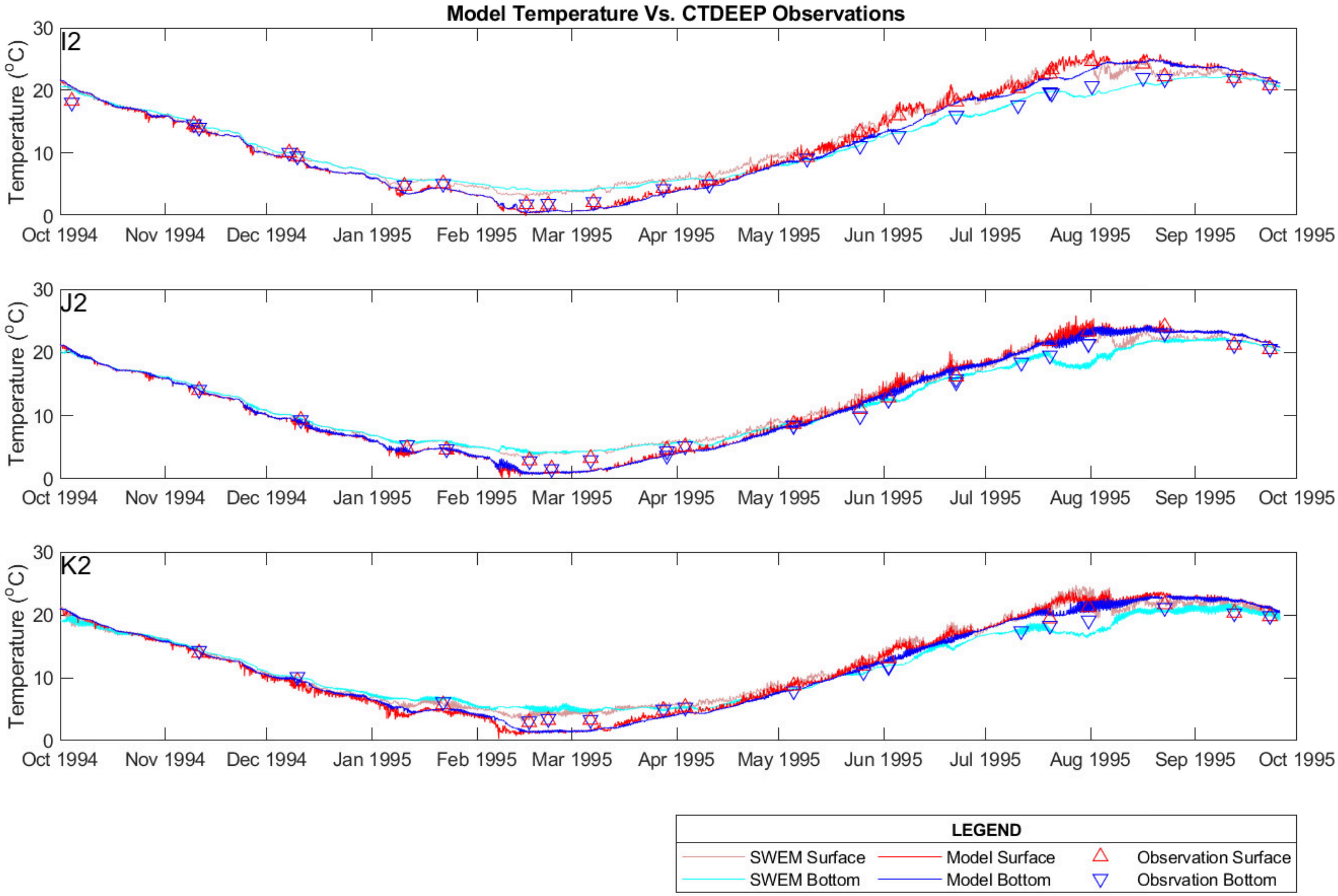

Model Temperature Vs. CTDEEP Observations
A4
C2
C1
Temperature (°C)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom

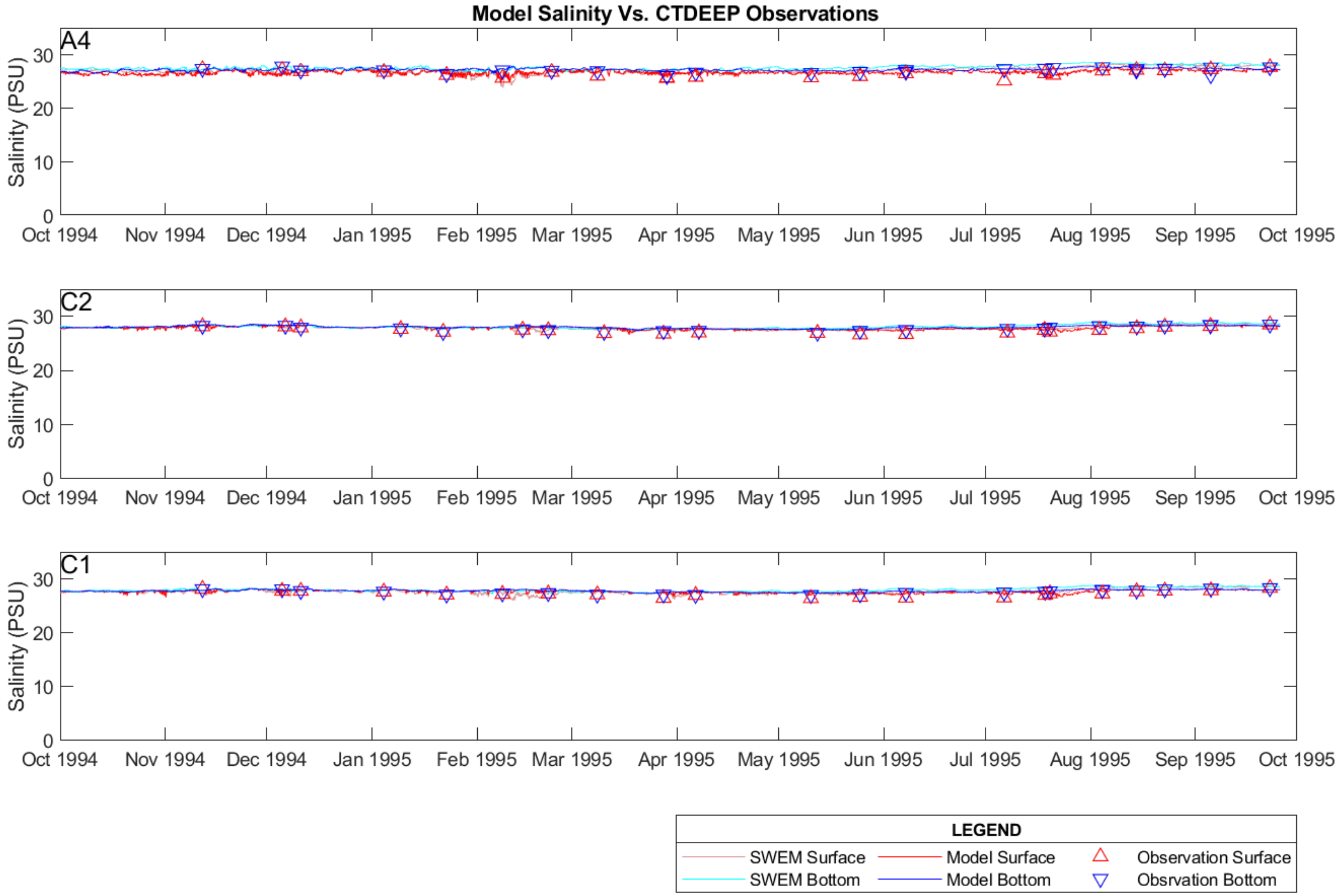


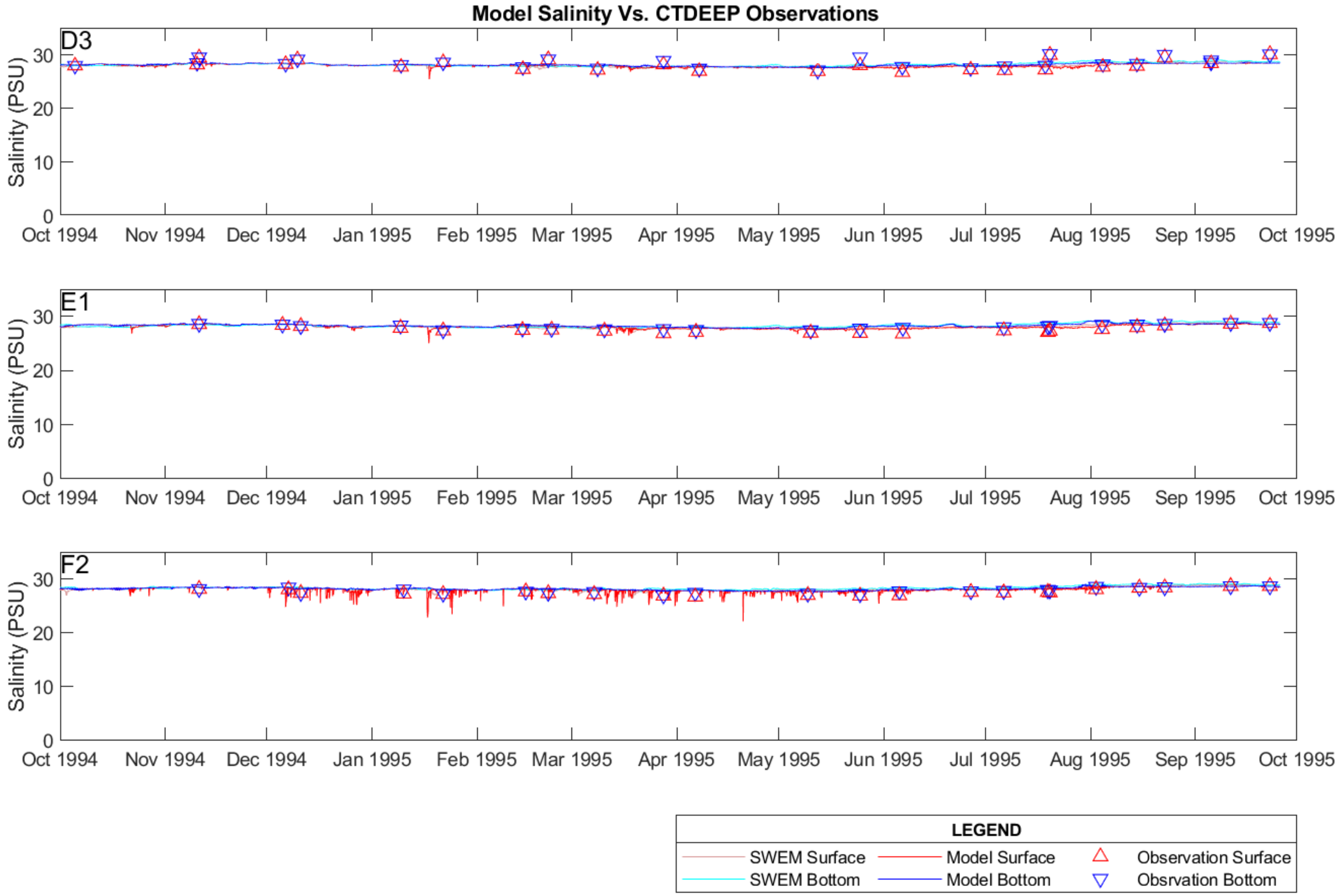
Model Temperature Vs. CTDEEP Observations
D3
E1
F2
Temperature (°C)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom

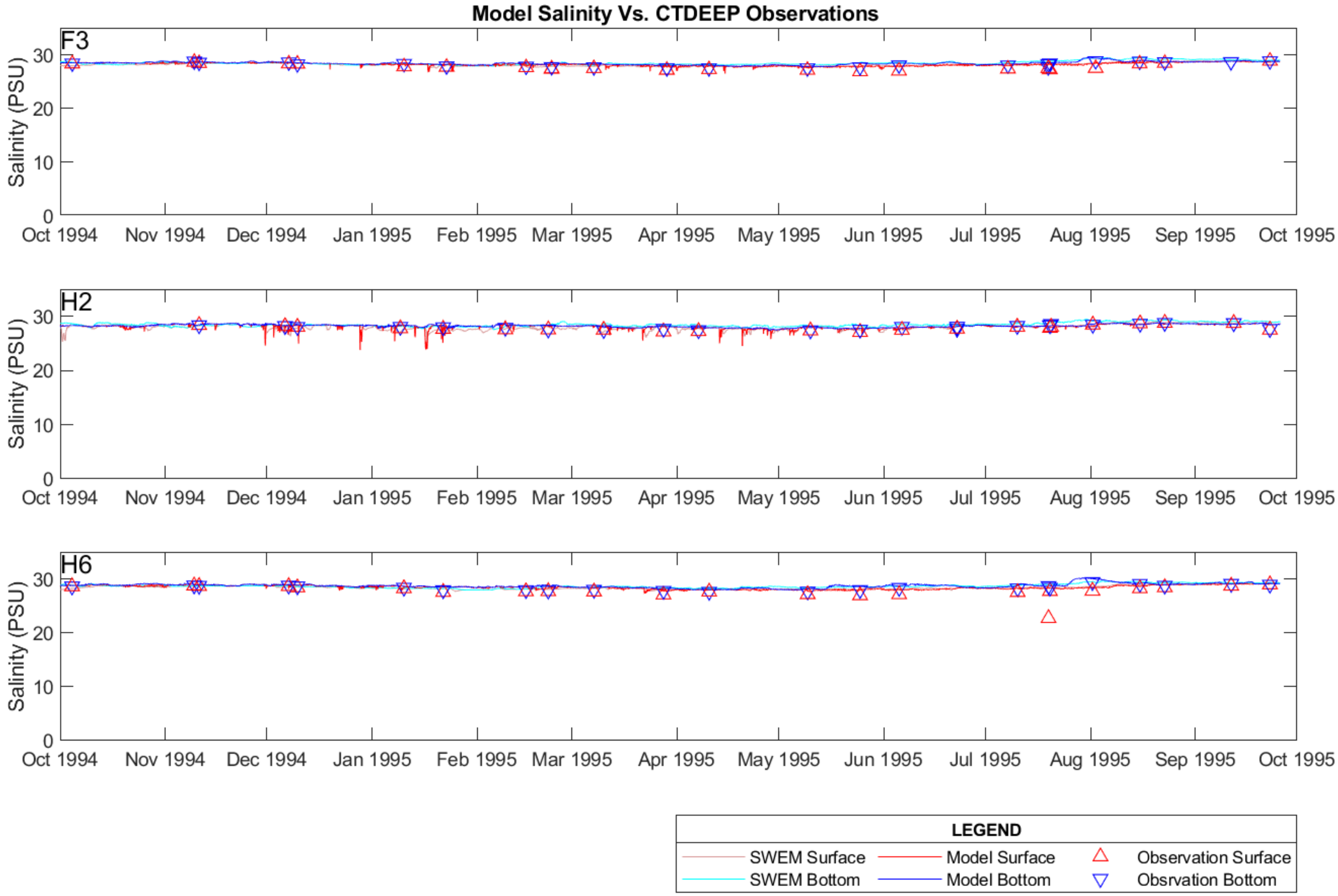


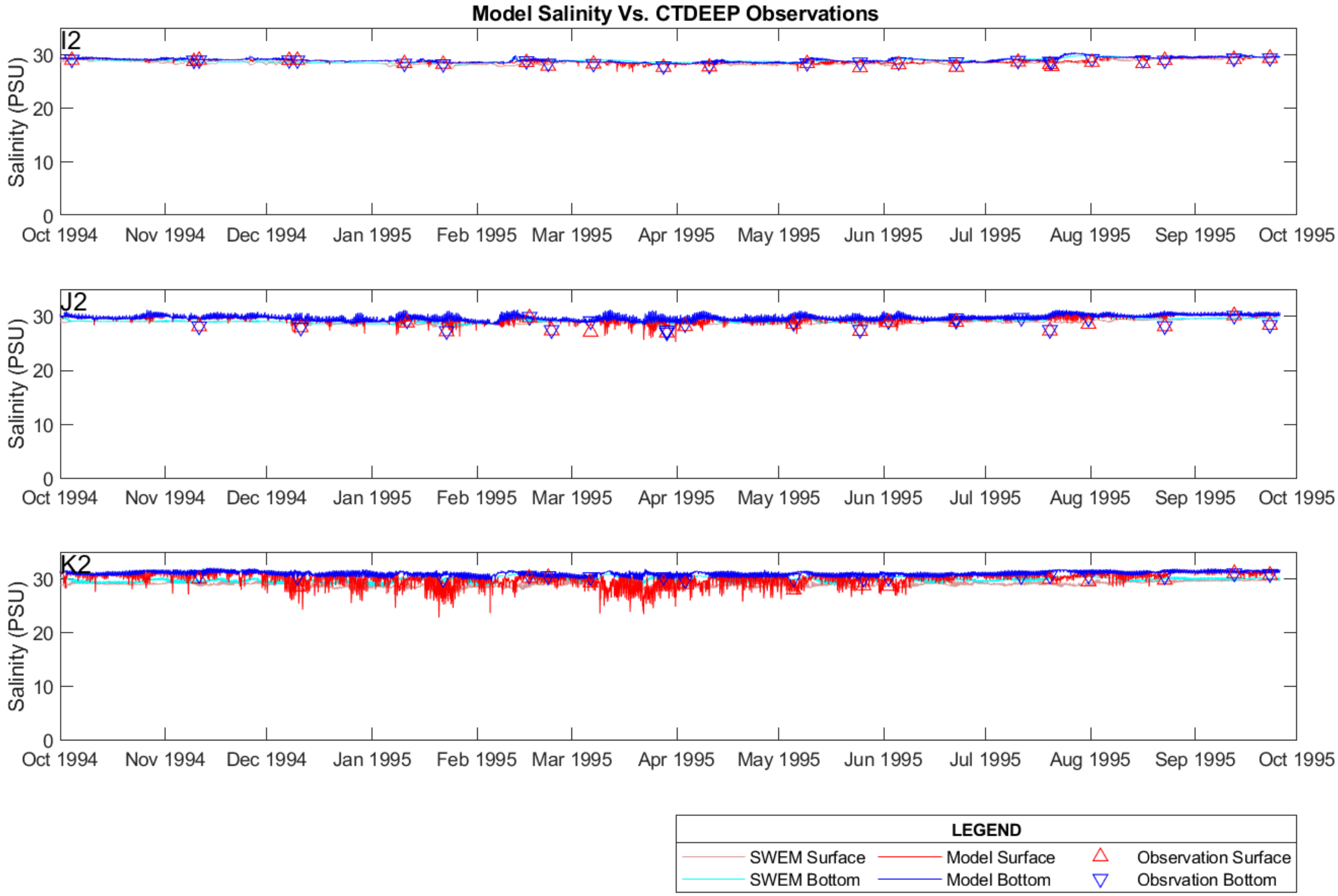
Model Temperature Vs. CTDEEP Observations
F3
H2
H6
Temperature (°C)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
Model Surface
Observation Surface
SWEM Bottom
Model Bottom
Obsrvation Bottom


Model Temperature Vs. CTDEEP Observations
I2
J2
K2
Temperature (°C)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom


Model Salinity Vs. CTDEEP Observations
A4
C2
C1
Salinity (PSU)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom


Model Salinity Vs. CTDEEP Observations
D3
E1
F2
Salinity (PSU)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
Model Surface
Observation Surface
SWEM Bottom
Model Bottom
Obsrvation Bottom


Model Salinity Vs. CTDEEP Observations
F3
H2
H6
Salinity (PSU)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
Model Surface
Observation Surface
SWEM Bottom
Model Bottom
Obsrvation Bottom



Model Salinity Vs. CTDEEP Observations
I2
J2
K2
Salinity (PSU)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
Model Surface
Observation Surface
SWEM Bottom
Model Bottom
Obsrvation Bottom

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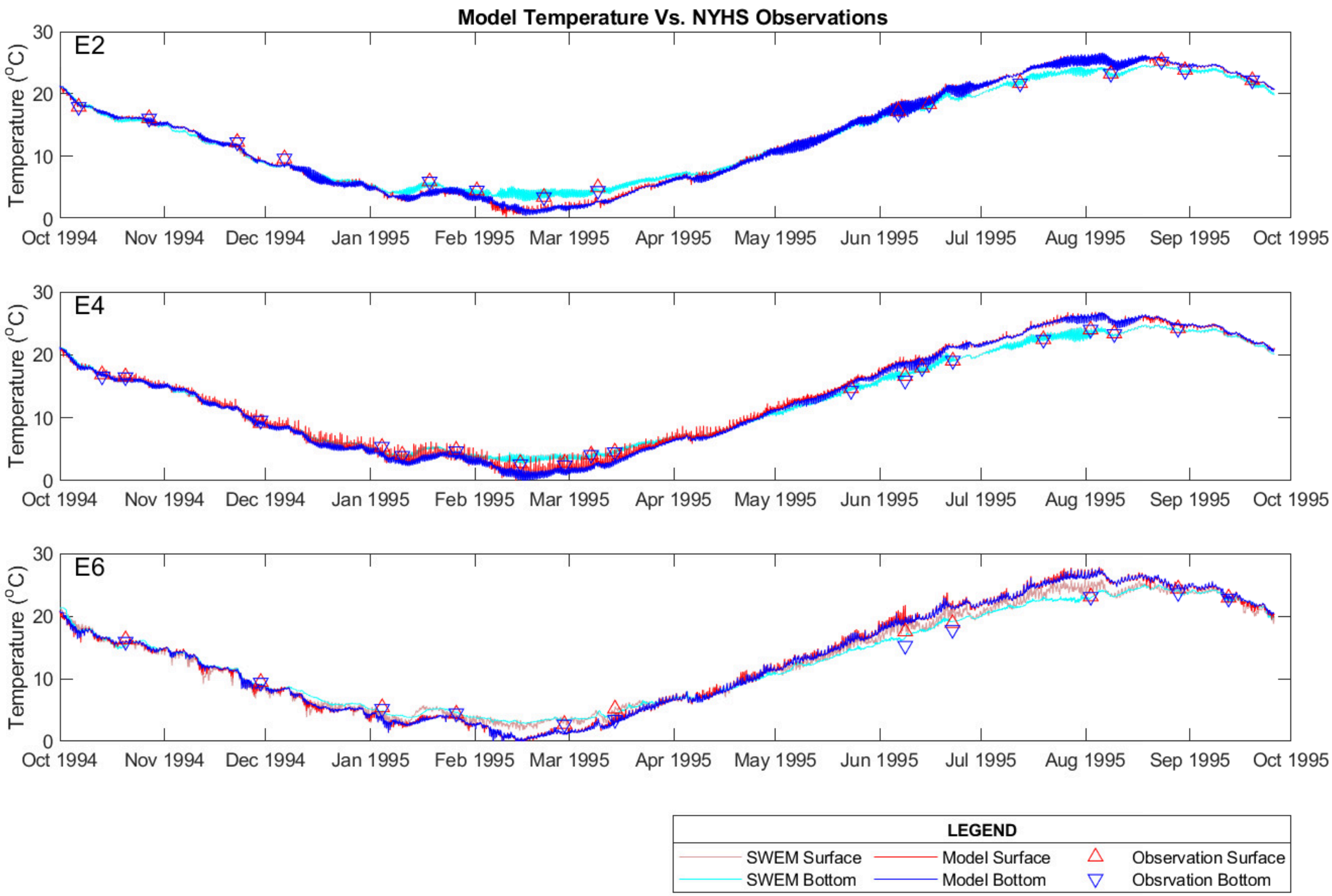
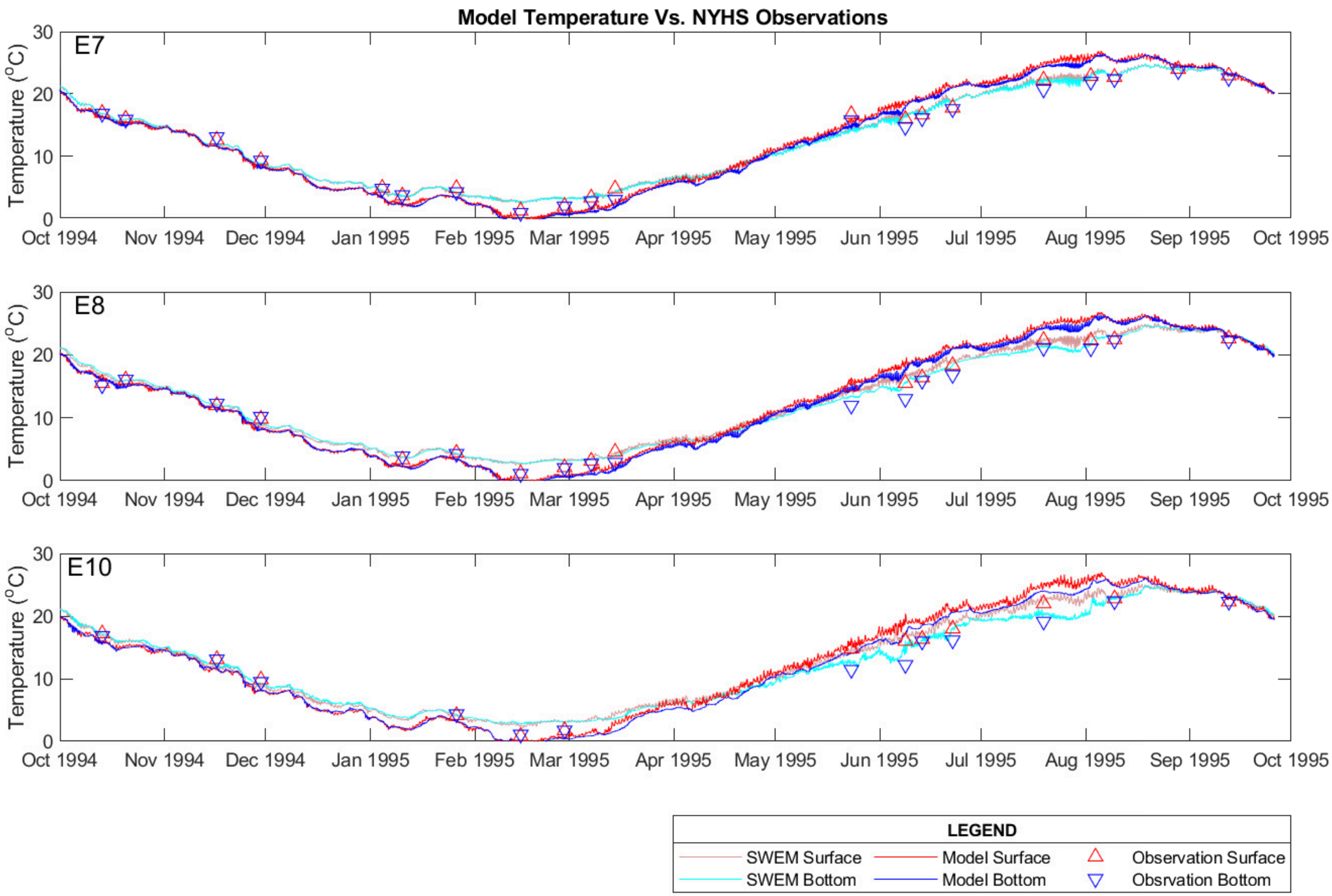
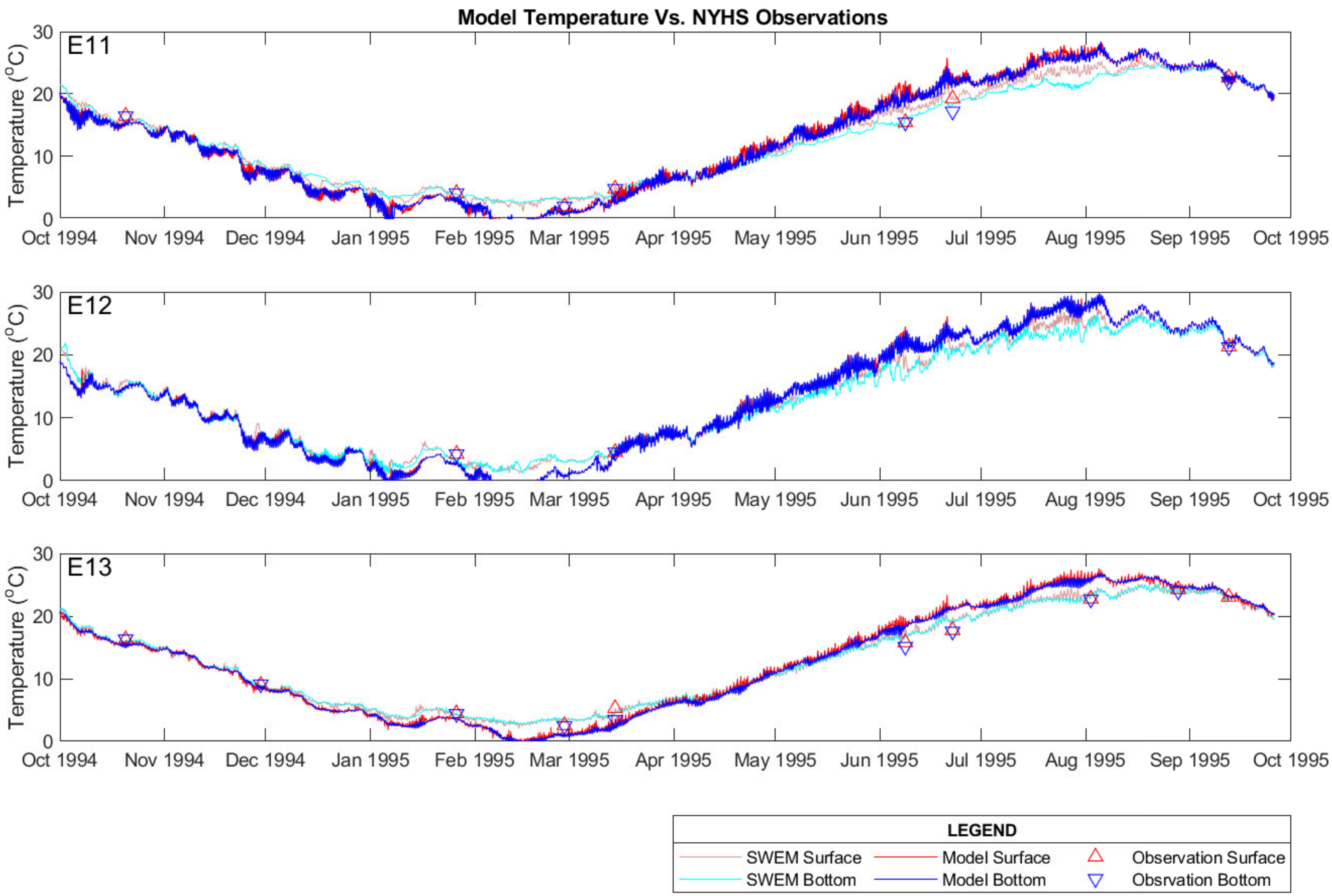
WY95 ROMS Baseline Temperature and Salinity Time-Series Comparisons at DEP Harbor Survey Stations

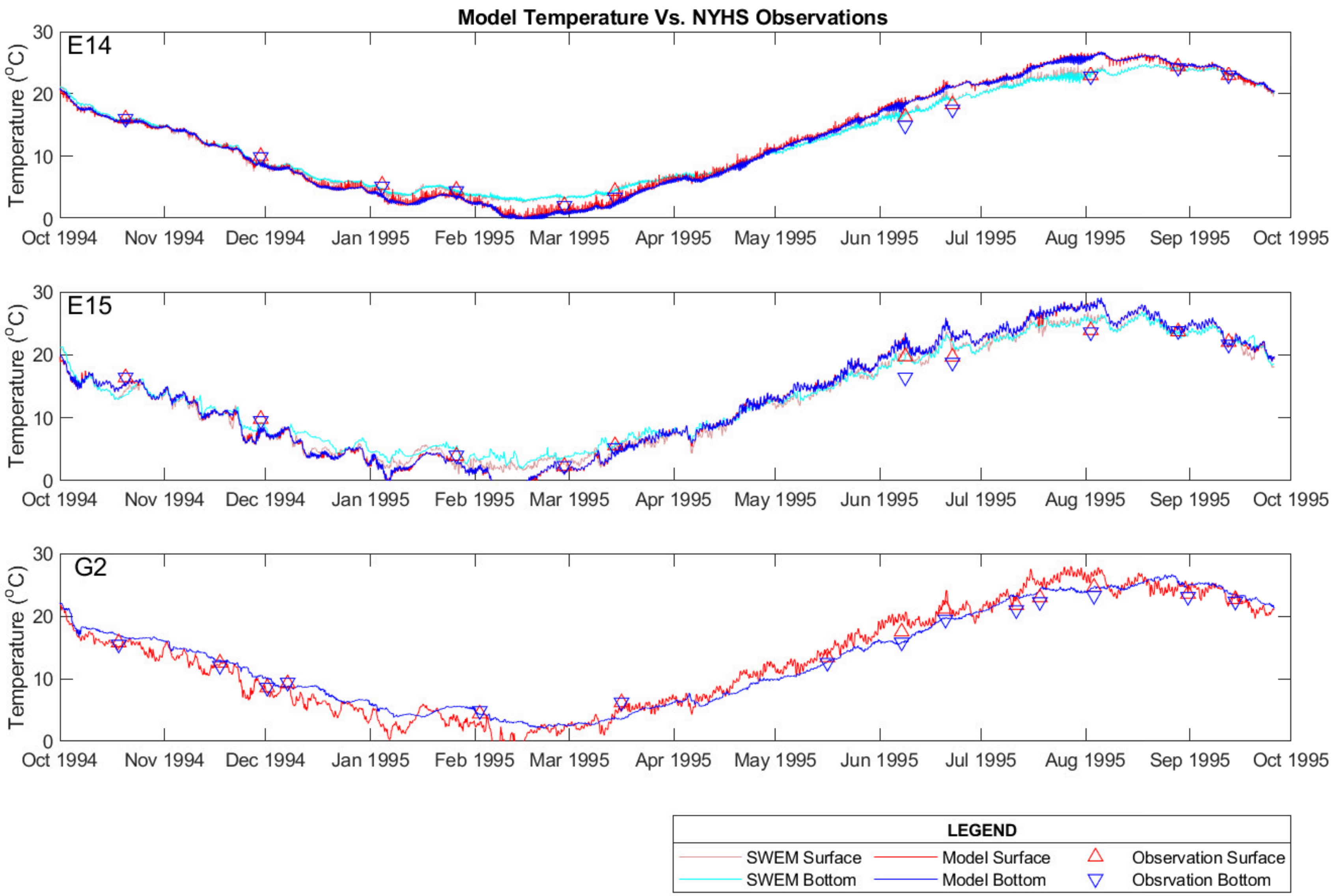


Model Temperature Vs. NYHS Observations
E2
E4
E6
Temperature (°C)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom

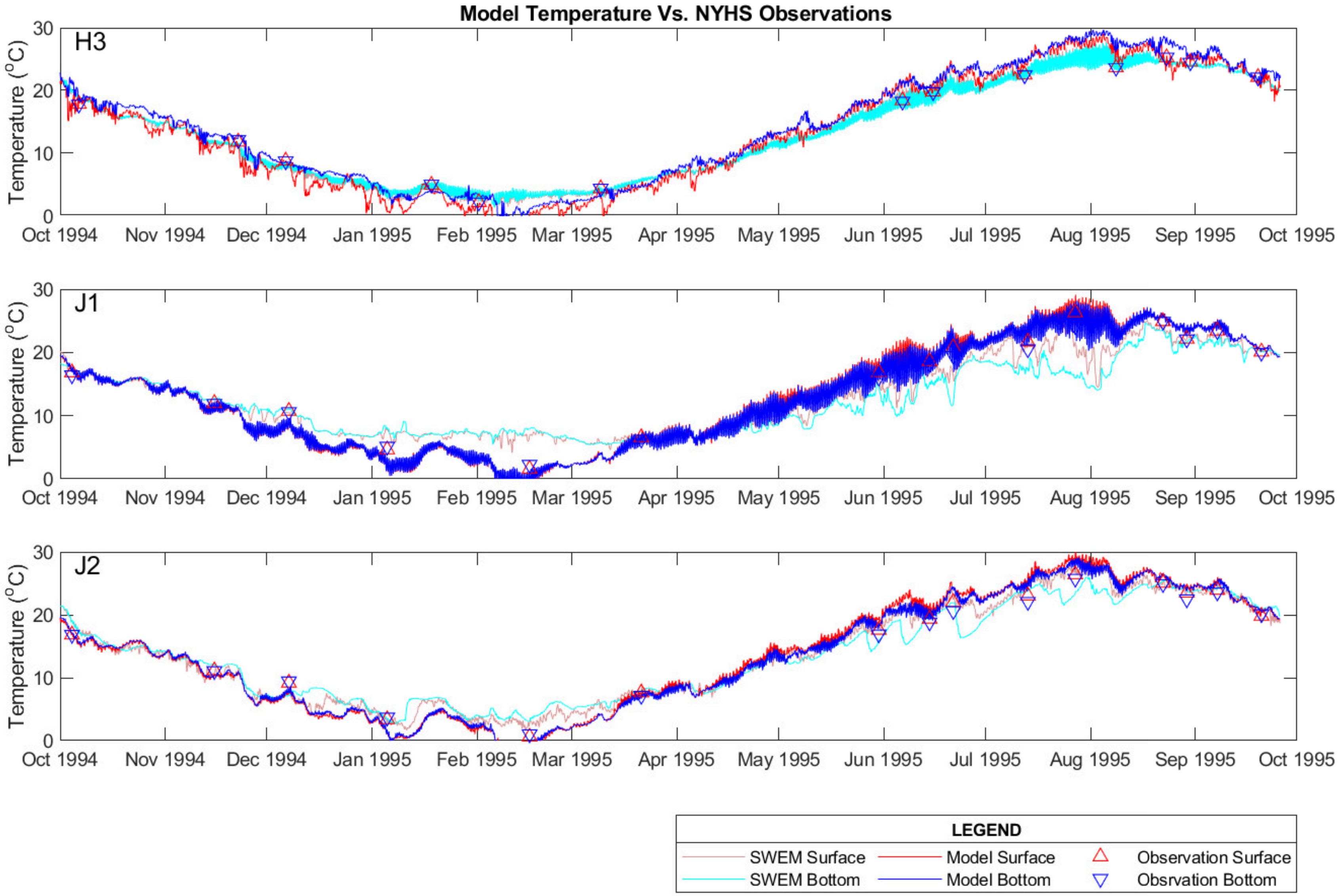

Model Temperature Vs. NYHS Observations
E7
E8
E10
Temperature (°C)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom

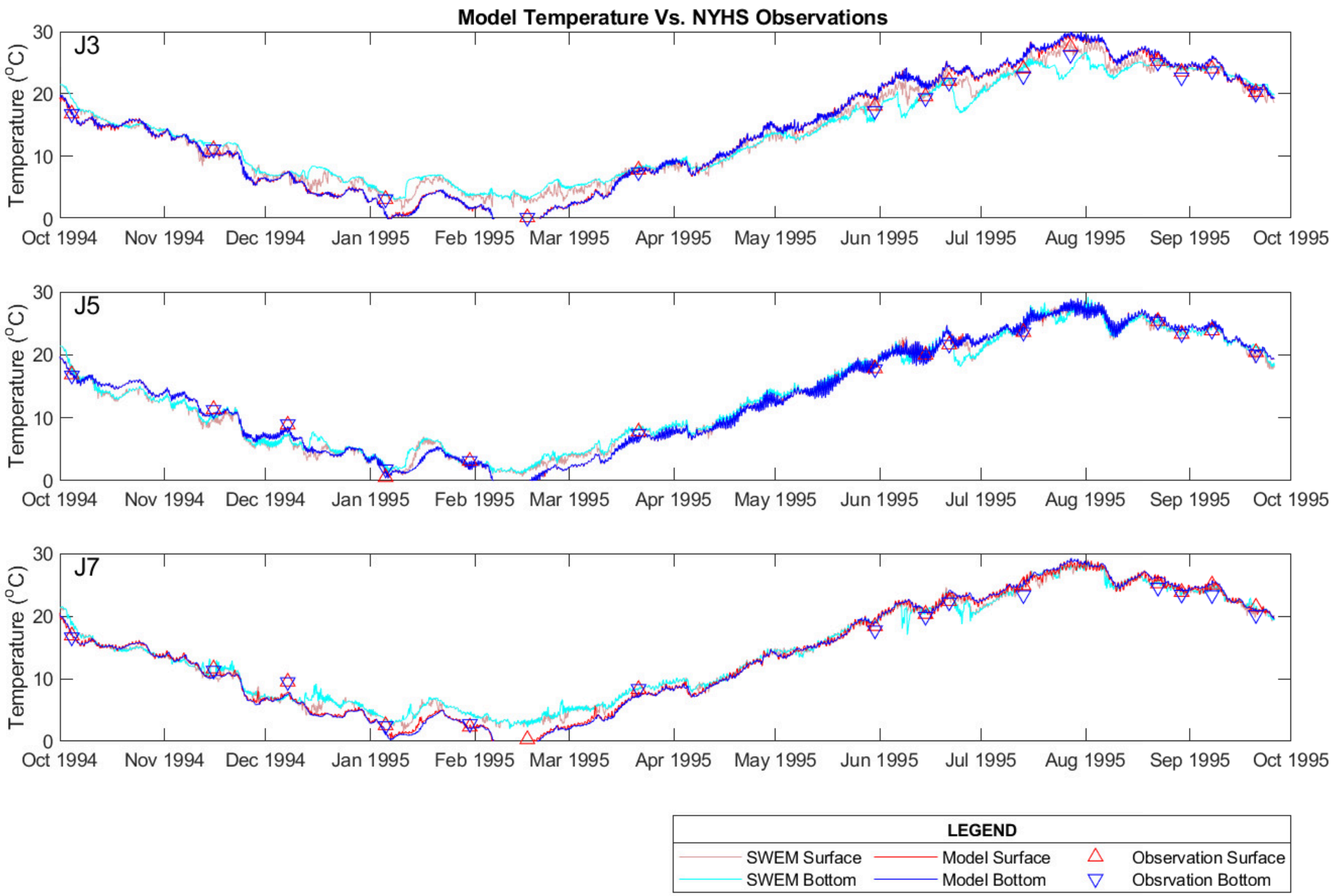


Model Temperature Vs. NYHS Observations
E11
E12
E13
Temperature (°C)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom

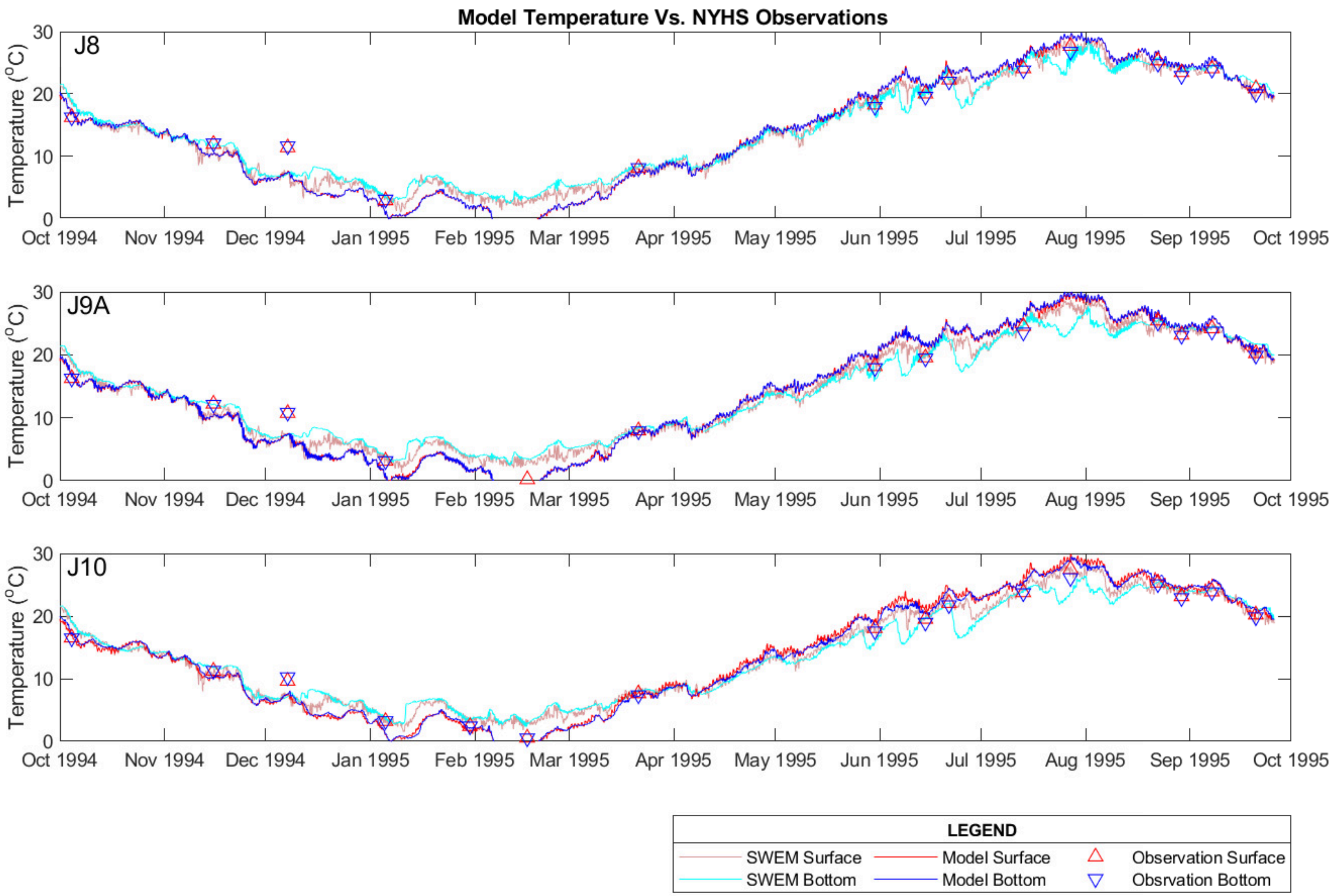


Model Temperature Vs. NYHS Observations
E14
E15
G2
Temperature (°C)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom

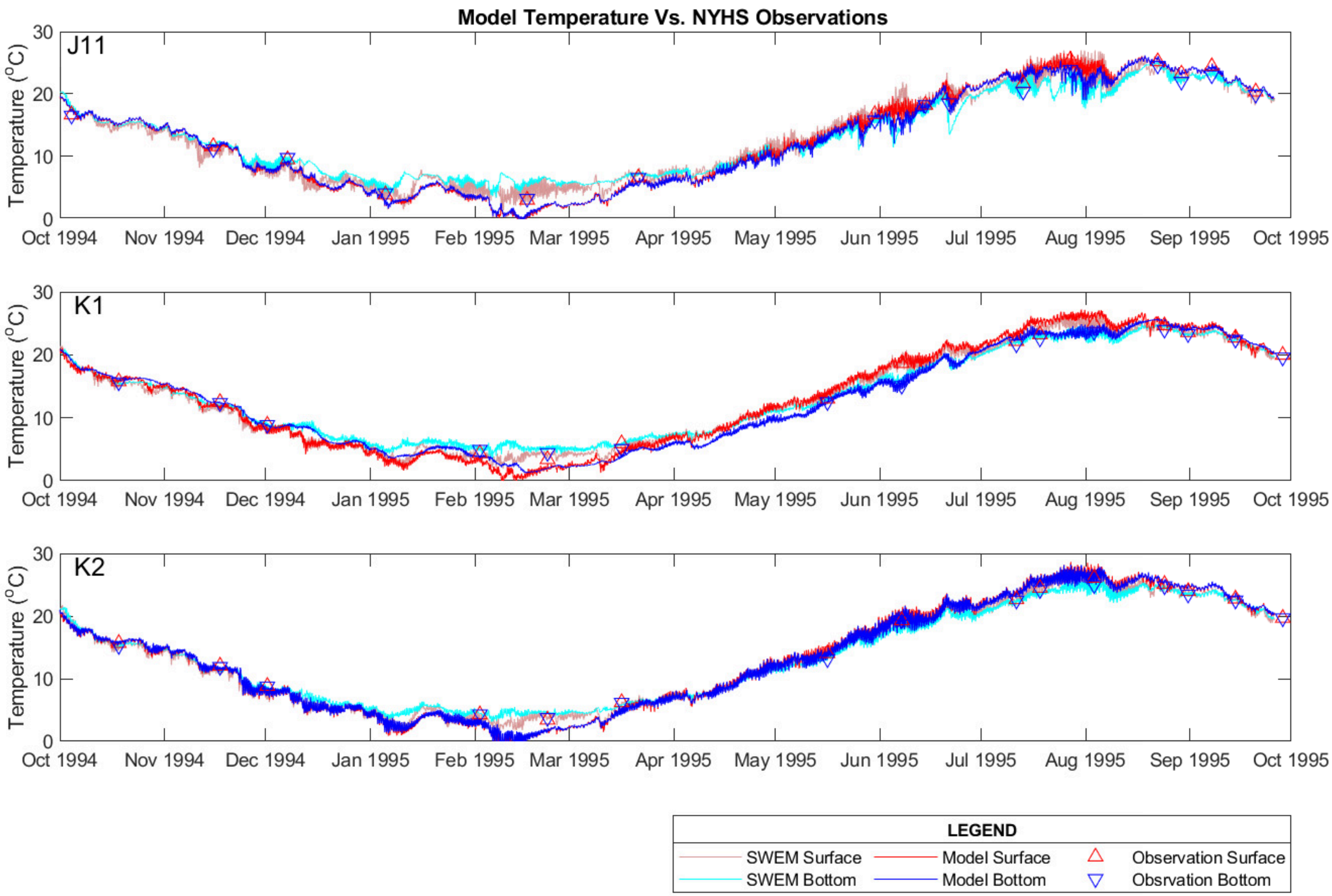

Model Temperature Vs. NYHS Observations
H3
J1
J2
Temperature (°C)
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom

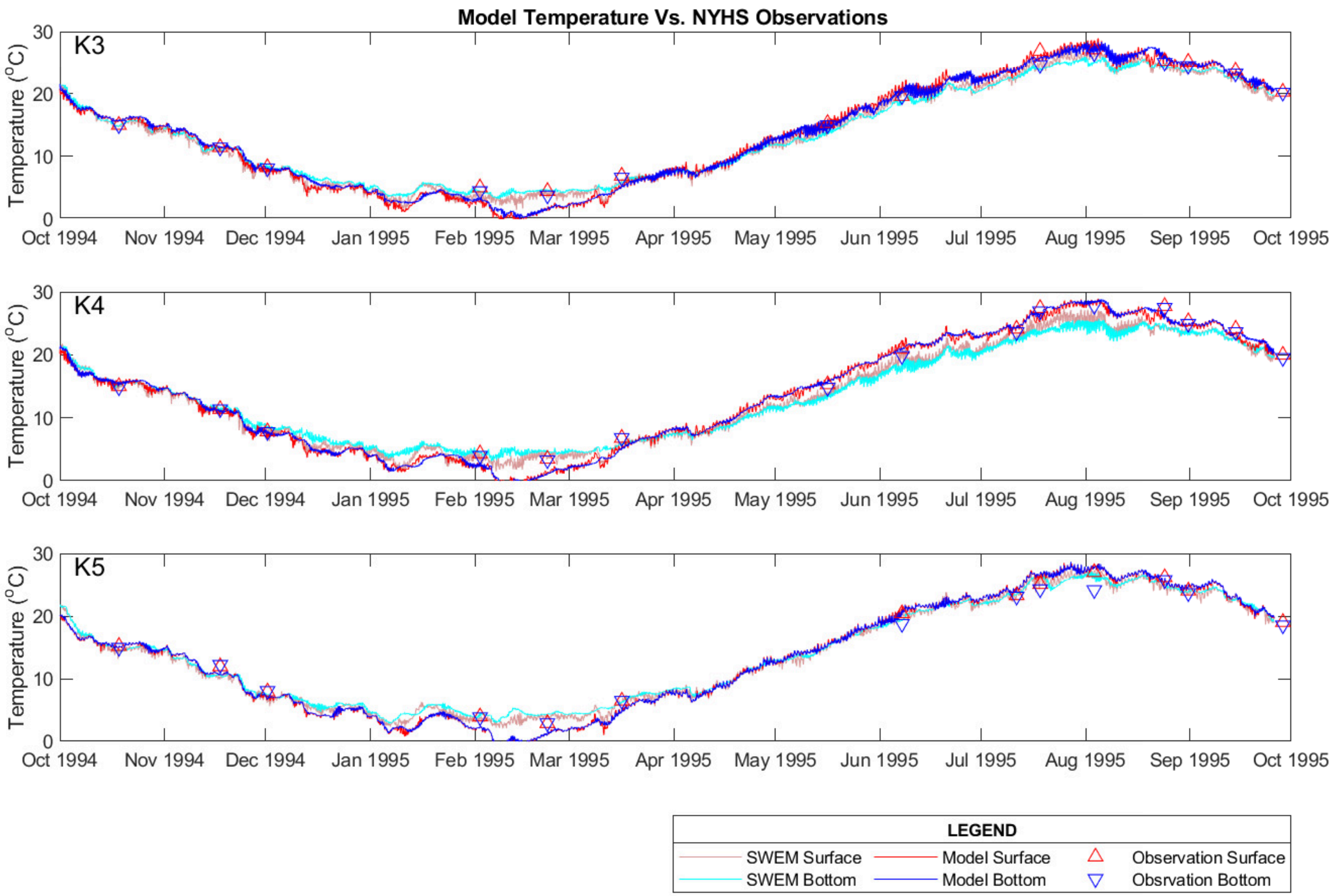


Model Temperature Vs. NYHS Observations
J3
J5
J7
Temperature (°C)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom

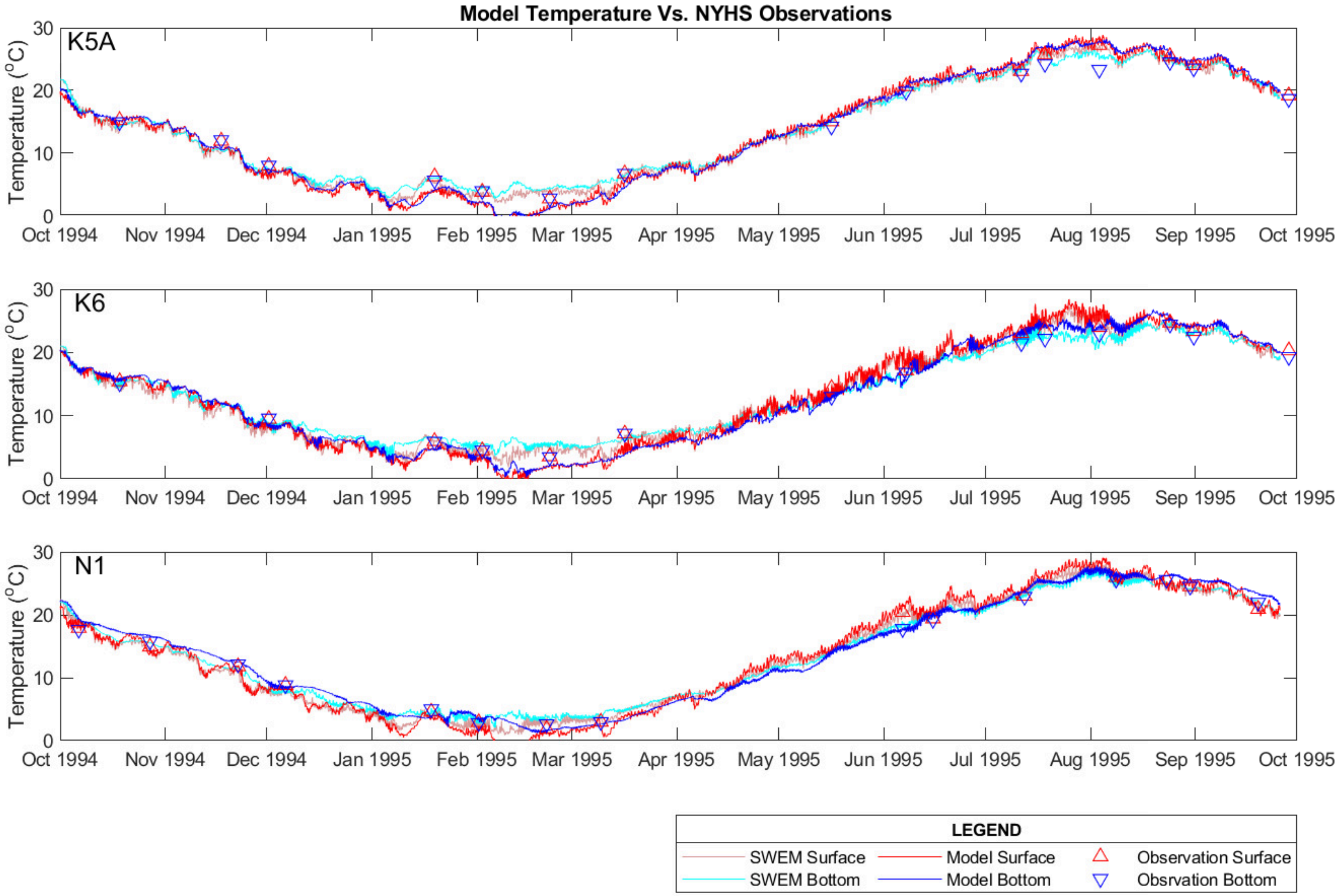


Model Temperature Vs. NYHS Observations
J8
J9A
J10
Temperature (°C)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
Model Surface
Observation Surface
SWEM Bottom
Model Bottom
Obsrvation Bottom

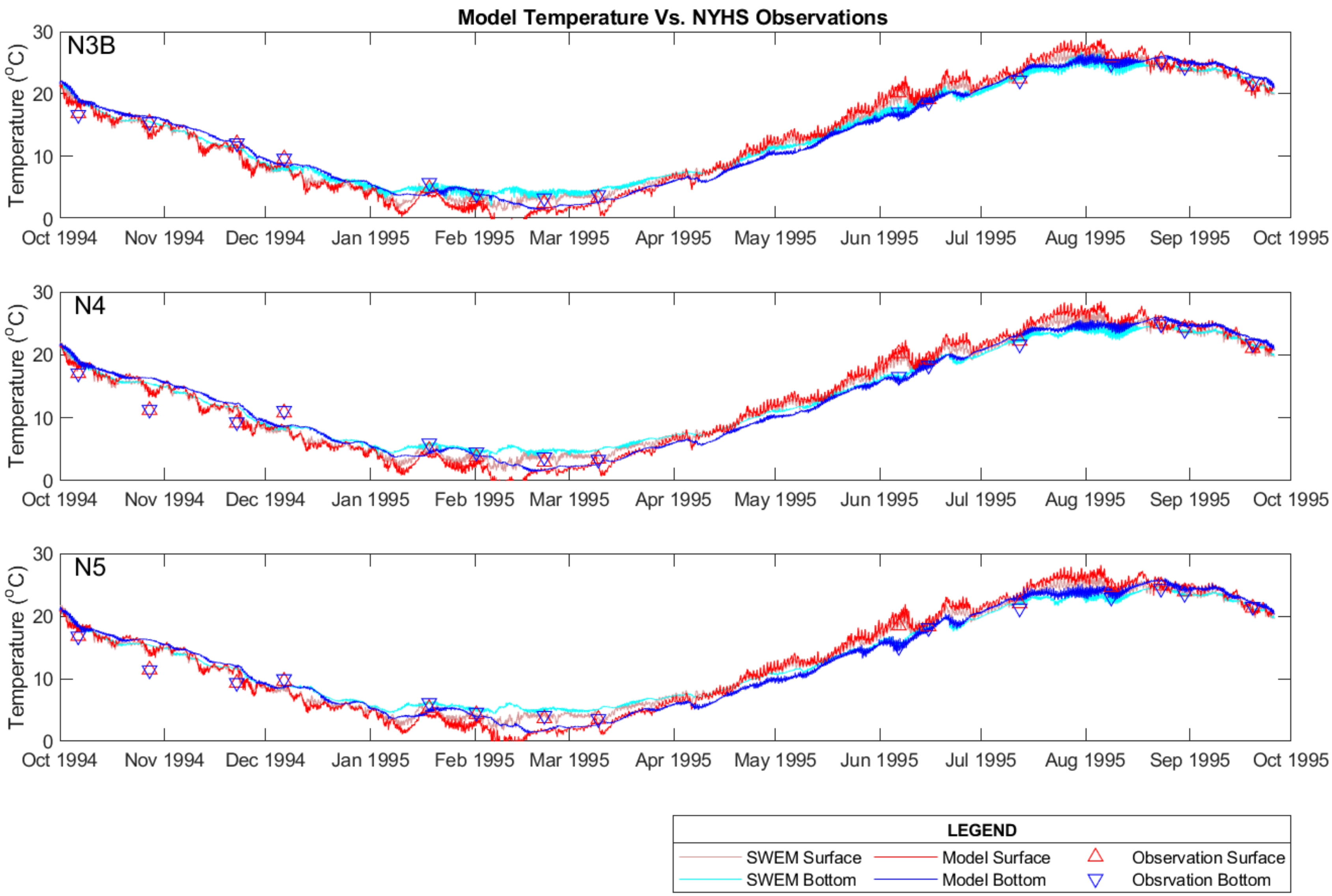

Model Temperature Vs. NYHS Observations
J11
K1
K2
Temperature (°C)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom

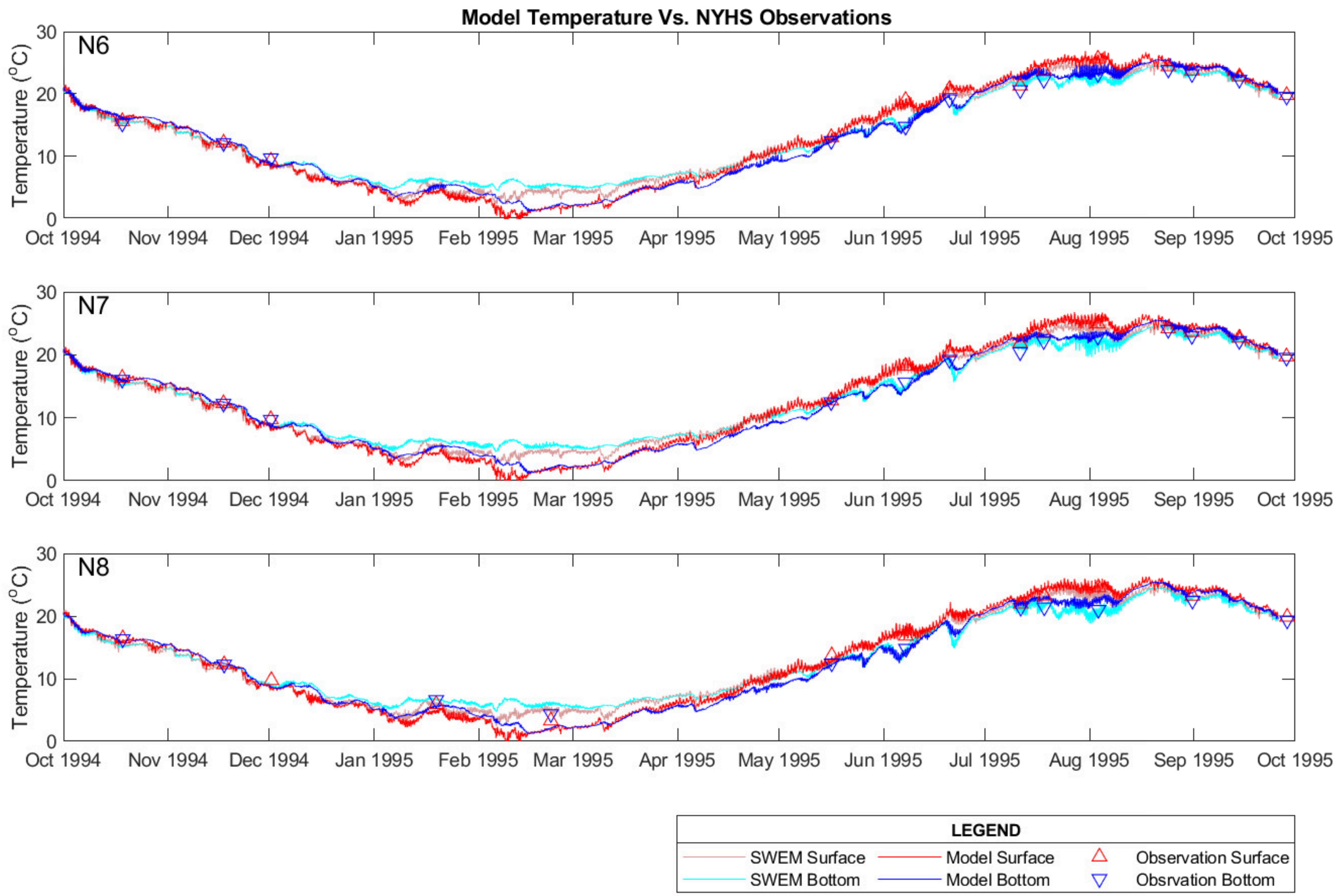


Model Temperature Vs. NYHS Observations
K3
K4
K5
Temperature (°C)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom

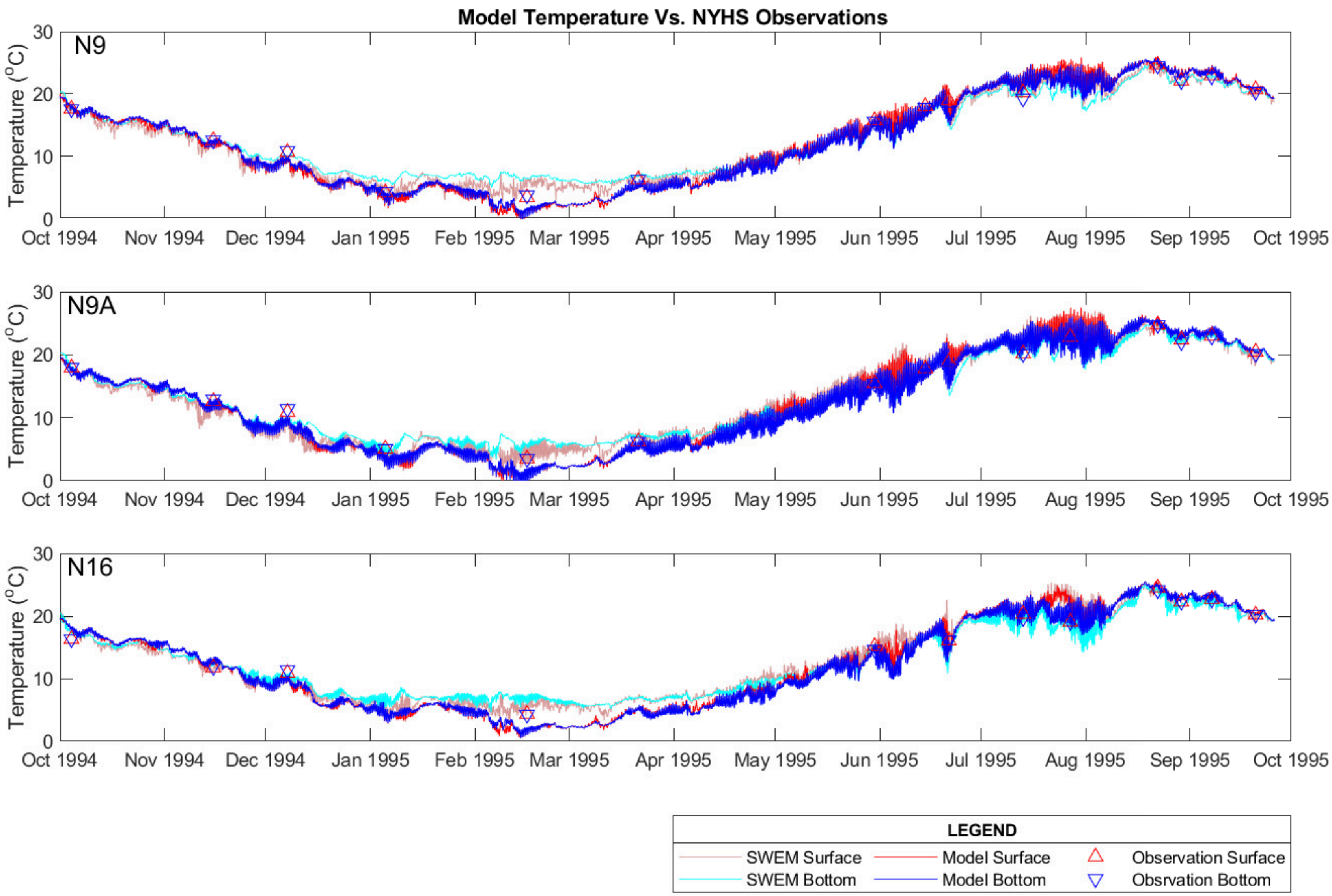


Model Temperature Vs. NYHS Observations
K5A
K6
N1
Temperature (°C)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom

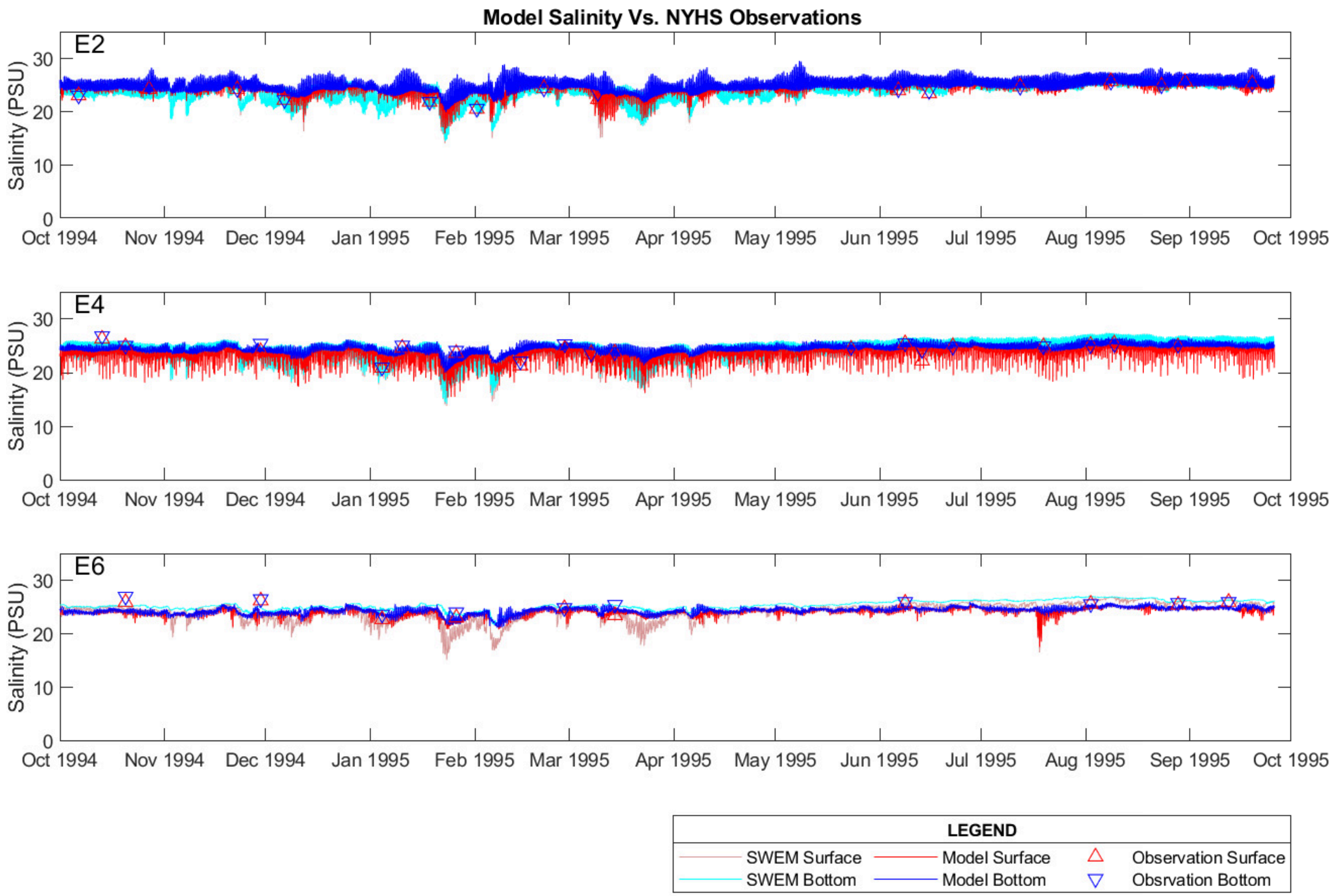

Model Temperature Vs. NYHS Observations
N3B
N4
N5
Temperature (°C)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom



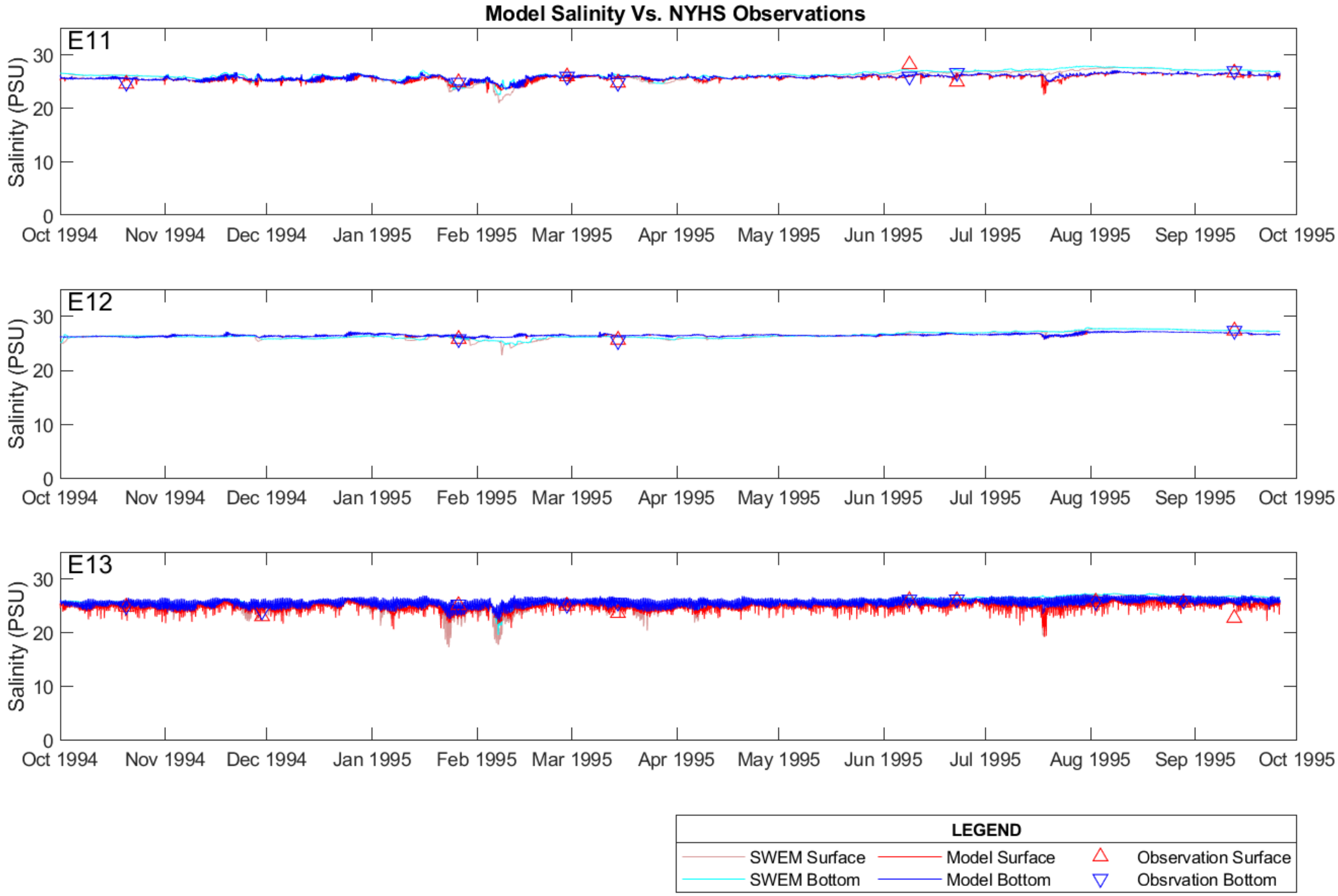
Model Temperature Vs. NYHS Observations
N6
N7
N8
Temperature (°C)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom



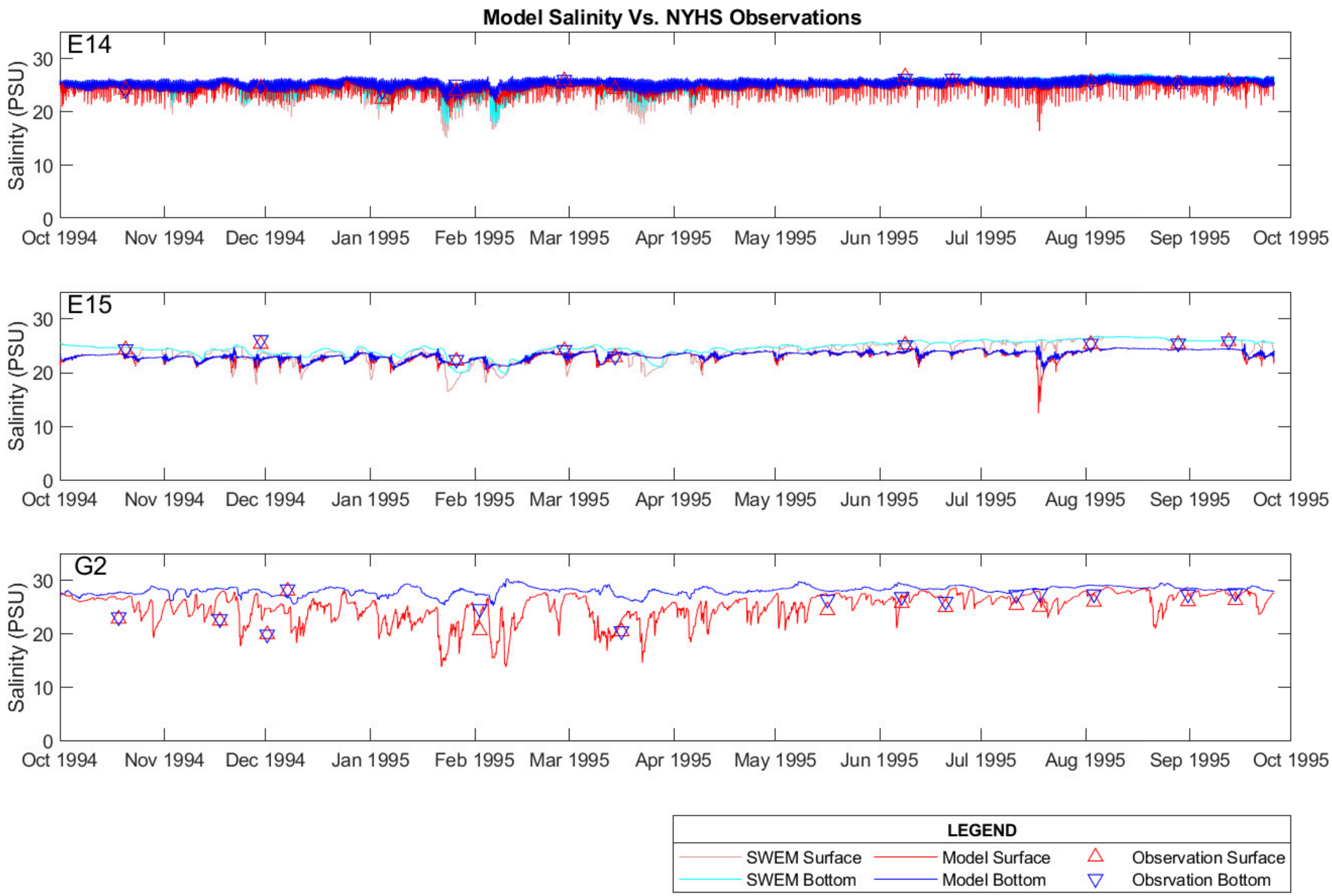
Model Temperature Vs. NYHS Observations
N9
N9A
N16
Temperature (°C)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom

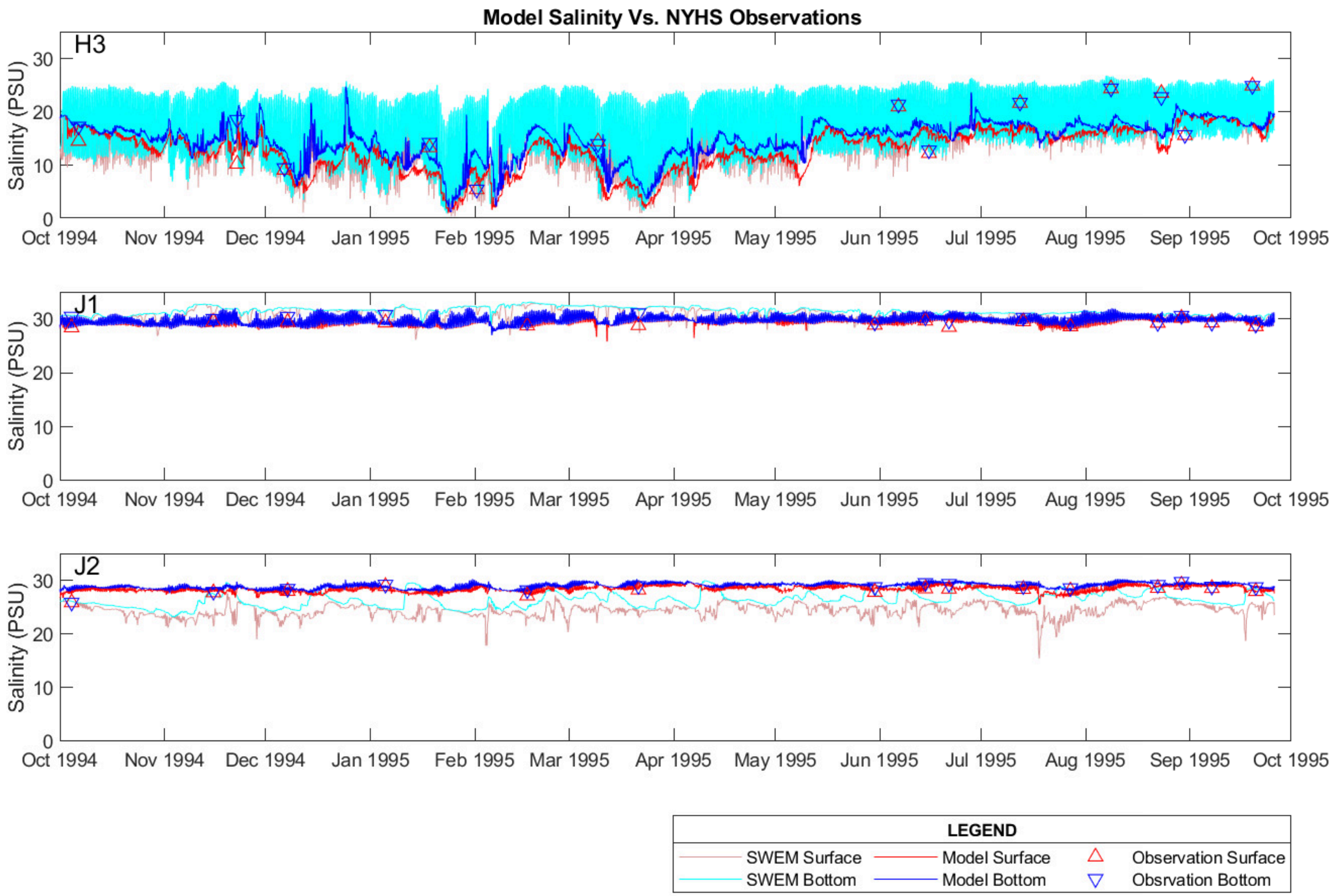

Model Salinity Vs. NYHS Observations
E2
E4
E6
Salinity (PSU)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom

Model Salinity Vs. NYHS Observations
E7
E8
E10
Salinity (PSU)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom

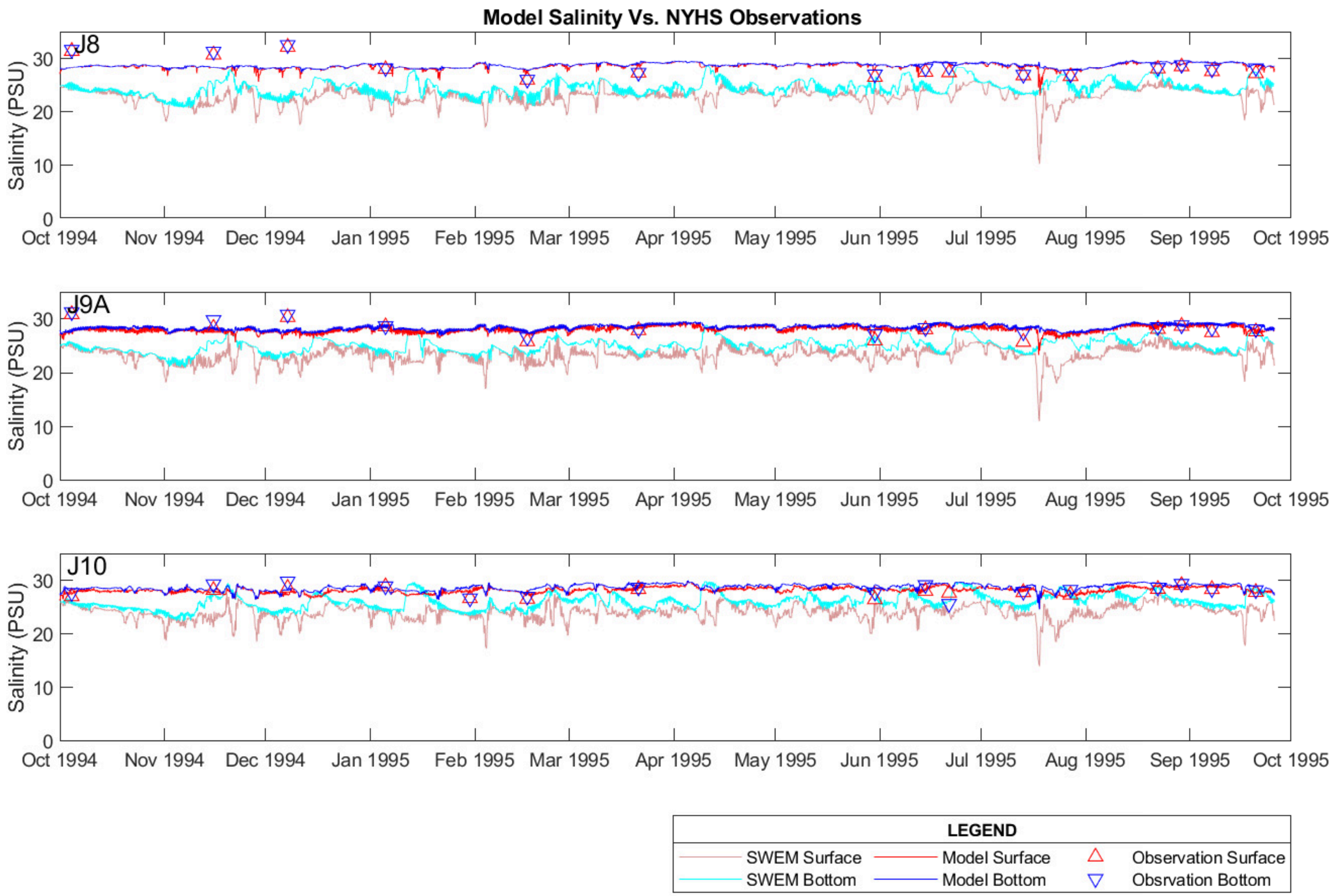


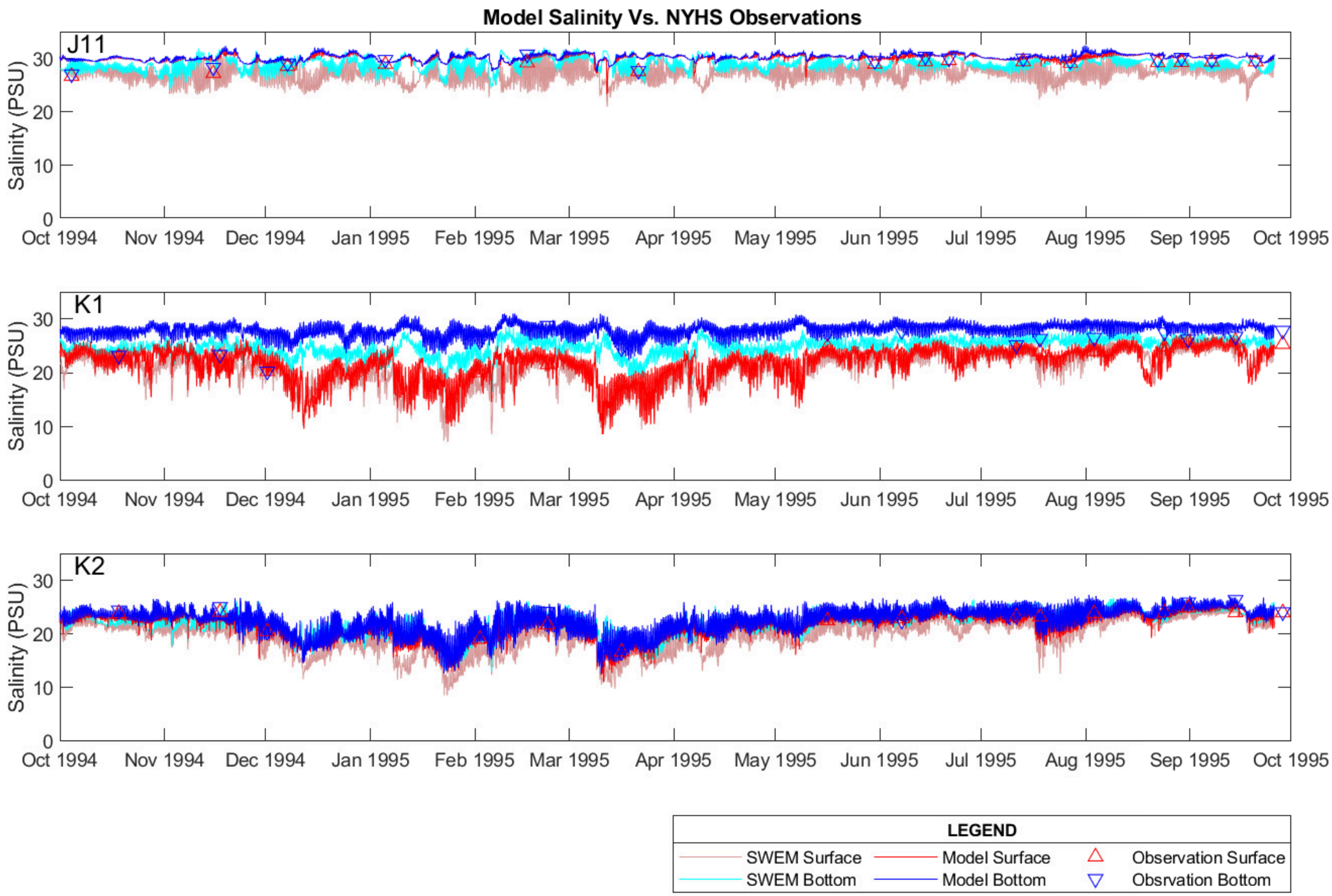
Model Salinity Vs. NYHS Observations
E11
E12
E13
Salinity (PSU)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom


Model Salinity Vs. NYHS Observations
E14
E15
G2
Salinity (PSU)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
Model Surface
Observation Surface
SWEM Bottom
Model Bottom
Obsrvation Bottom

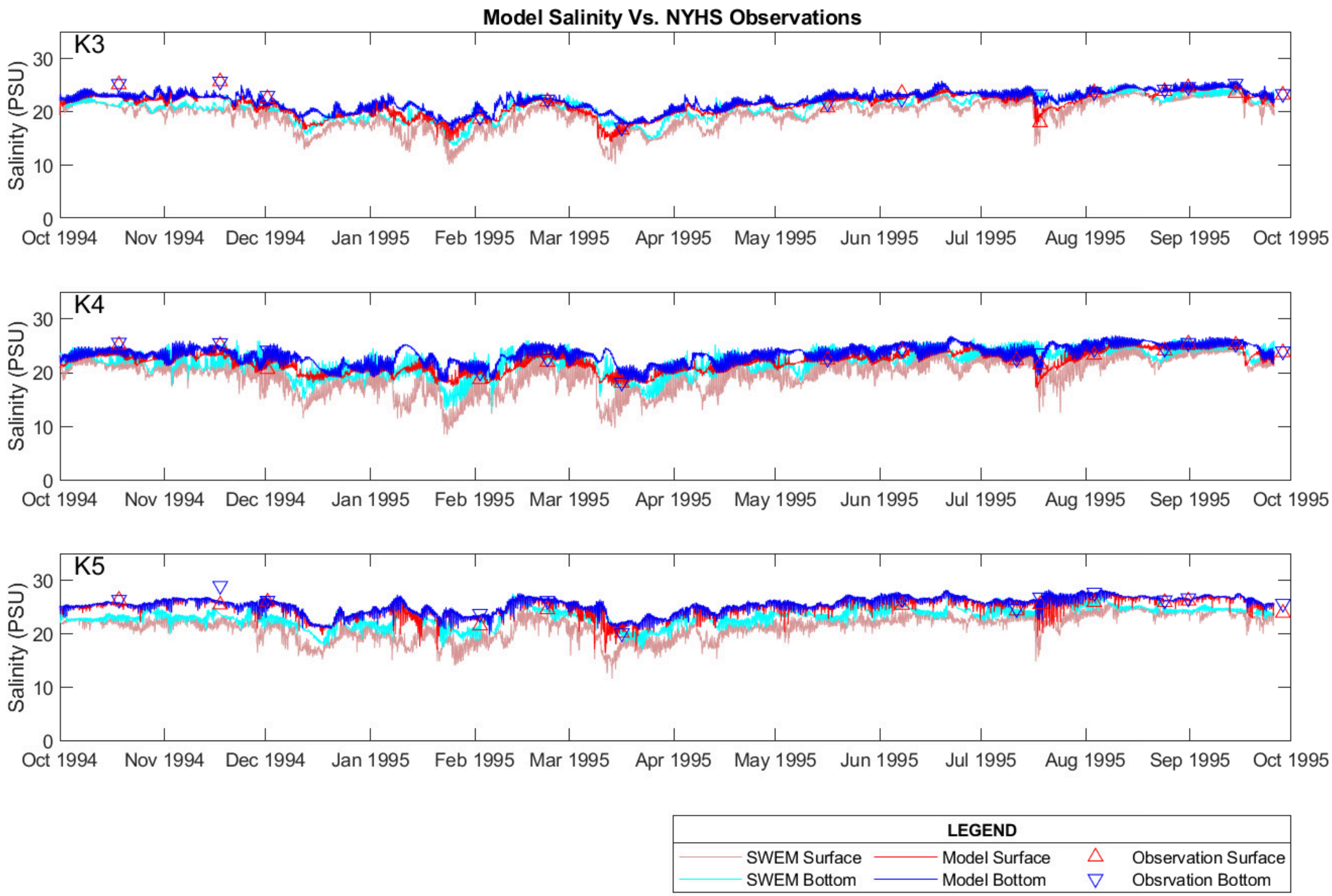

Model Salinity Vs. NYHS Observations
H3
J1
J2
Salinity (PSU)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom


Model Salinity Vs. NYHS Observations
J3
J5
J7
Salinity (PSU)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom

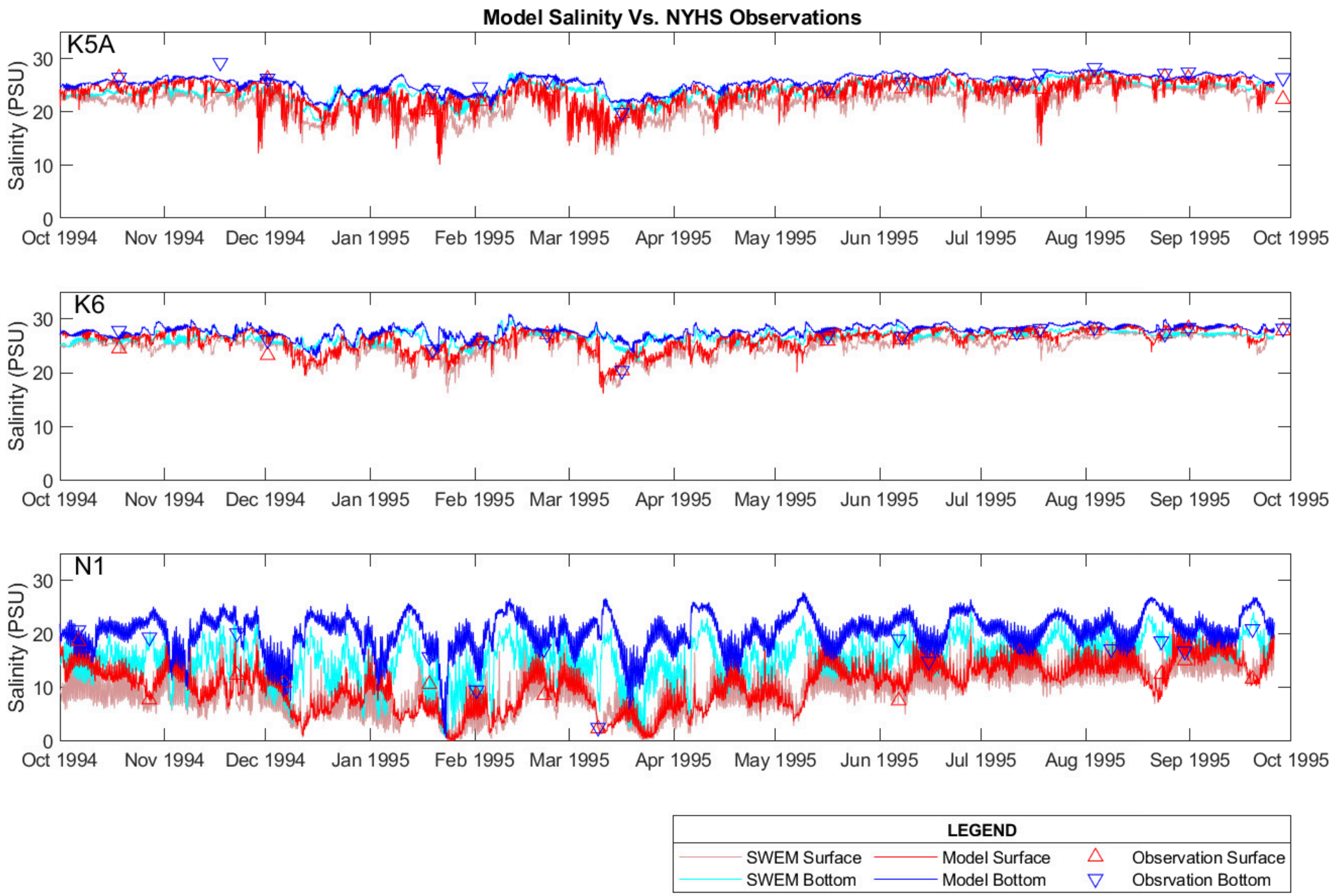

Model Salinity Vs. NYHS Observations
J8
J9A
J10
Salinity (PSU)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom



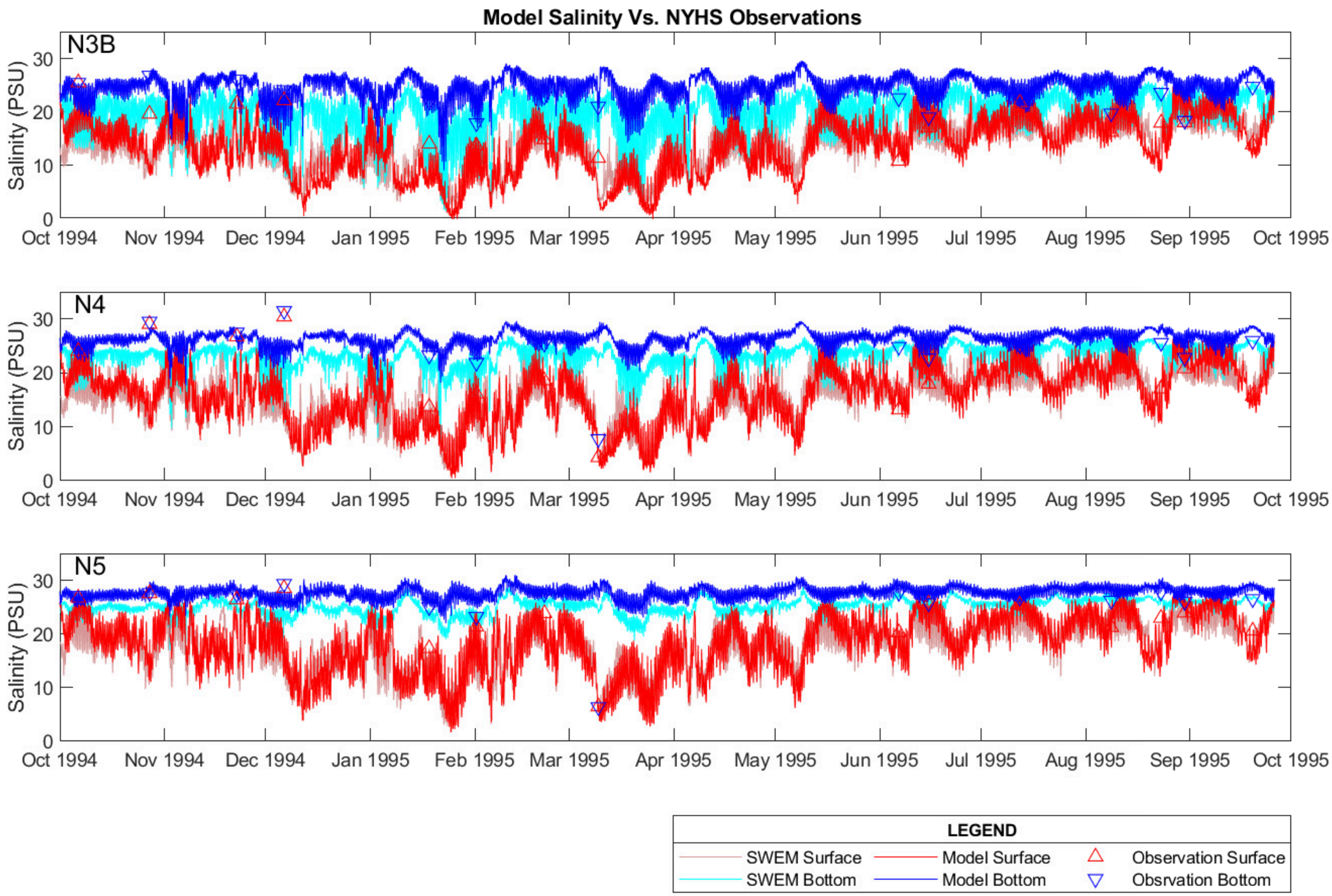
Model Salinity Vs. NYHS Observations
J11
K1
K2
Salinity (PSU)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom



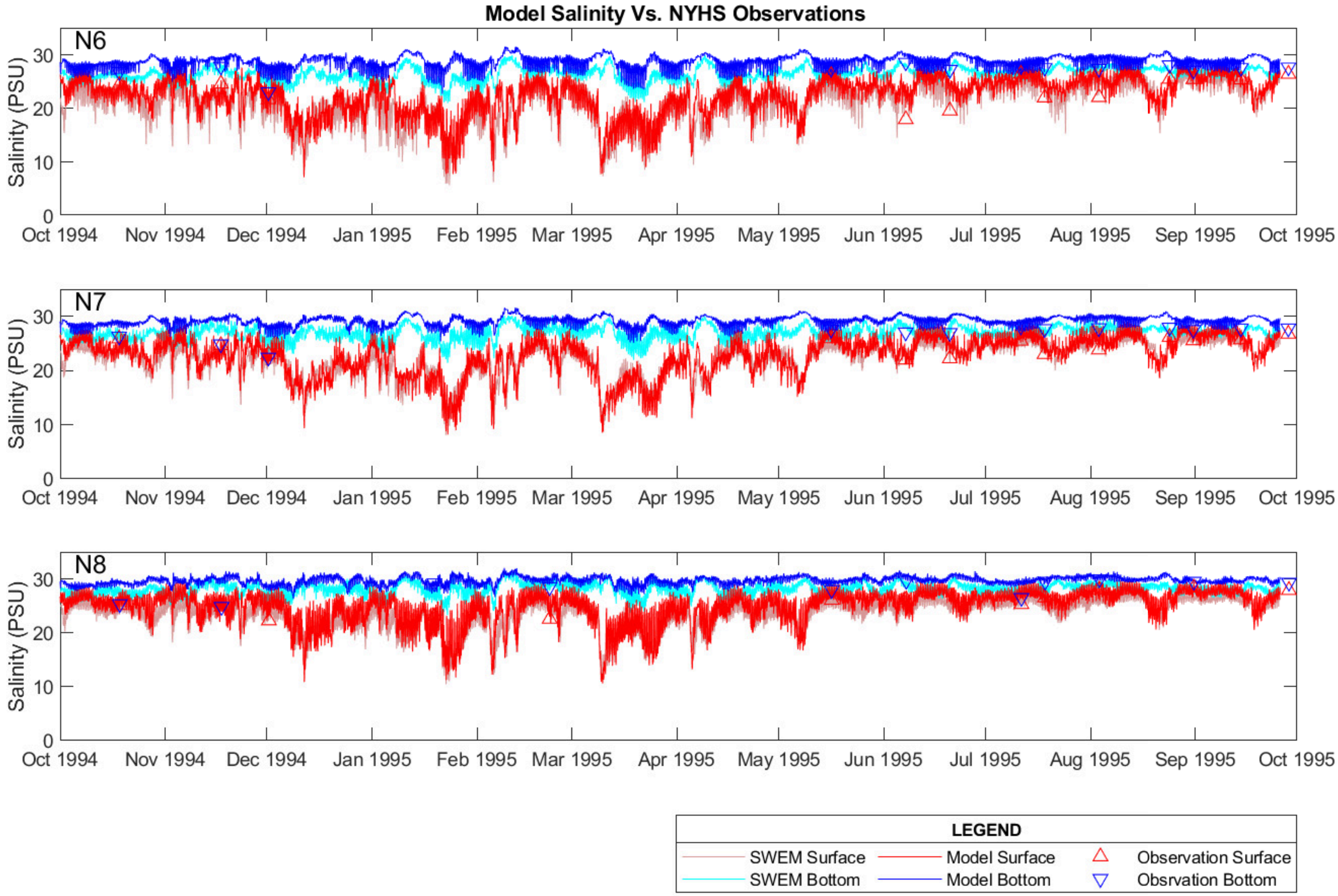
Model Salinity Vs. NYHS Observations
K3
K4
K5
Salinity (PSU)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
Model Surface
Observation Surface
SWEM Bottom
Model Bottom
Obsrvation Bottom



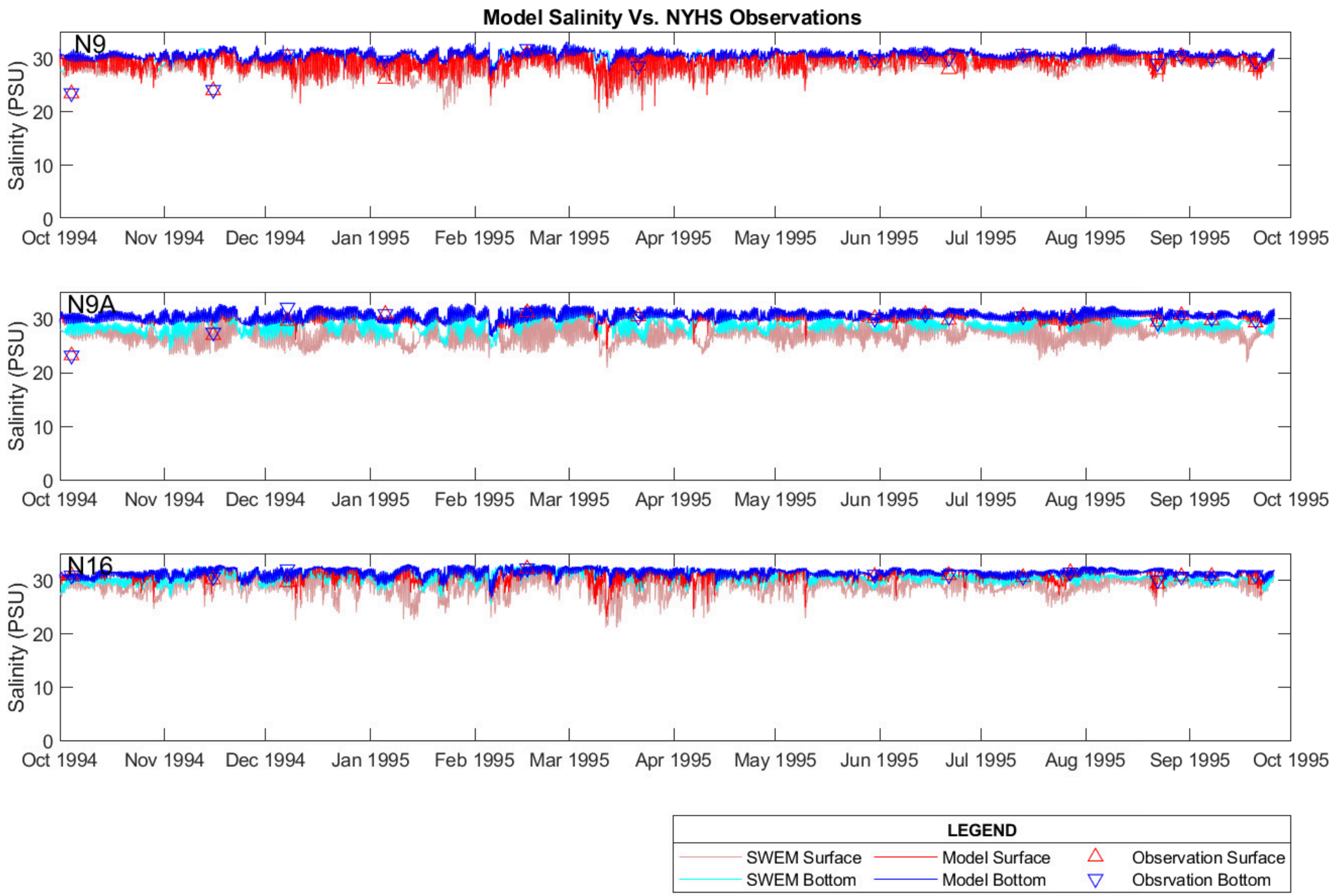
Model Salinity Vs. NYHS Observations
K5A
K6
N1
Salinity (PSU)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom



Model Salinity Vs. NYHS Observations
N3B
N4
N5
Salinity (PSU)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
Model Surface
Observation Surface
SWEM Bottom
Model Bottom
Obsrvation Bottom



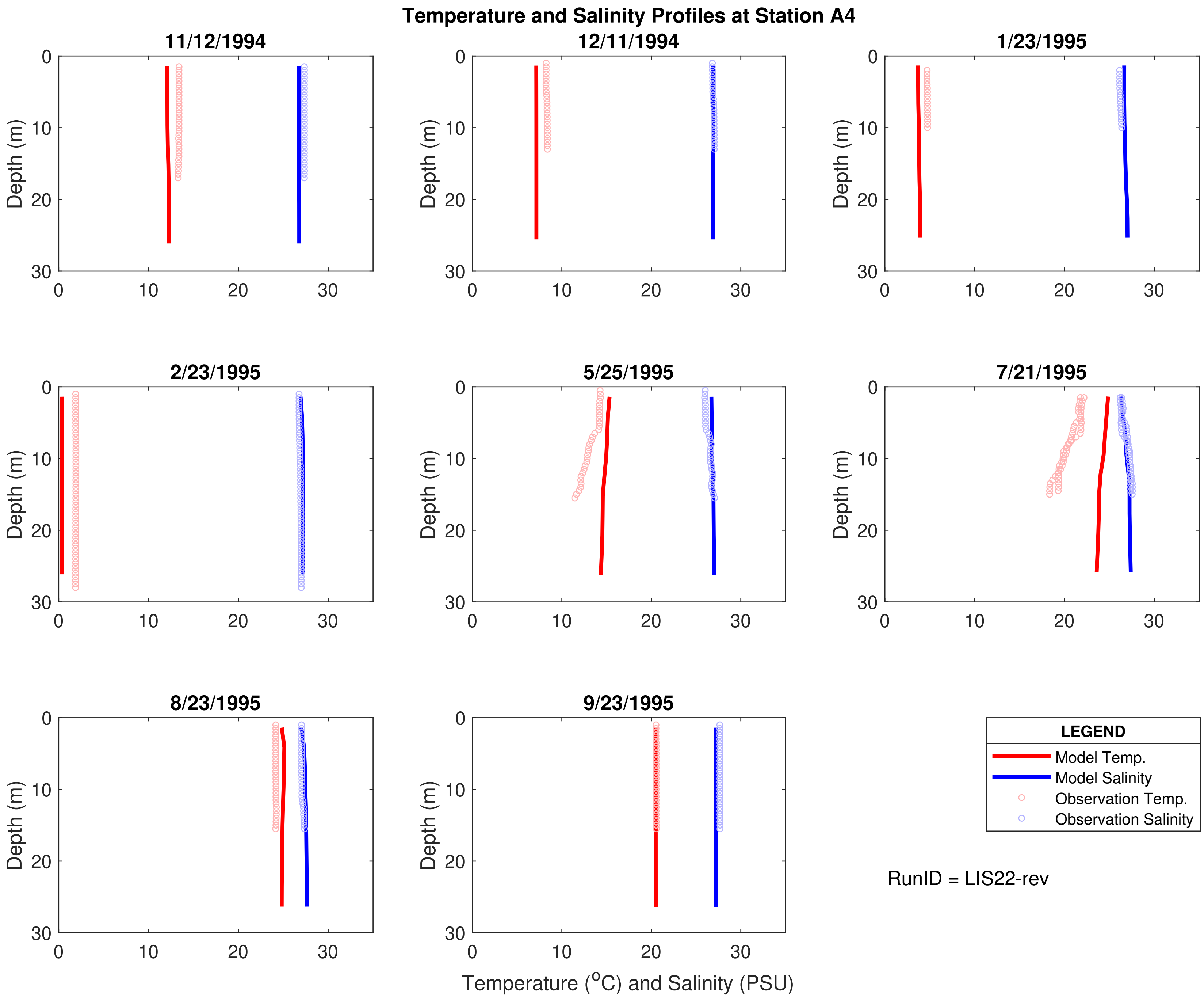
Model Salinity Vs. NYHS Observations
N6
N7
N8
Salinity (PSU)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom



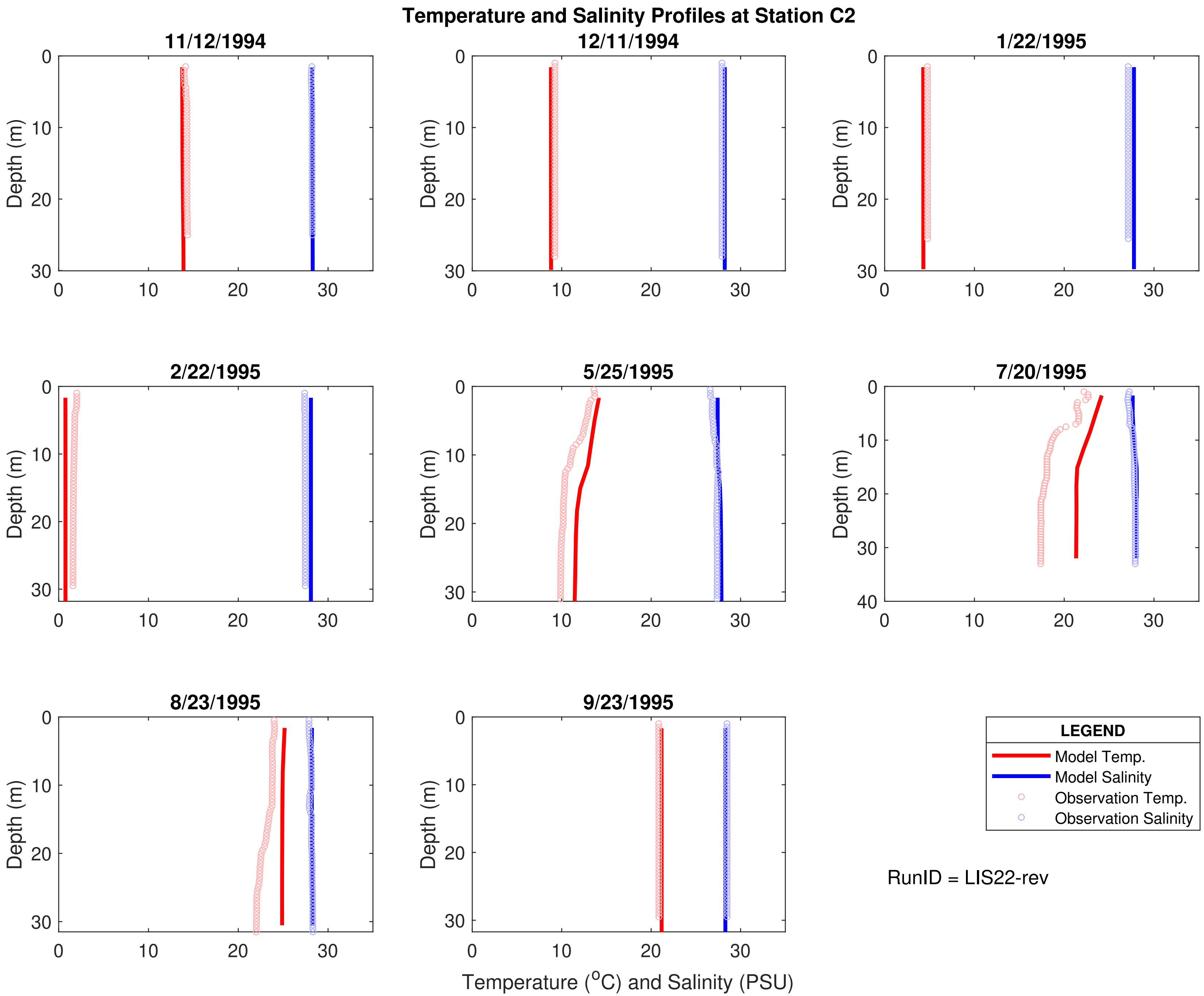
Model Salinity Vs. NYHS Observations
N9
N9A
N16
Salinity (PSU)
0
10
20
30
Oct 1994
Nov 1994
Dec 1994
Jan 1995
Feb 1995
Mar 1995
Apr 1995
May 1995
Jun 1995
Jul 1995
Aug 1995
Sep 1995
Oct 1995
LEGEND
SWEM Surface
SWEM Bottom
Model Surface
Model Bottom
Observation Surface
Obsrvation Bottom

5

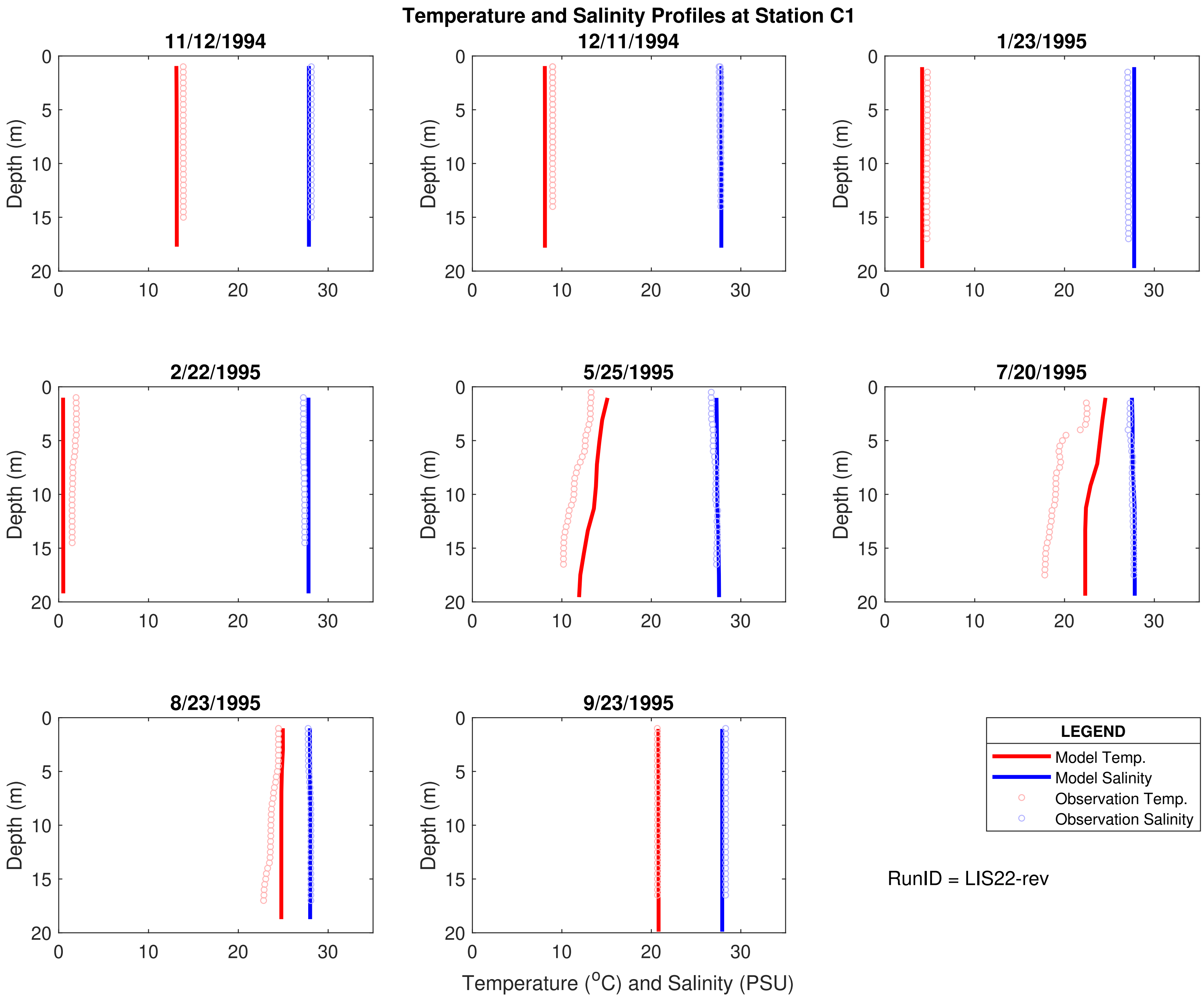
WY95 ROMS Baseline Temperature and Salinity Vertical Profile Comparisons at CTDEEP Stations

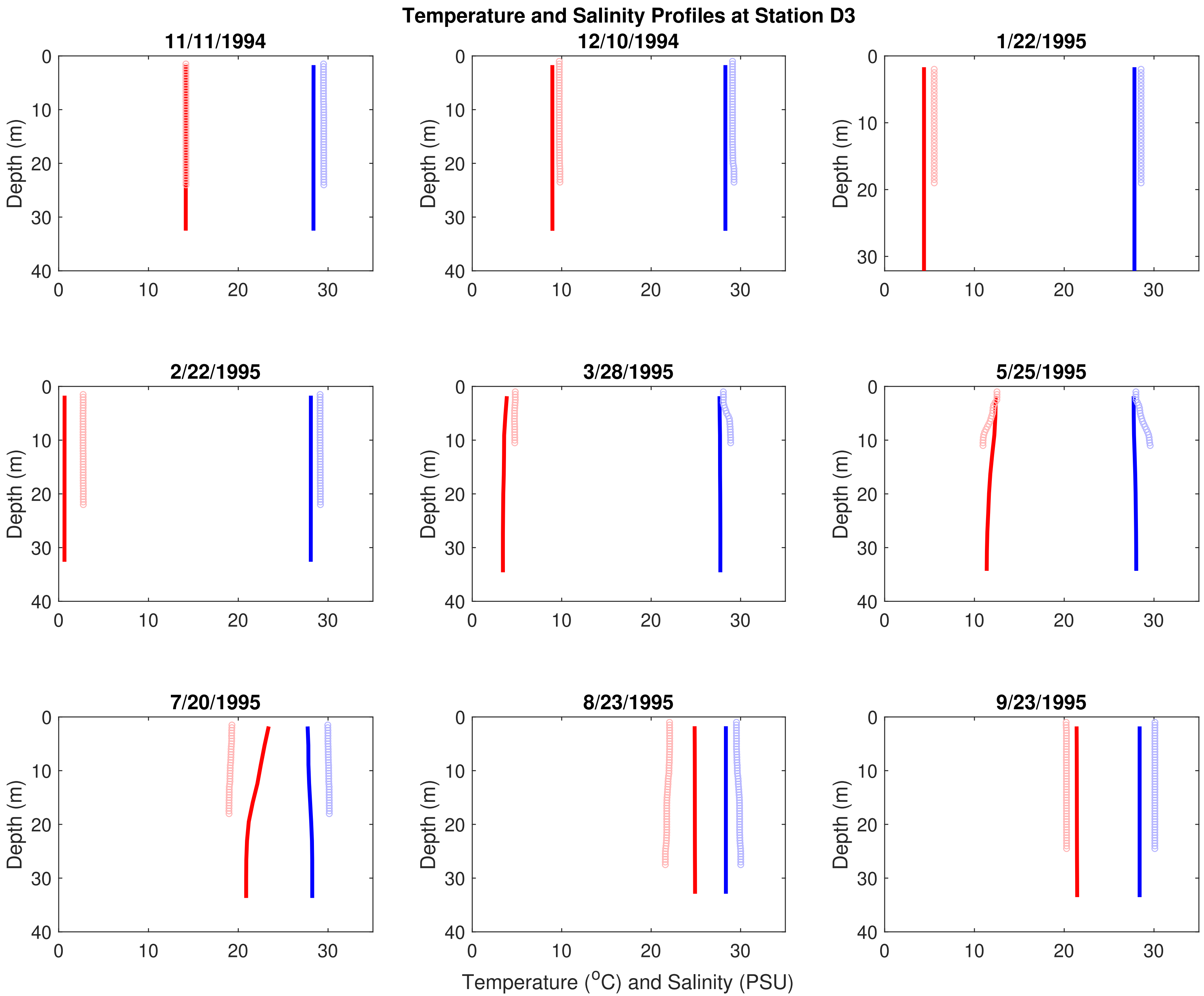


Temperature and Salinity Profiles at Station A4
11/12/1994
12/11/1994
1/23/1995
2/23/1995
5/25/1995
7/21/1995
8/23/1995
9/23/1995
Depth (m)
Temperature (°C) and Salinity (PSU)
LEGEND
Model Temp.
Model Salinity
Observation Temp.
Observation Salinity
RunID = LIS22-rev

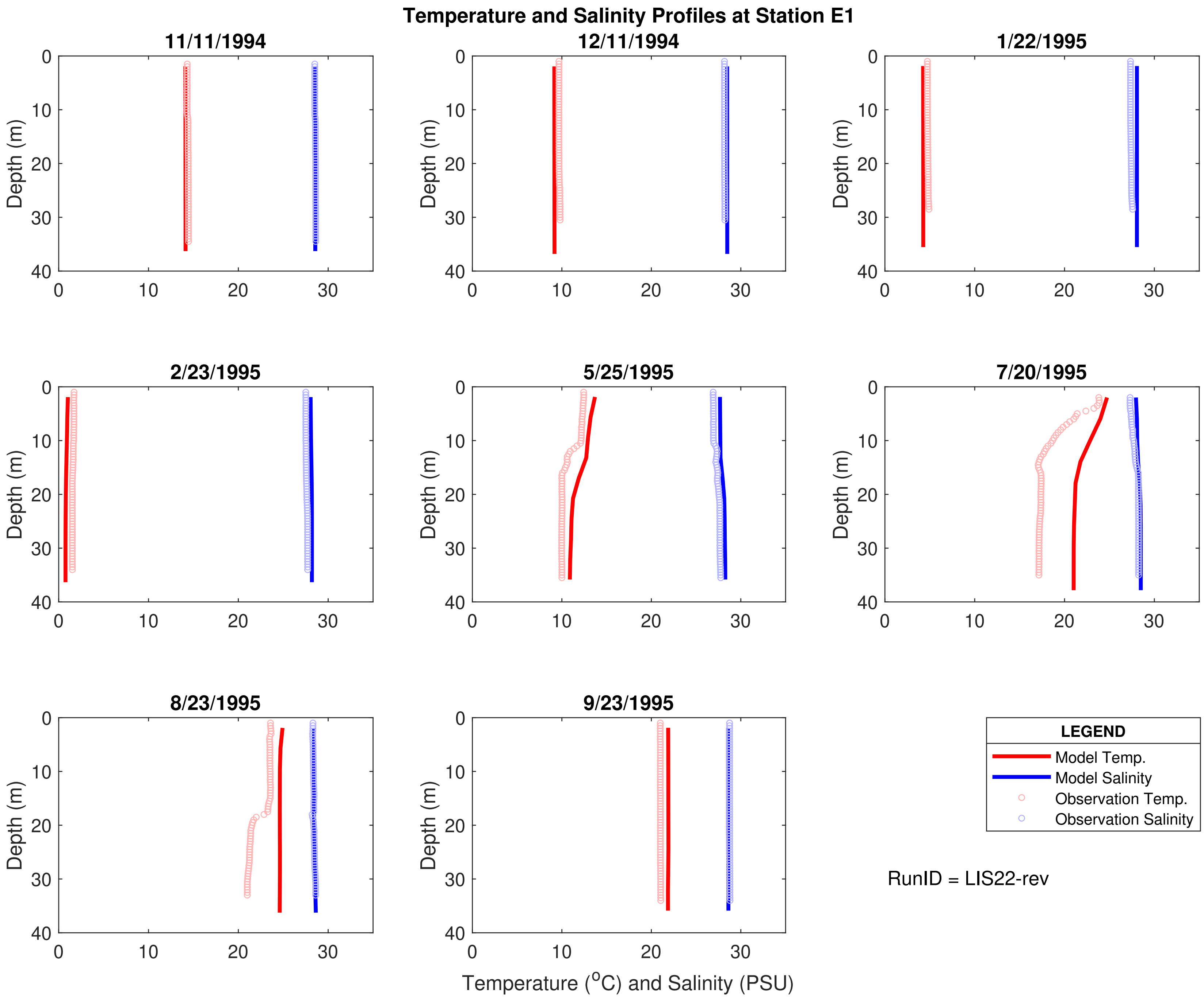


Temperature and Salinity Profiles at Station C2
11/12/1994
12/11/1994
1/22/1995
2/22/1995
5/25/1995
7/20/1995
8/23/1995
9/23/1995
Depth (m)
Temperature (°C) and Salinity (PSU)
LEGEND
Model Temp.
Model Salinity
Observation Temp.
Observation Salinity
RunID = LIS22-rev

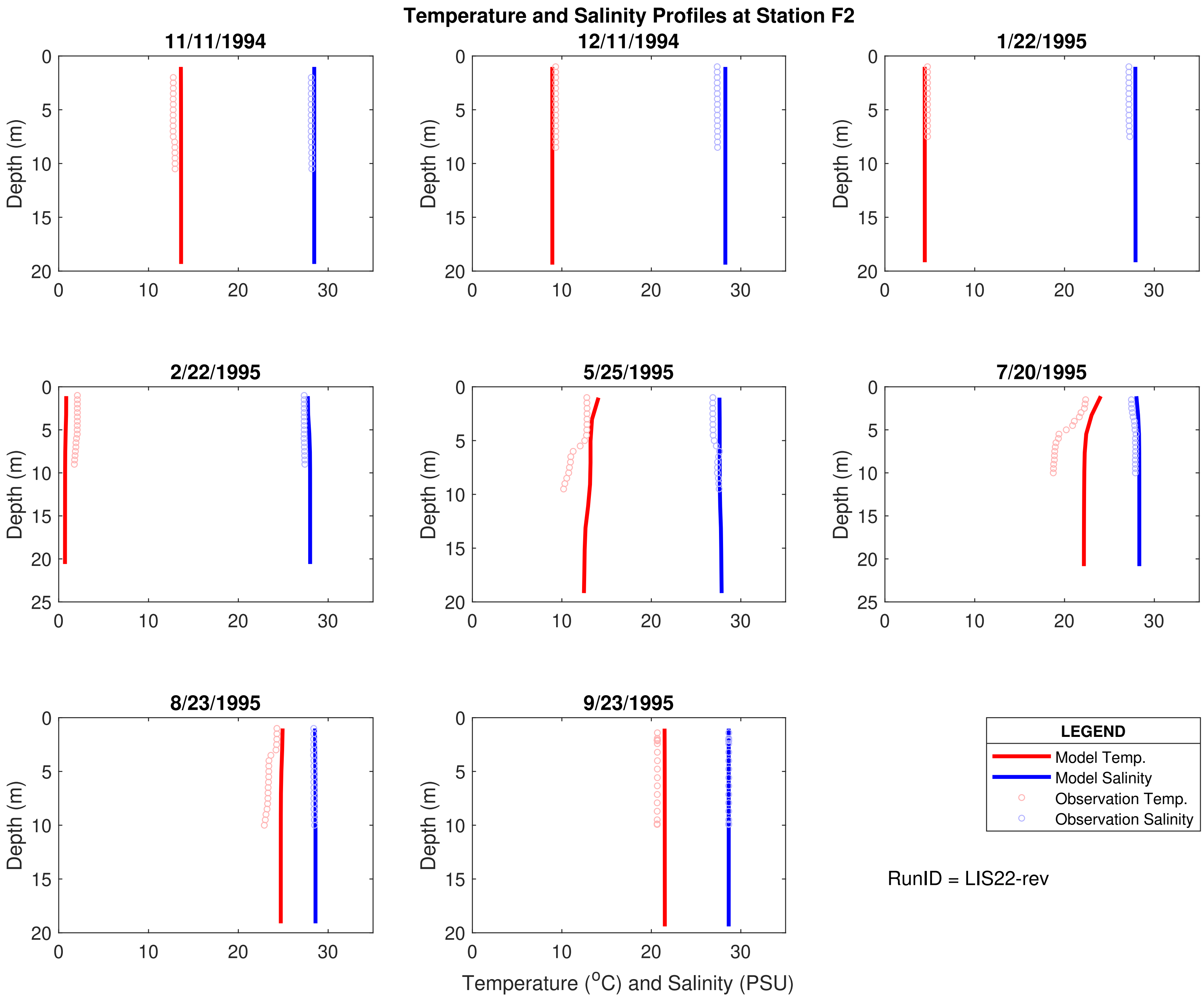

Temperature and Salinity Profiles at Station C1
11/12/1994
12/11/1994
1/23/1995
2/22/1995
5/25/1995
7/20/1995
8/23/1995
9/23/1995
Depth (m)
Temperature (°C) and Salinity (PSU)
LEGEND
Model Temp.
Model Salinity
Observation Temp.
Observation Salinity
RunID = LIS22-rev



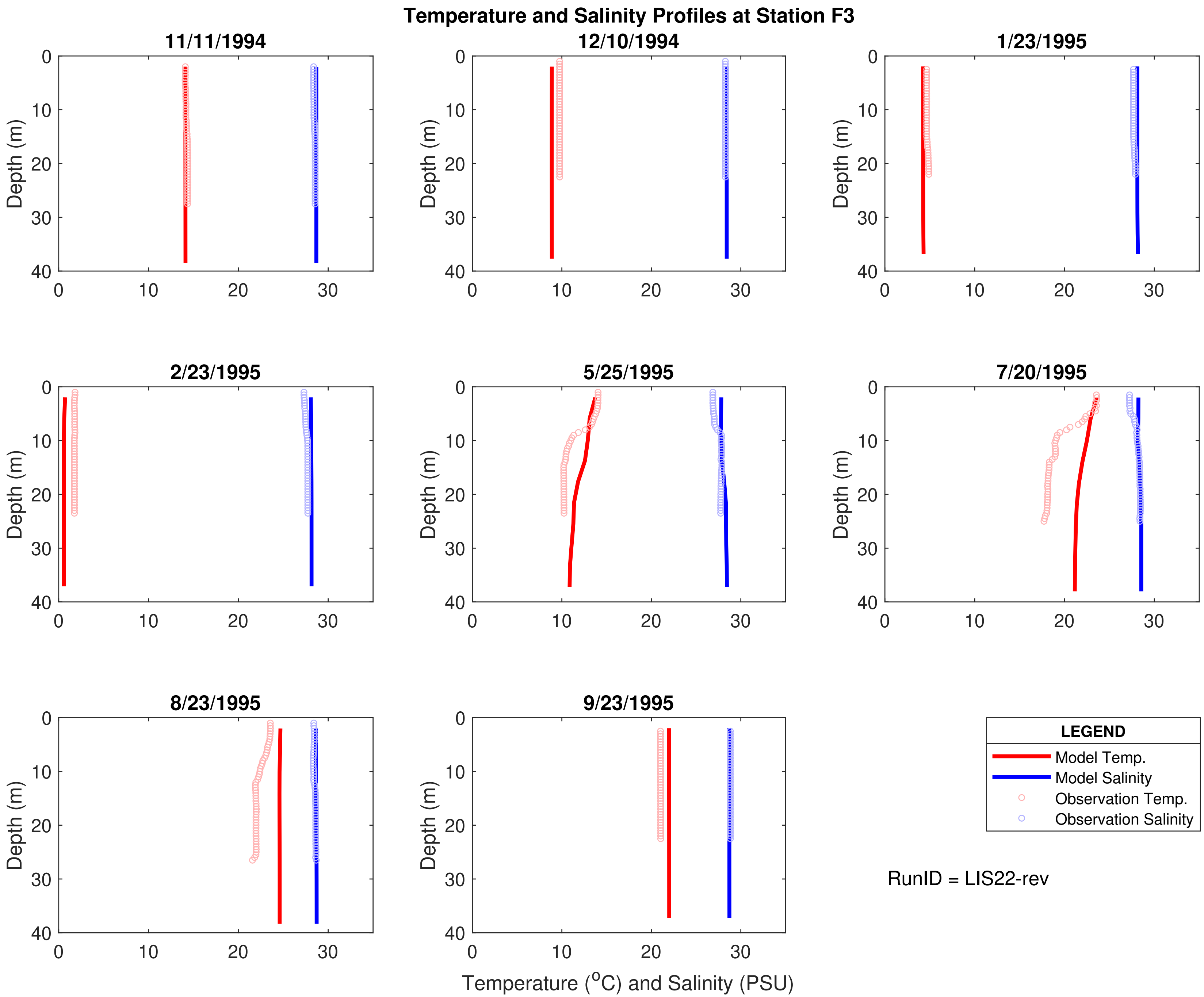
Temperature and Salinity Profiles at Station D3
11/11/1994
12/10/1994
1/22/1995
2/22/1995
3/28/1995
5/25/1995
7/20/1995
8/23/1995
9/23/1995
Depth (m)
0
10
20
30
40
0
10
20
30
Temperature (°C) and Salinity (PSU)



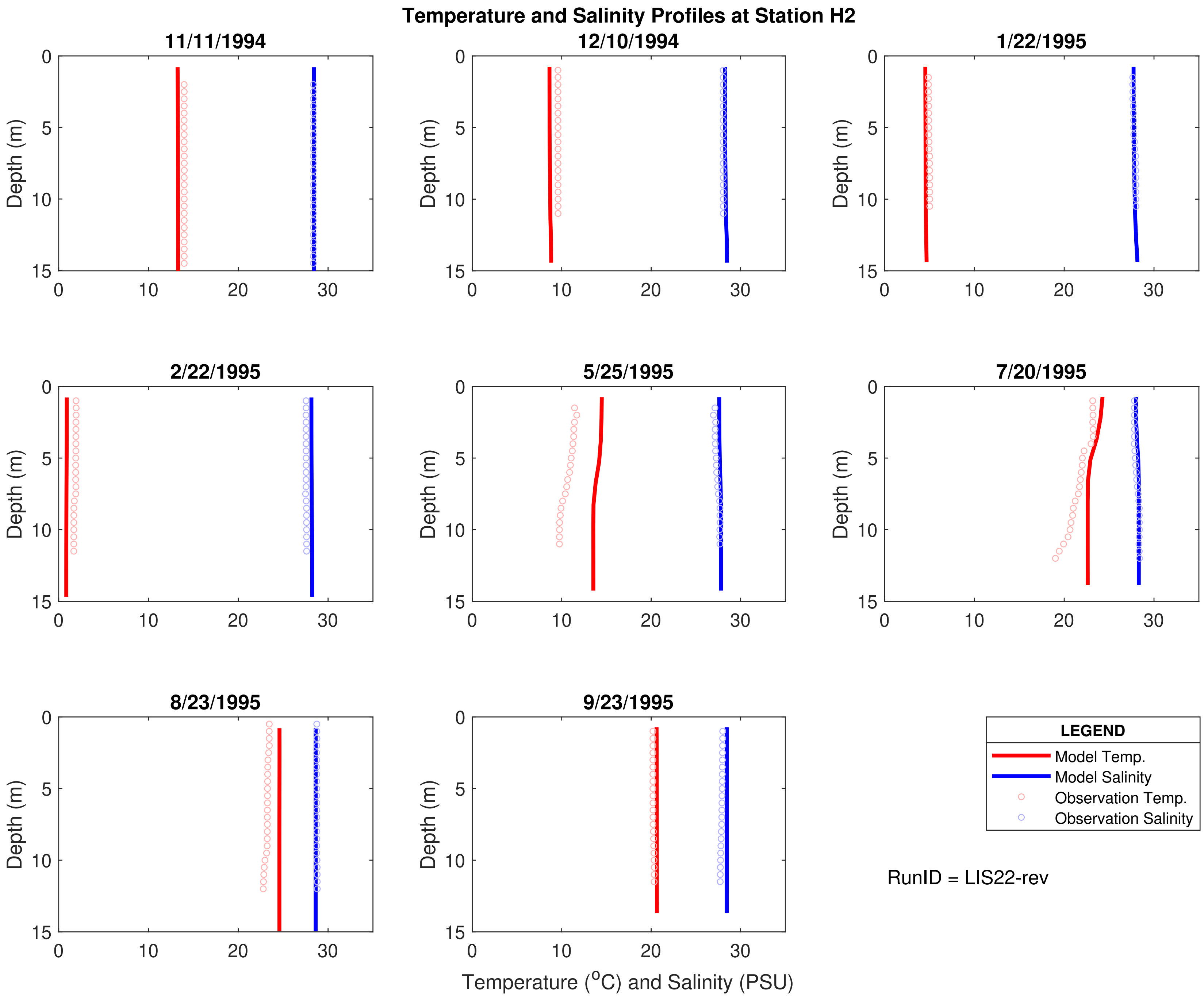
Temperature and Salinity Profiles at Station E1
11/11/1994
12/11/1994
1/22/1995
2/23/1995
5/25/1995
7/20/1995
8/23/1995
9/23/1995
Depth (m)
Temperature (°C) and Salinity (PSU)
LEGEND
Model Temp.
Model Salinity
Observation Temp.
Observation Salinity
RunID = LIS22-rev



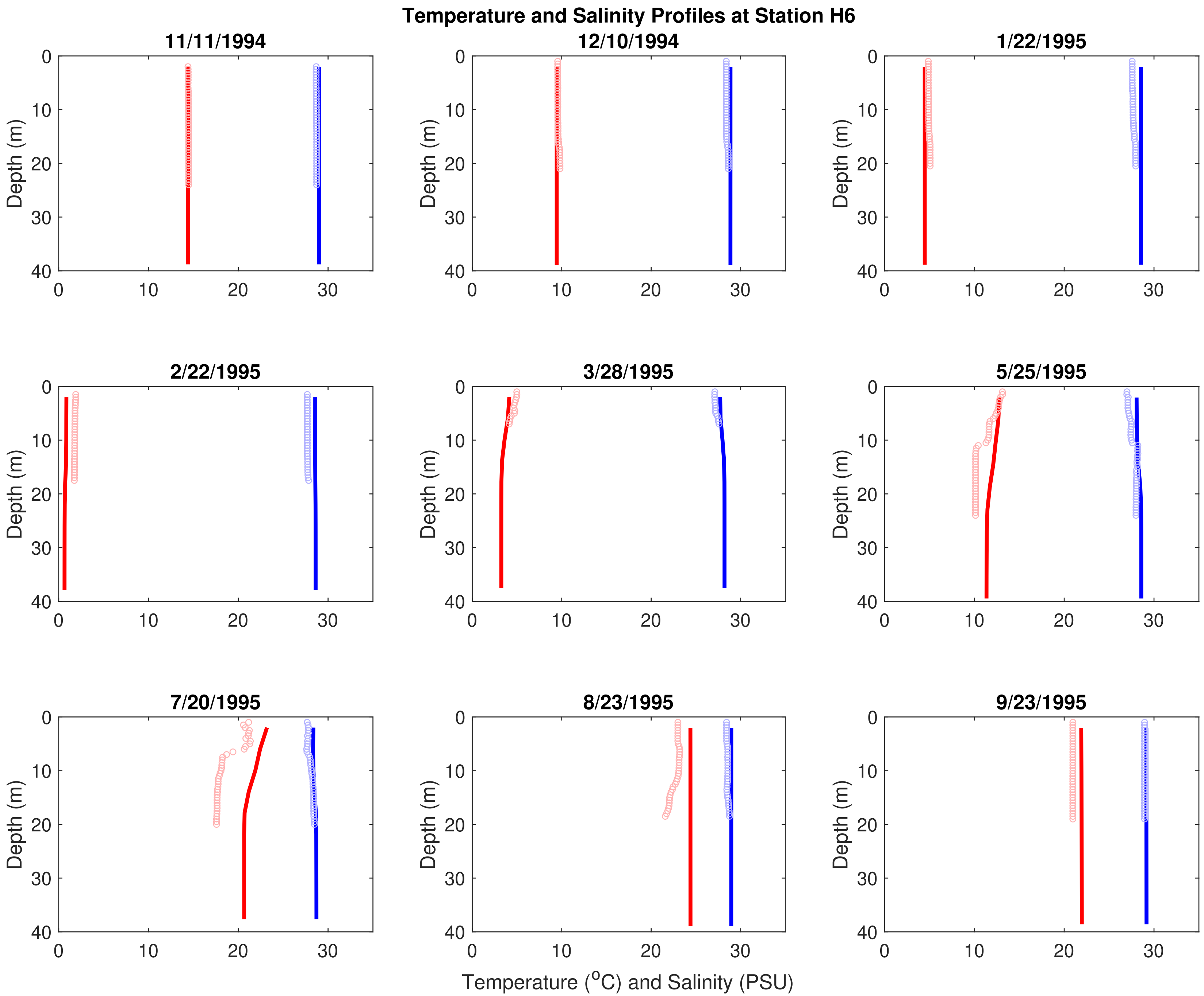
Temperature and Salinity Profiles at Station F2
11/11/1994
12/11/1994
1/22/1995
2/22/1995
5/25/1995
7/20/1995
8/23/1995
9/23/1995
Depth (m)
Temperature (°C) and Salinity (PSU)
LEGEND
Model Temp.
Model Salinity
Observation Temp.
Observation Salinity
RunID = LIS22-rev

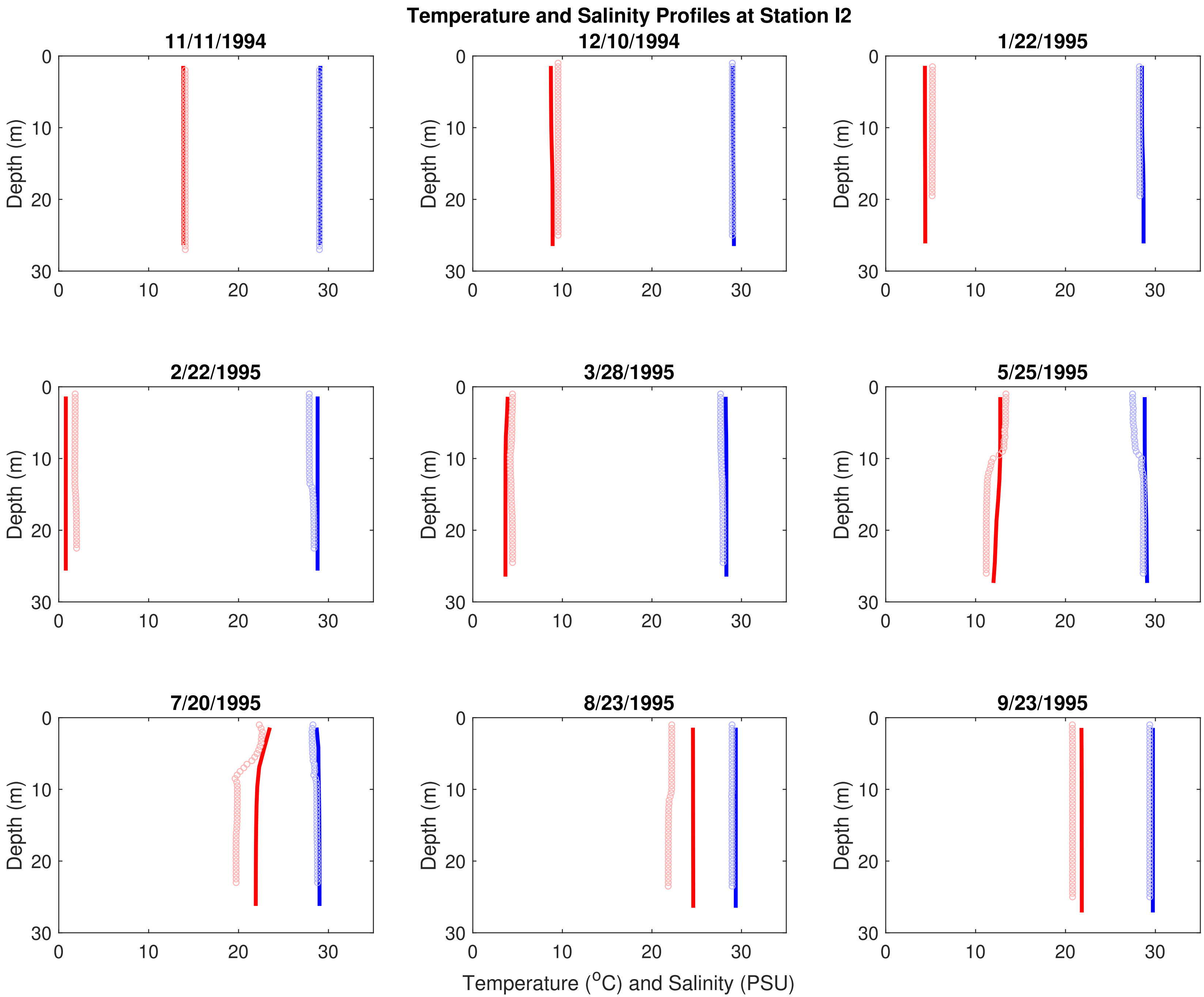


Temperature and Salinity Profiles at Station F3
11/11/1994
12/10/1994
1/23/1995
2/23/1995
5/25/1995
7/20/1995
8/23/1995
9/23/1995
Depth (m)
Temperature (°C) and Salinity (PSU)
LEGEND
Model Temp.
Model Salinity
Observation Temp.
Observation Salinity
RunID = LIS22-rev

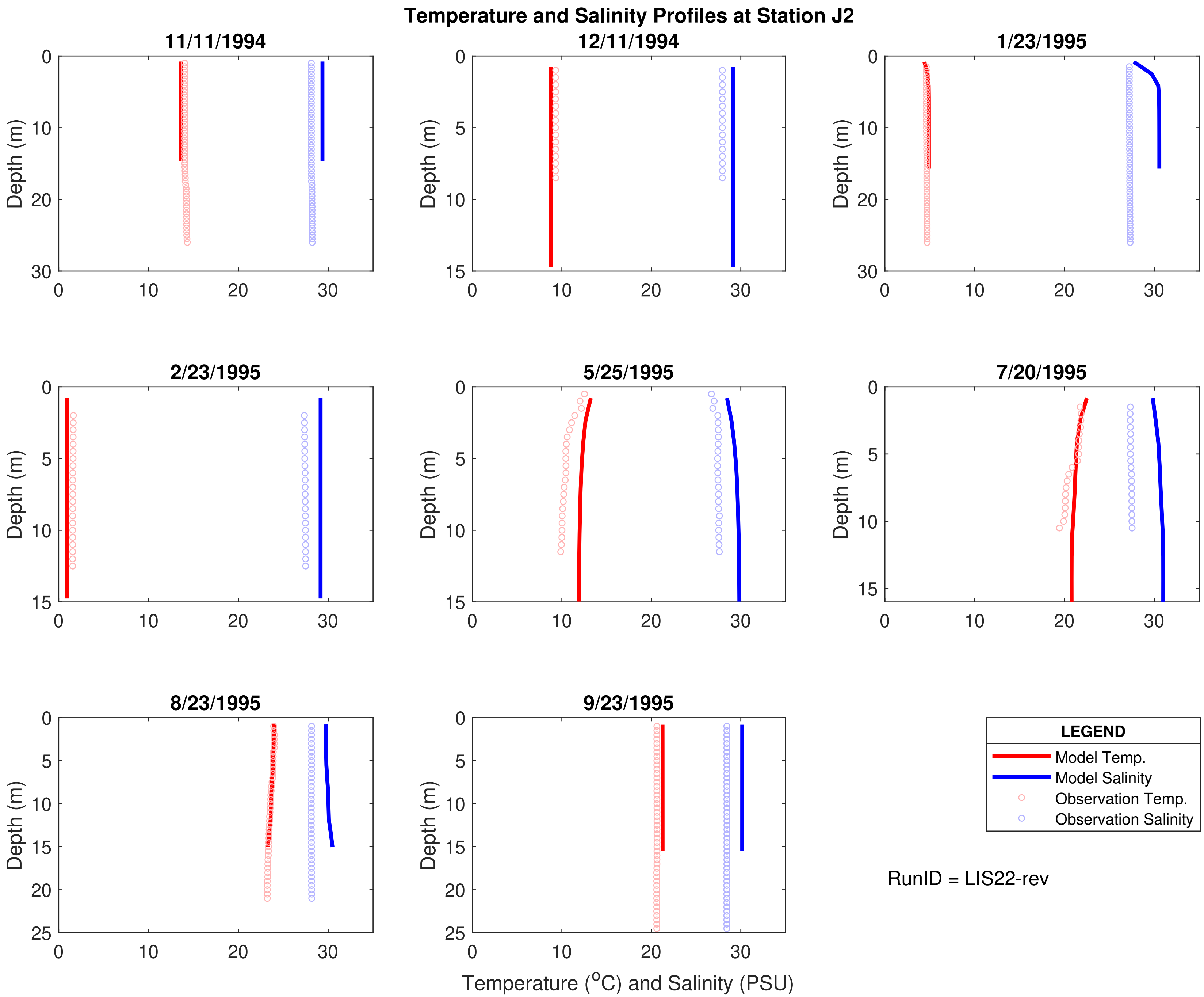


Temperature and Salinity Profiles at Station H2
11/11/1994
12/10/1994
1/22/1995
2/22/1995
5/25/1995
7/20/1995
8/23/1995
9/23/1995
Depth (m)
0
5
10
15
0
10
20
30
Temperature (°C) and Salinity (PSU)
LEGEND
Model Temp.
Model Salinity
Observation Temp.
Observation Salinity
RunID = LIS22-rev

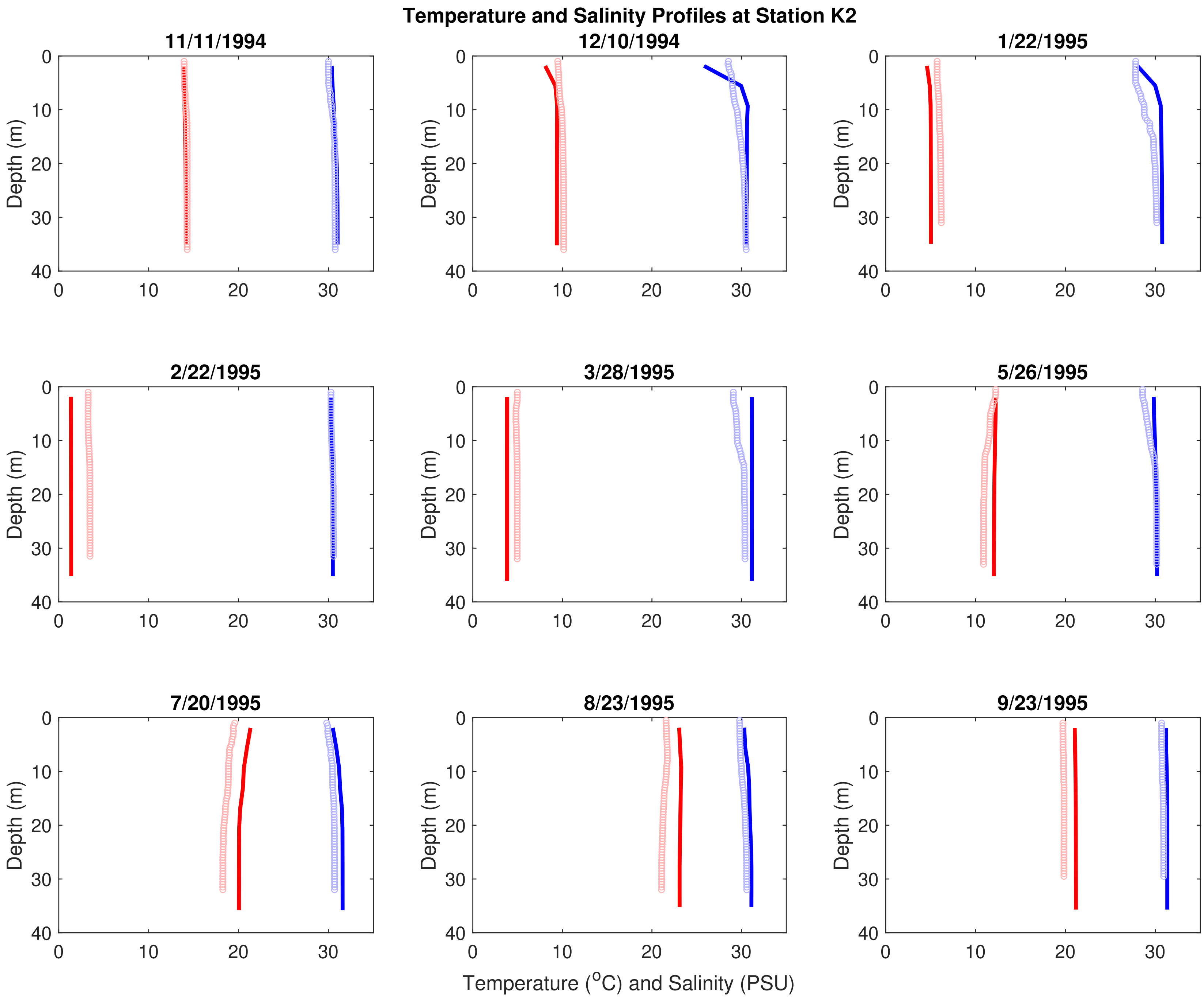

Temperature and Salinity Profiles at Station H6
11/11/1994
12/10/1994
1/22/1995
2/22/1995
3/28/1995
5/25/1995
7/20/1995
8/23/1995
9/23/1995
Depth (m)
Temperature (°C) and Salinity (PSU)

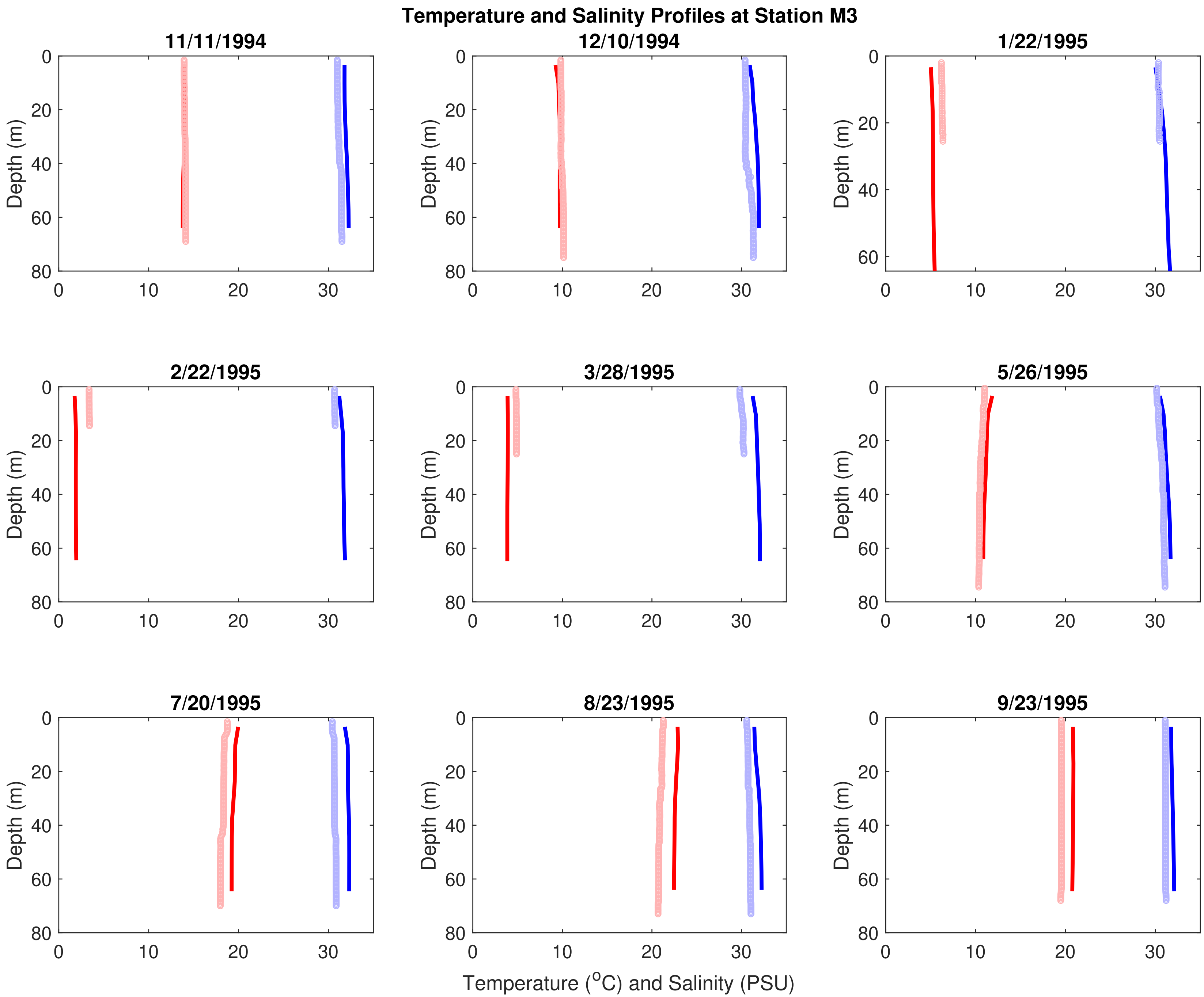


Temperature and Salinity Profiles at Station I2
11/11/1994
12/10/1994
1/22/1995
2/22/1995
3/28/1995
5/25/1995
7/20/1995
8/23/1995
9/23/1995
Depth (m)
0
10
20
30
Temperature (°C) and Salinity (PSU)



Temperature and Salinity Profiles at Station J2
11/11/1994
12/11/1994
1/23/1995
2/23/1995
5/25/1995
7/20/1995
8/23/1995
9/23/1995
Depth (m)
Temperature (°C) and Salinity (PSU)
LEGEND
Model Temp.
Model Salinity
Observation Temp.
Observation Salinity
RunID = LIS22-rev


Temperature and Salinity Profiles at Station K2
11/11/1994
12/10/1994
1/22/1995
2/22/1995
3/28/1995
5/26/1995
7/20/1995
8/23/1995
9/23/1995
Depth (m)
Temperature (°C) and Salinity (PSU)


Temperature and Salinity Profiles at Station M3
11/11/1994
12/10/1994
1/22/1995
2/22/1995
3/28/1995
5/26/1995
7/20/1995
8/23/1995
9/23/1995
Depth (m)
Temperature (°C) and Salinity (PSU)

6a

ROMS Vertical Closure Scheme Sensitivity

(k-epsilon vs. k-kl)

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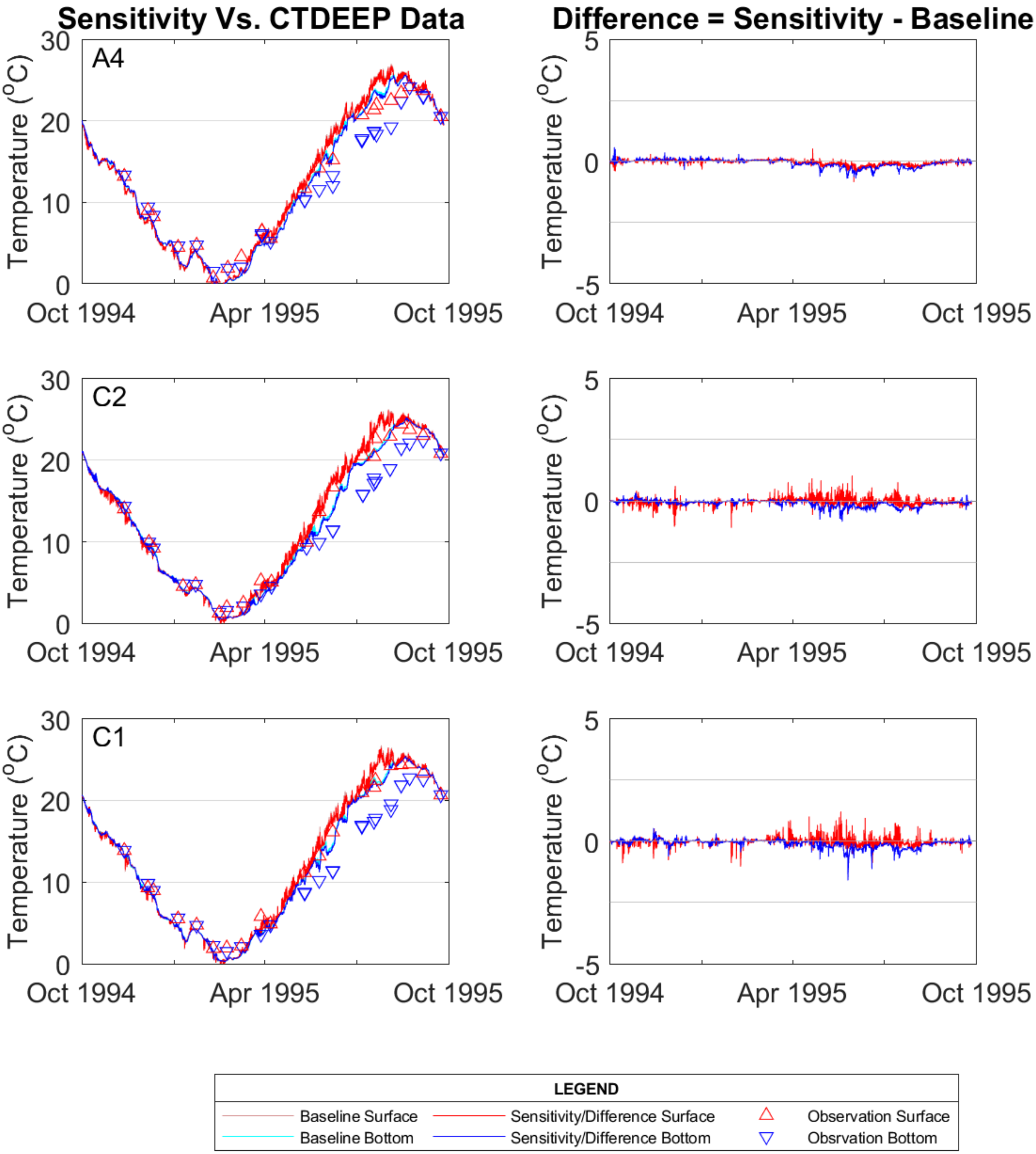
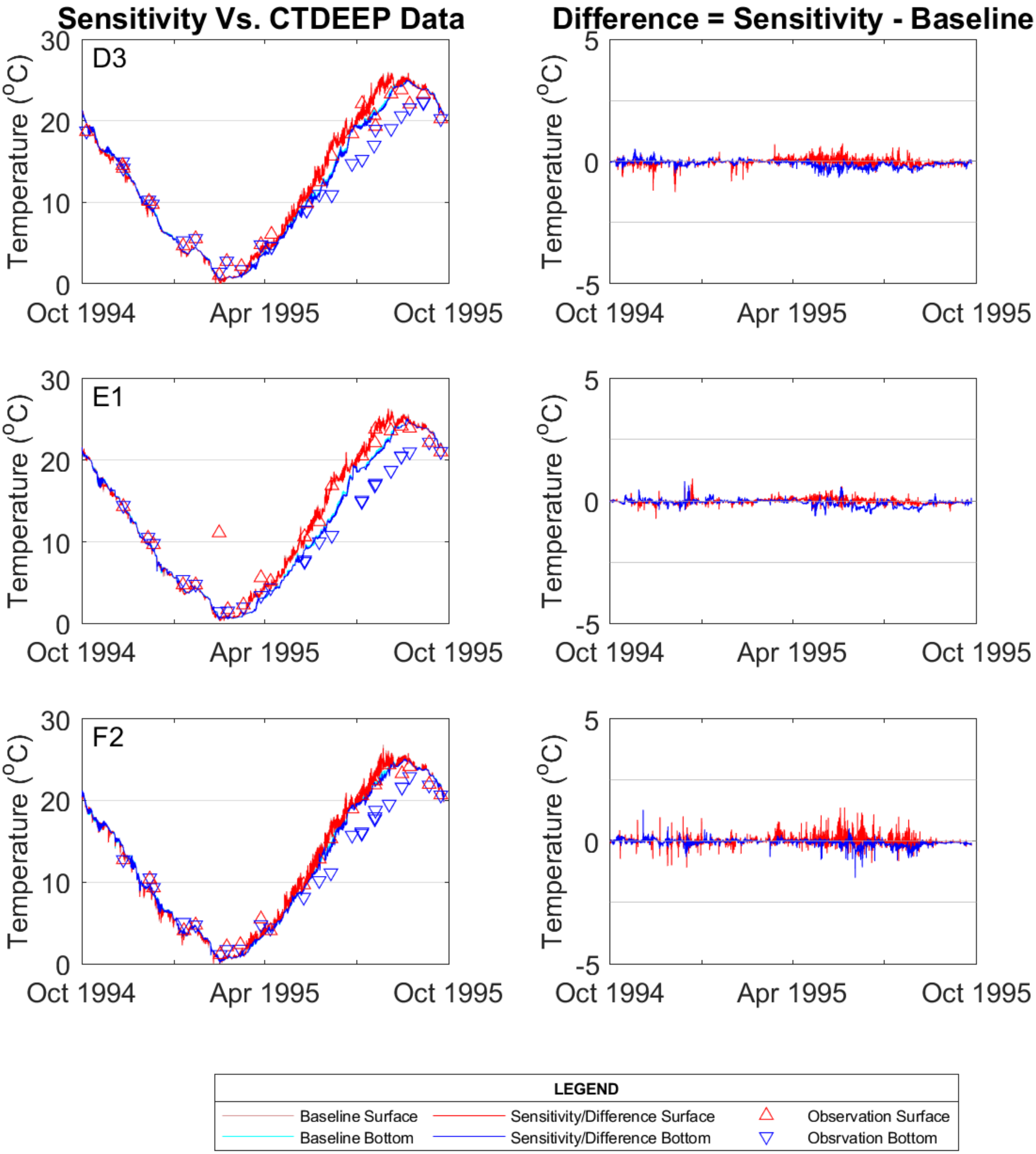
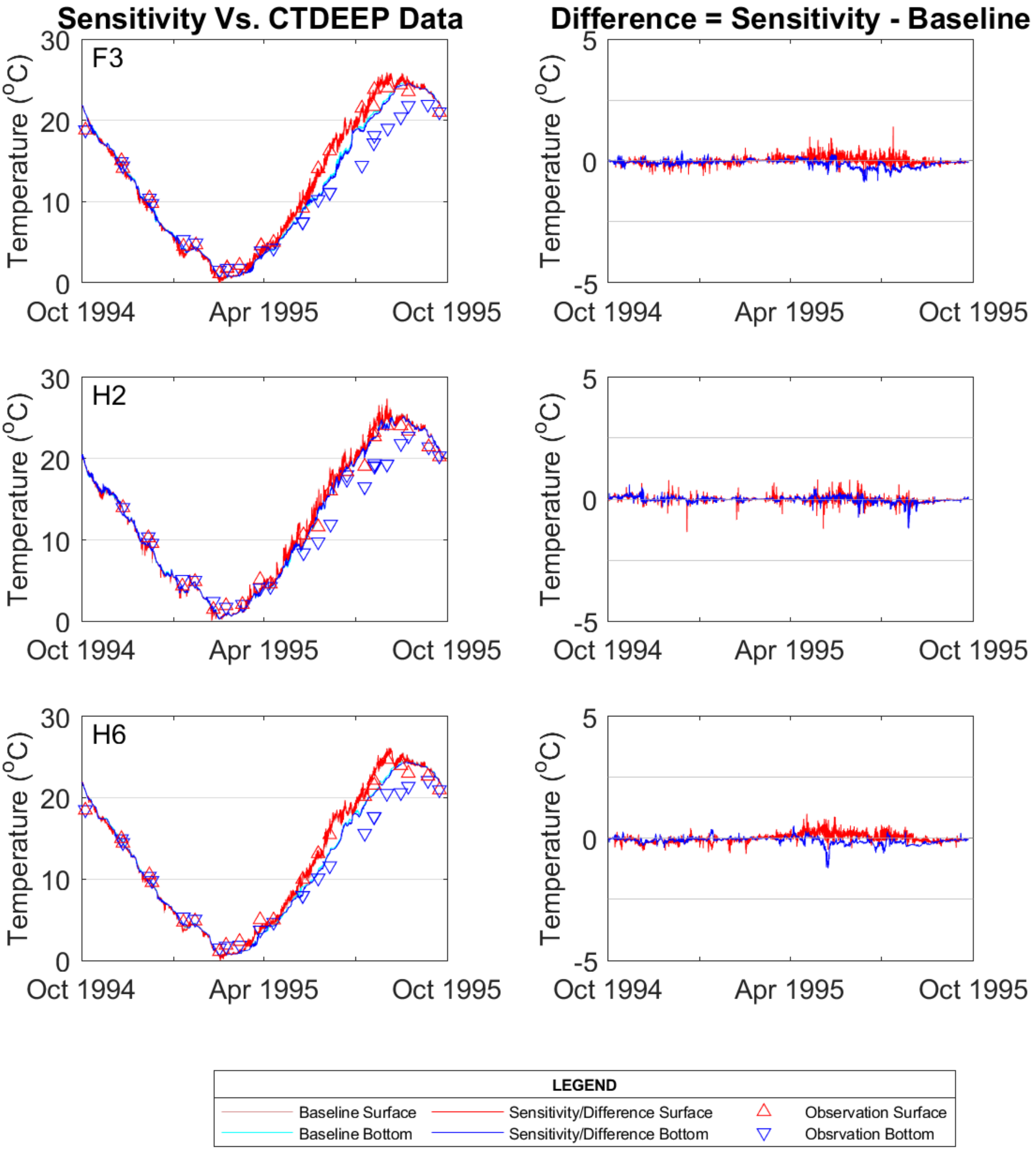


Baseline = k-epsilon Turbulent Closure

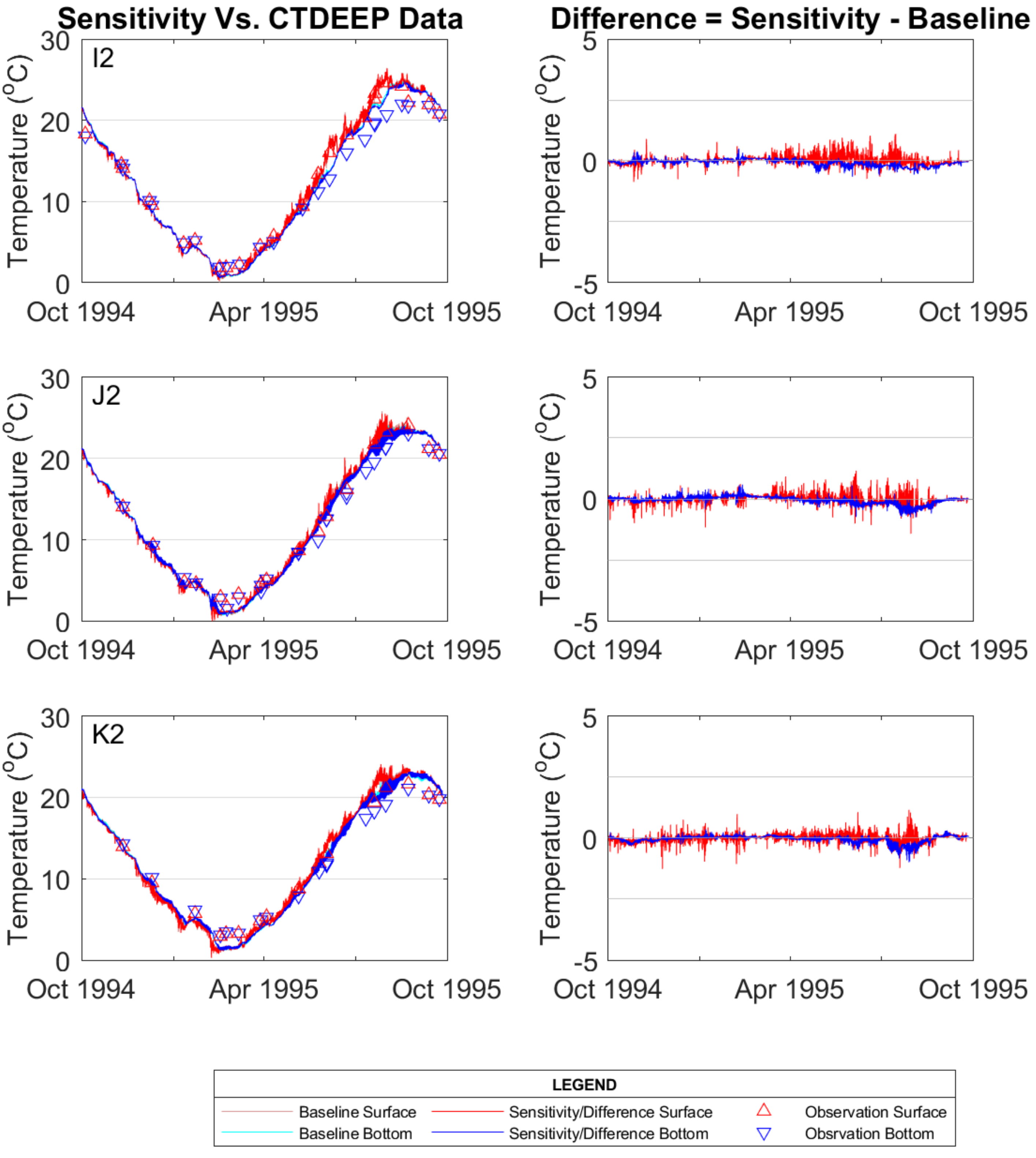
Sensitivity = k-kl Turbulent Closure



Baseline = k-epsilon Turbulent Closure
Sensitivity = k-kl Turbulent Closure

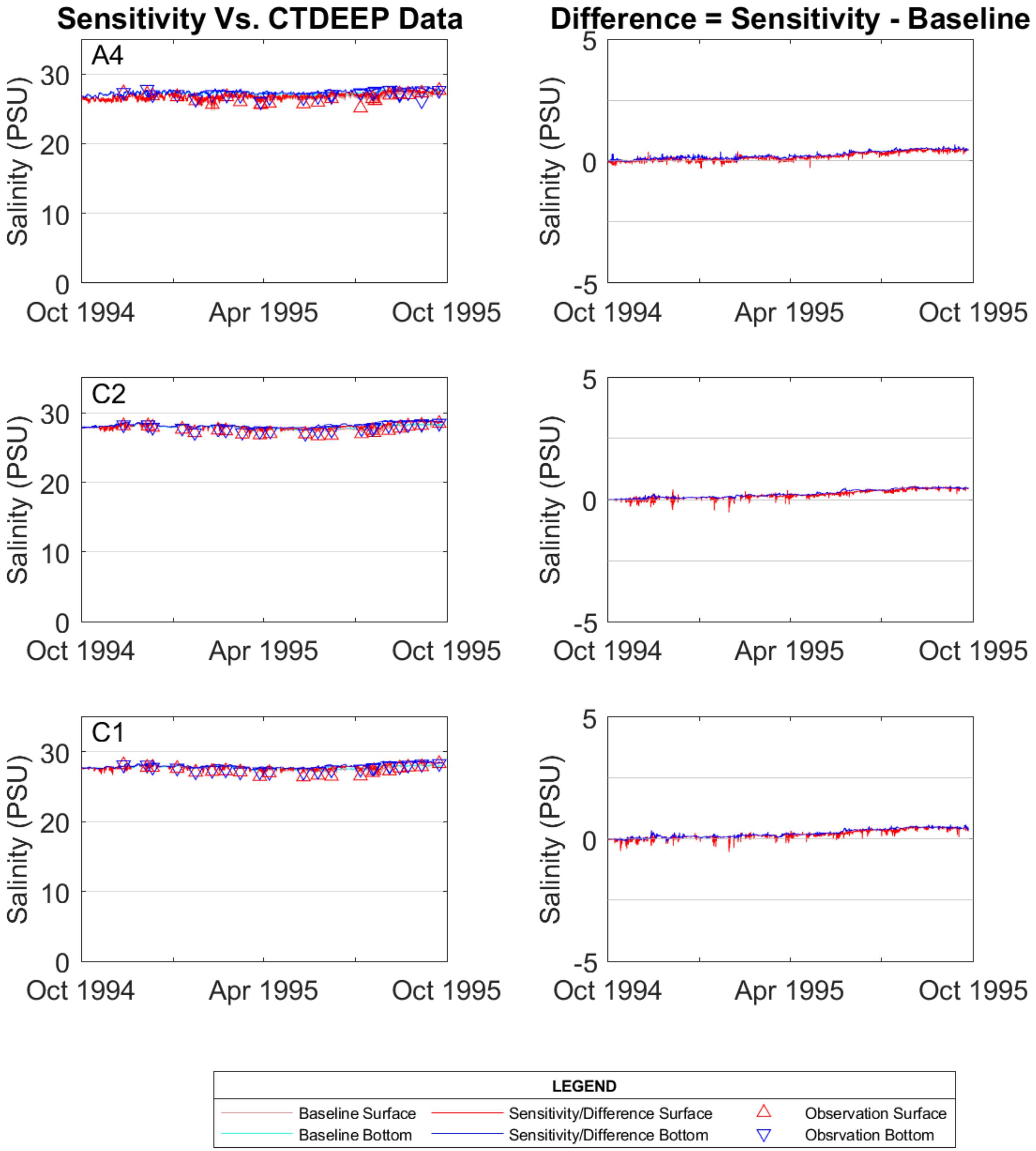


Baseline = k-epsilon Turbulent Closure
Sensitivity = k-kl Turbulent Closure



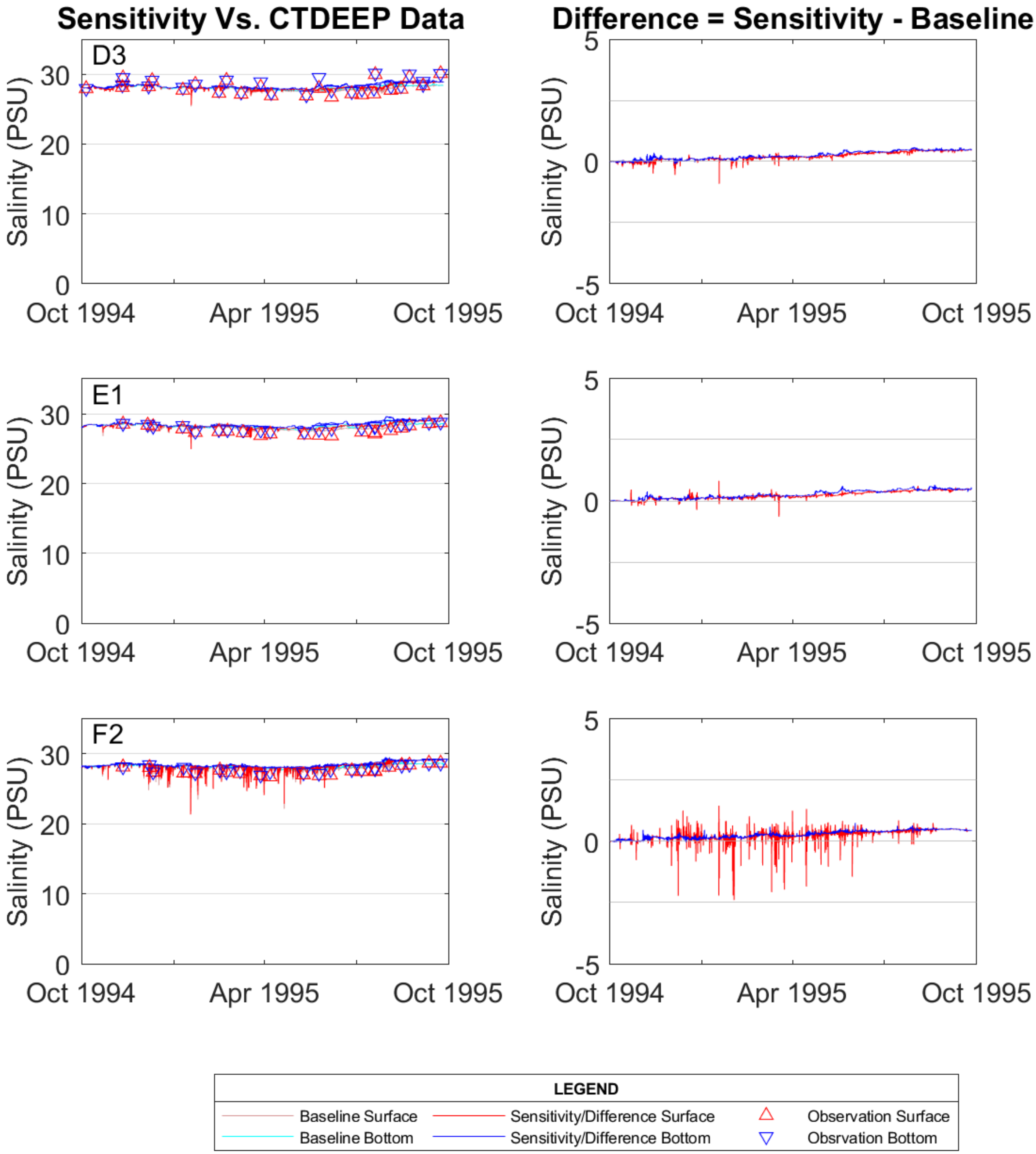
Baseline = k-epsilon Turbulent Closure

Sensitivity = k-kl Turbulent Closure



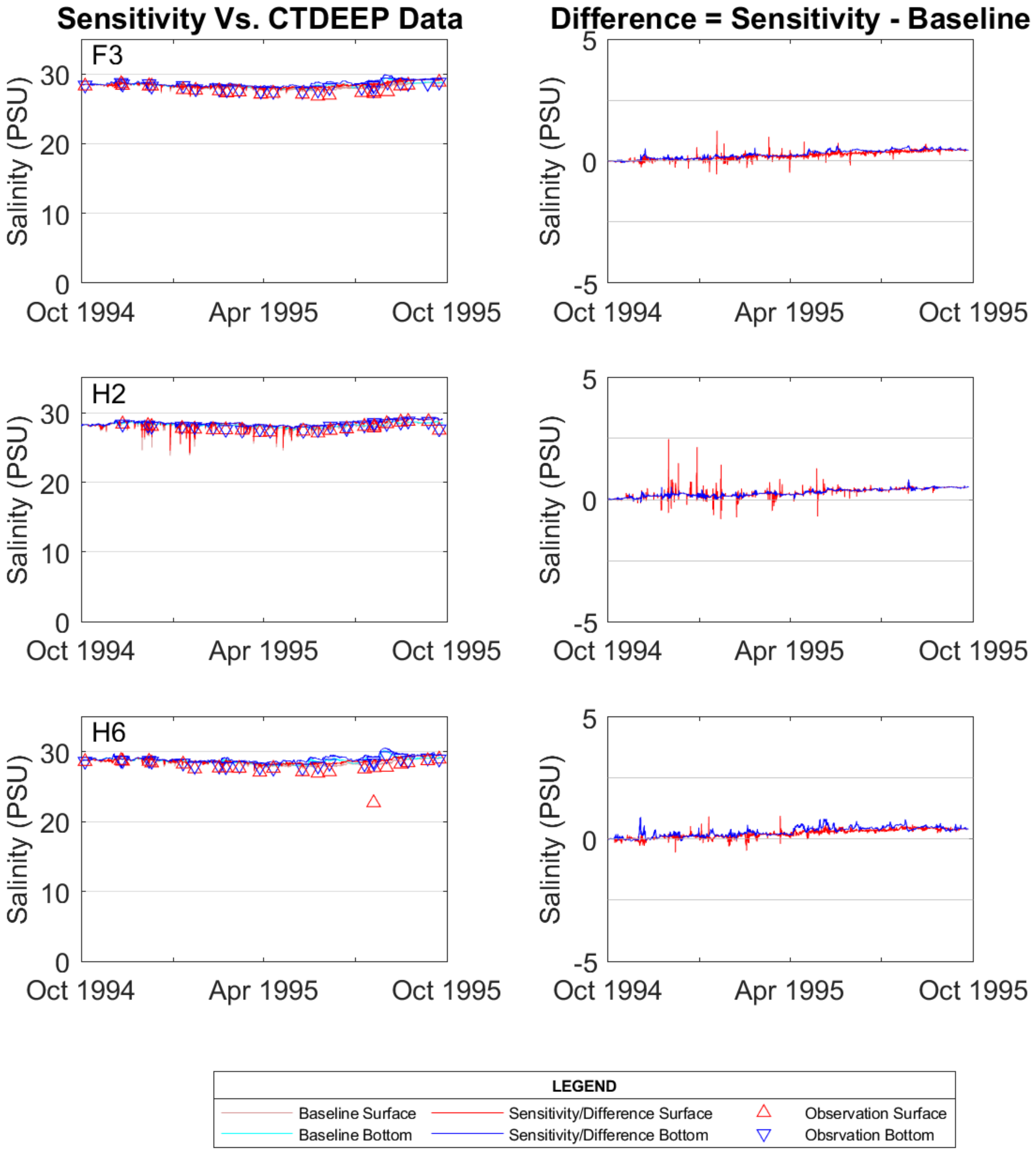
Baseline = k-epsilon Turbulent Closure

Sensitivity = k-kl Turbulent Closure

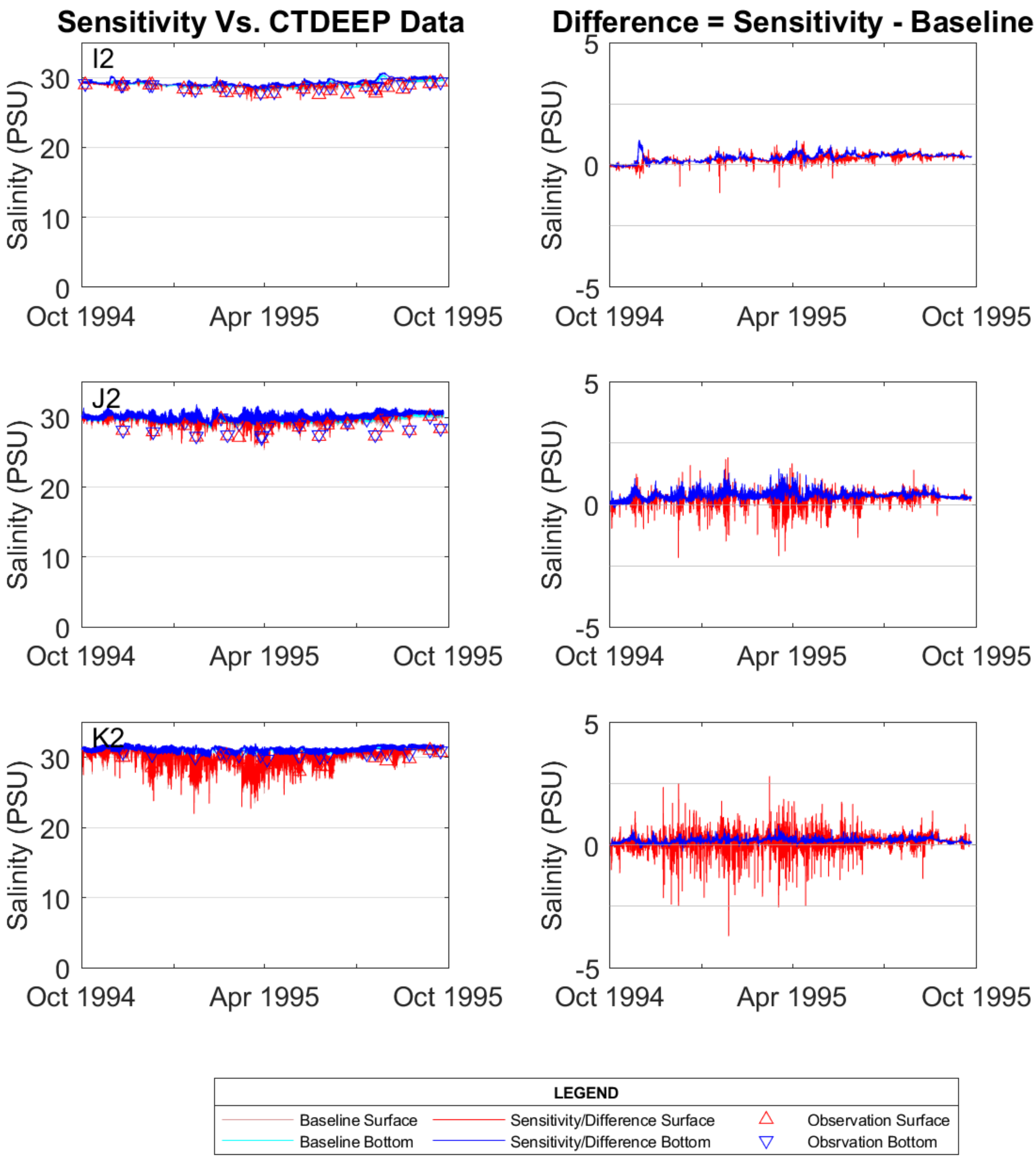


Baseline = k-epsilon Turbulent Closure

Sensitivity = k-kl Turbulent Closure



Baseline = k-epsilon Turbulent Closure
Sensitivity = k-kl Turbulent Closure

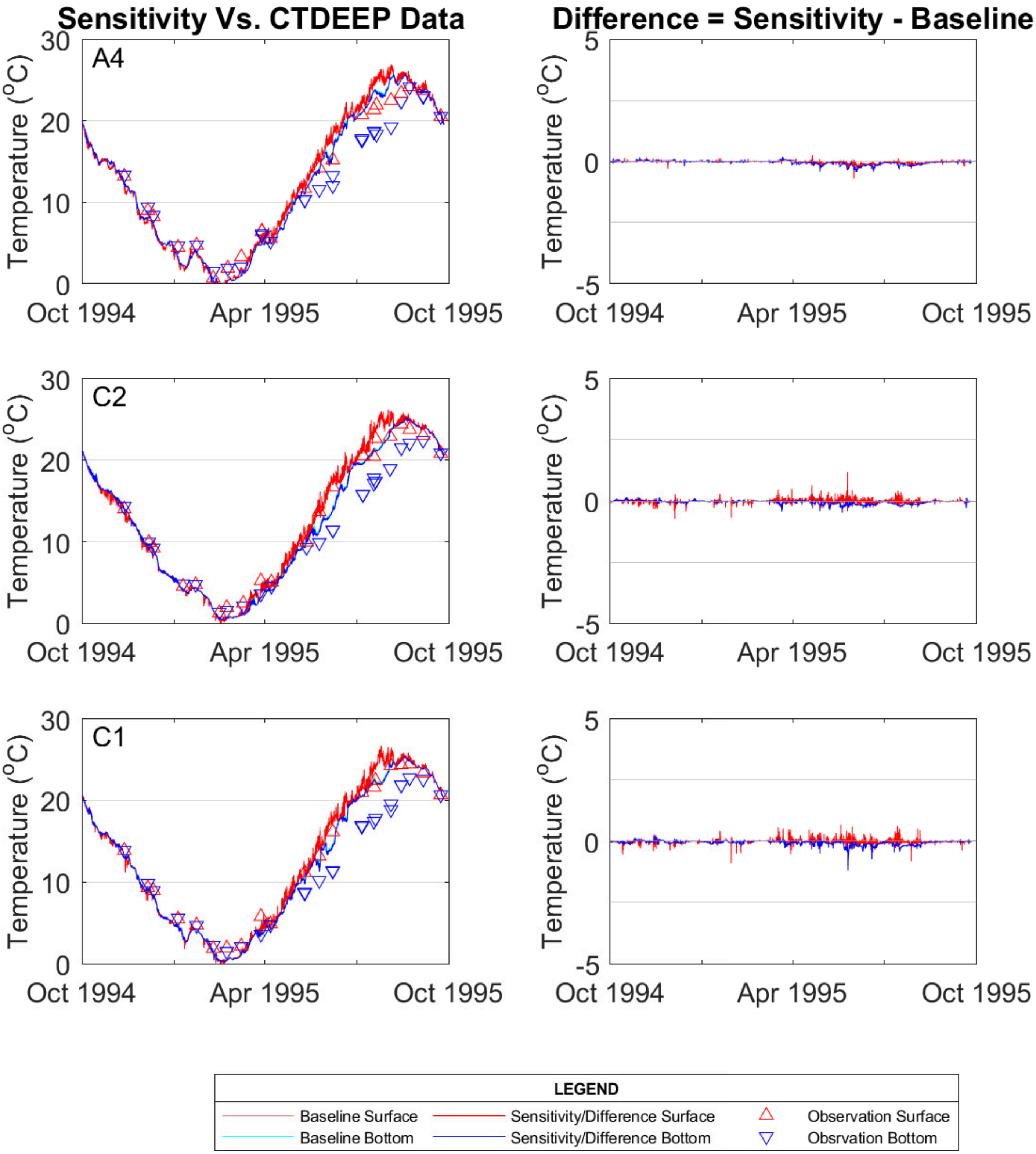


Baseline = k-epsilon Turbulent Closure
Sensitivity = k-kl Turbulent Closure

6b

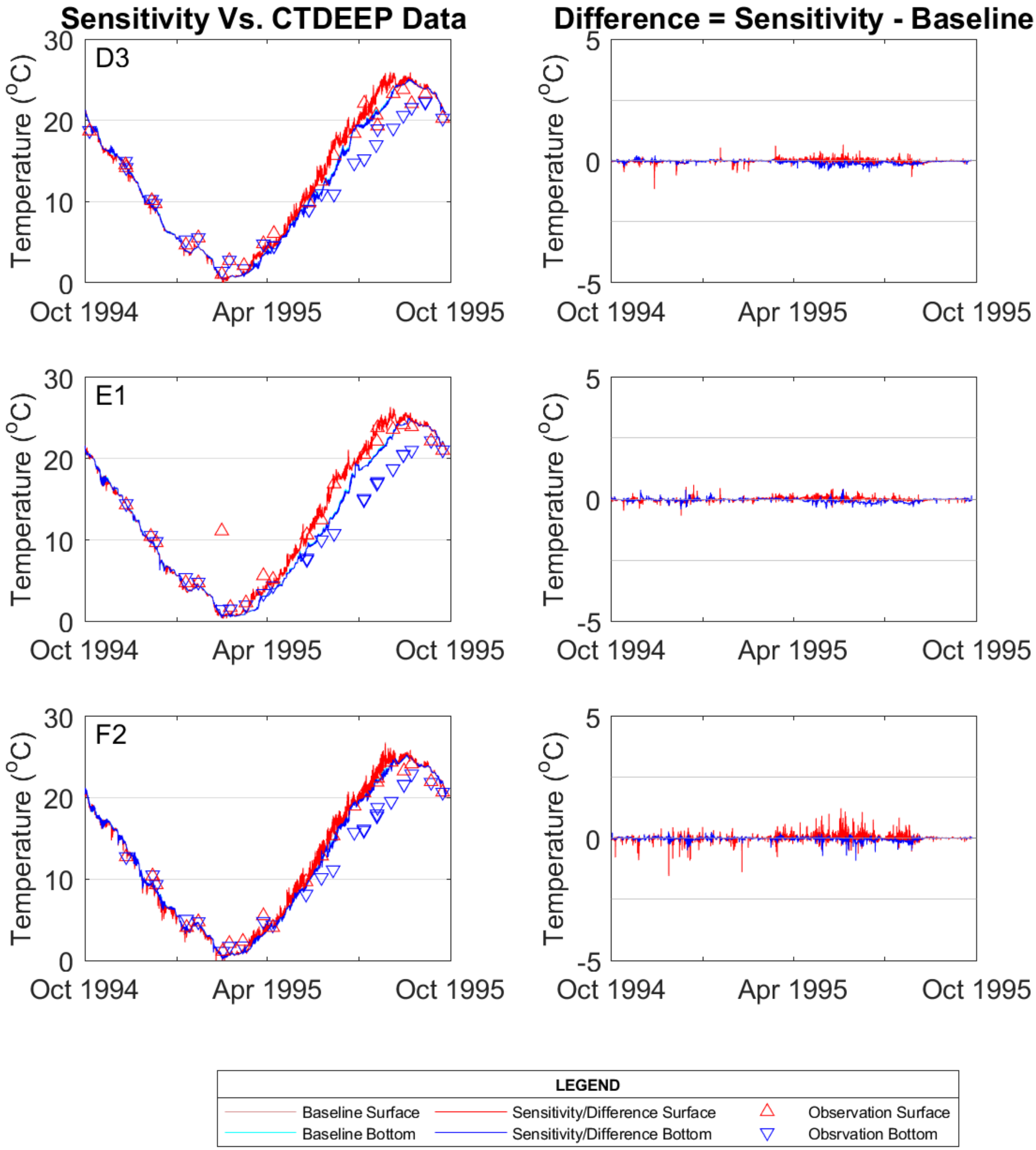
ROMS Vertical Closure Scheme Sensitivity

(k-epsilon vs. k-omega)

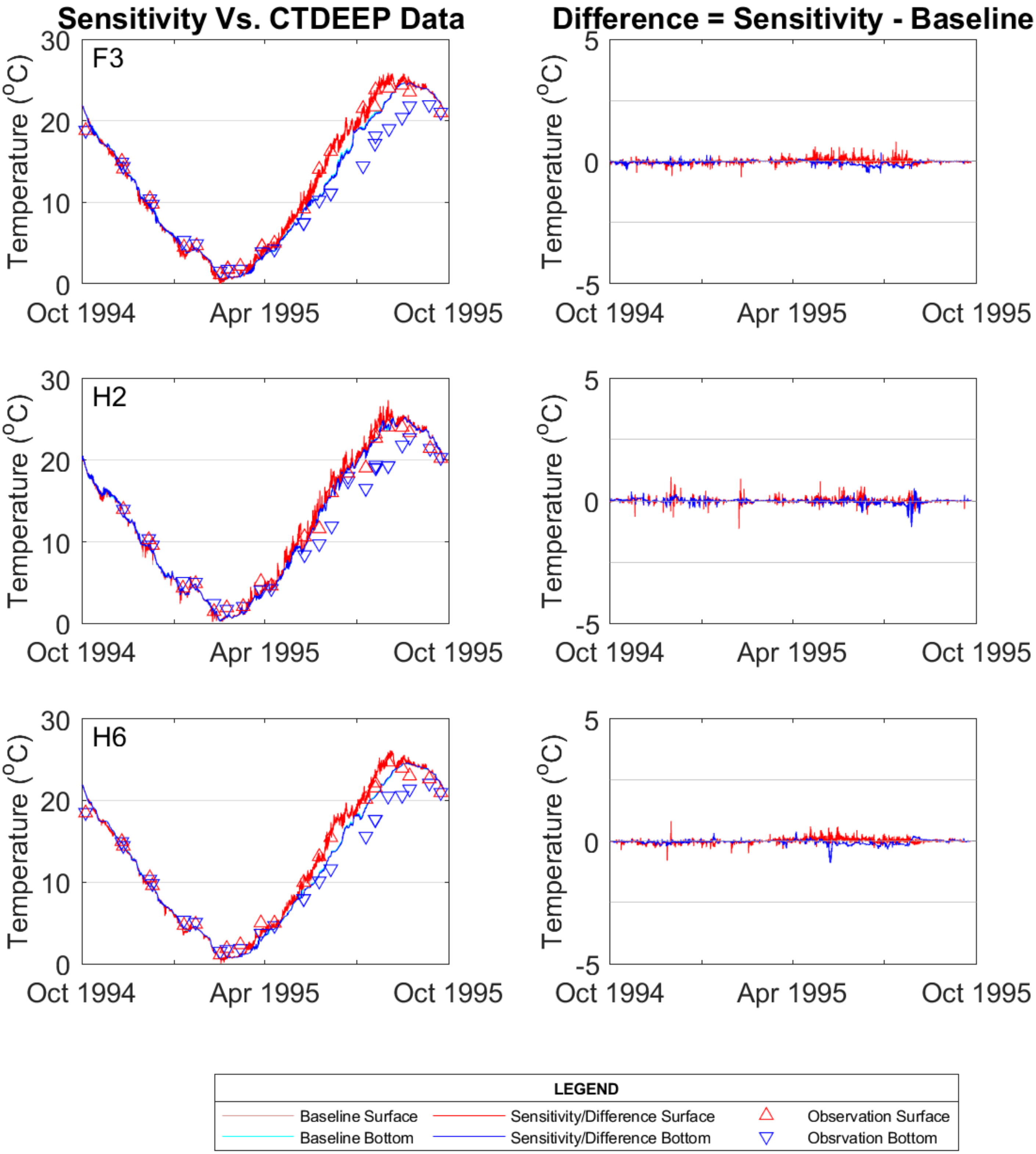


Baseline = k-epsilon Turbulent Closure

Sensitivity = k-omega Turbulent Closure

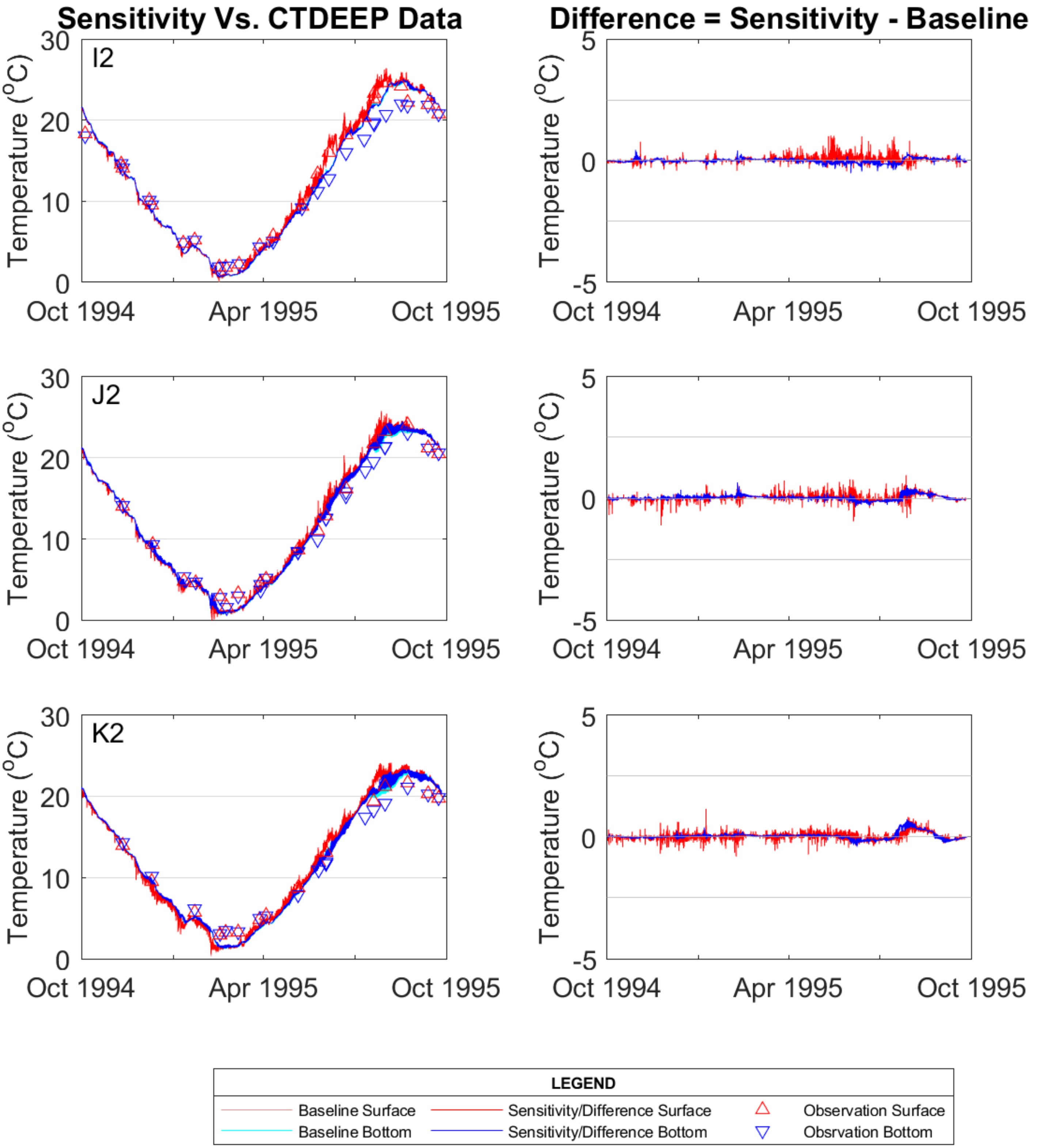


Baseline = k-epsilon Turbulent Closure
Sensitivity = k-omega Turbulent Closure

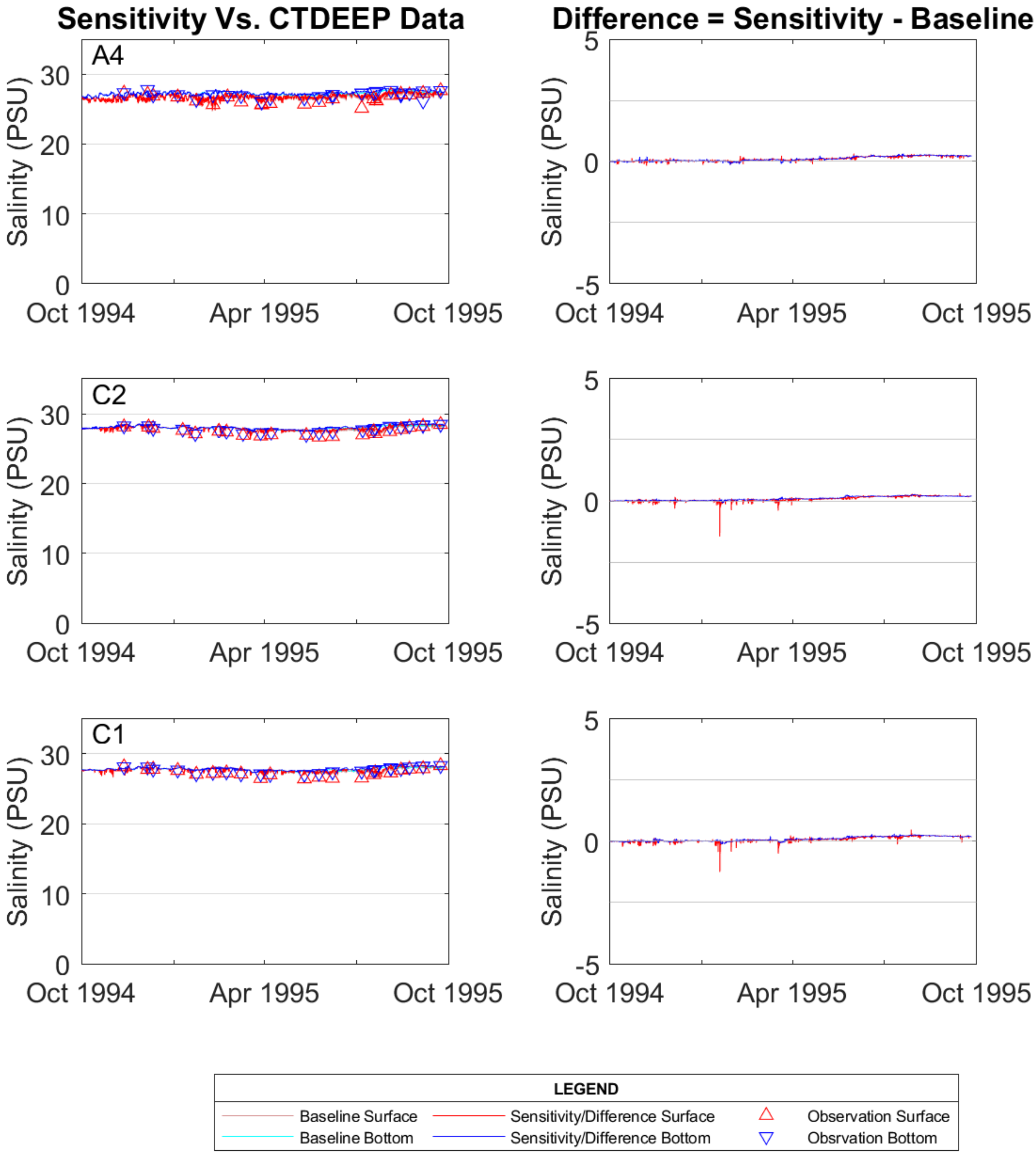


Baseline = k-epsilon Turbulent Closure

Sensitivity = k-omega Turbulent Closure

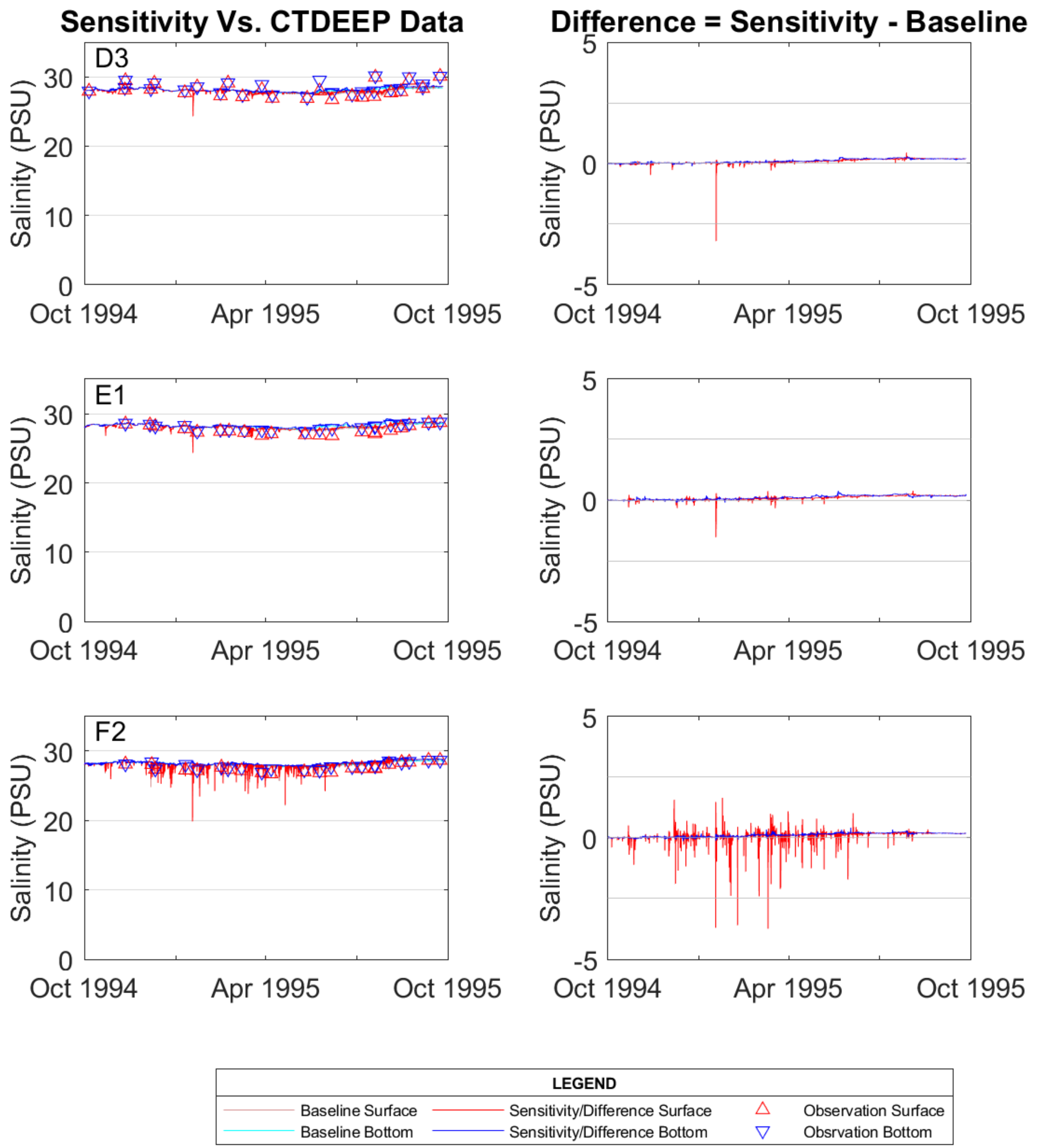


Baseline = k-epsilon Turbulent Closure
Sensitivity = k-omega Turbulent Closure



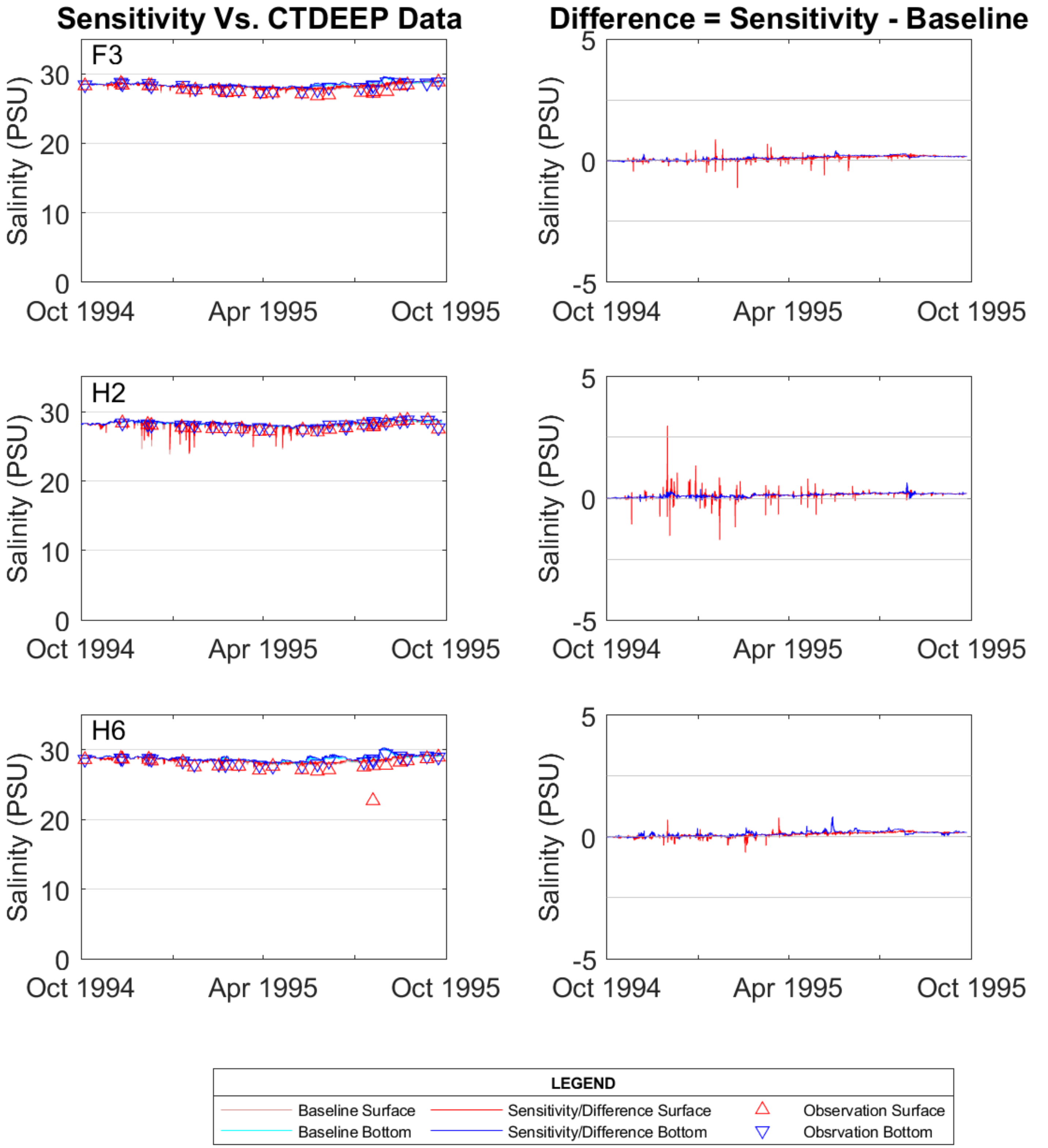
Baseline = k-epsilon Turbulent Closure

Sensitivity = k-omega Turbulent Closure

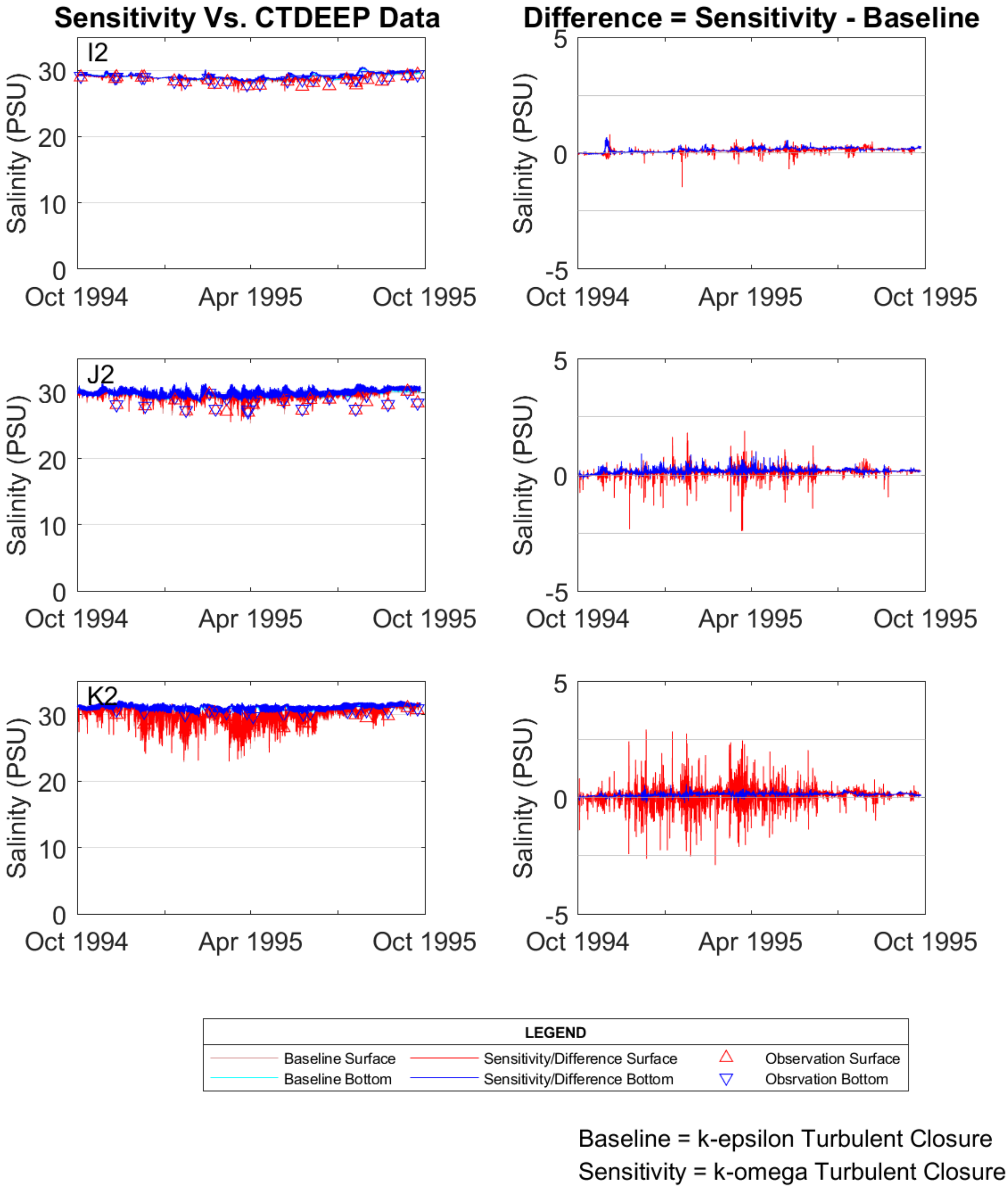


Baseline = k-epsilon Turbulent Closure

Sensitivity = k-omega Turbulent Closure



Baseline = k-epsilon Turbulent Closure
Sensitivity = k-omega Turbulent Closure


Sensitivity Vs. CTDEEP Data
Difference = Sensitivity - Baseline
I2
J2
K2
Salinity (PSU)
Oct 1994
Apr 1995
Oct 1995
LEGEND
Baseline Surface
Baseline Bottom
Sensitivity/Difference Surface
Sensitivity/Difference Bottom
Observation Surface
Obsrvation Bottom
Baseline = k-epsilon Turbulent Closure
Sensitivity = k-omega Turbulent Closure

6c

ROMS Vertical Closure Scheme Sensitivity

(k-epsilon vs. gen)

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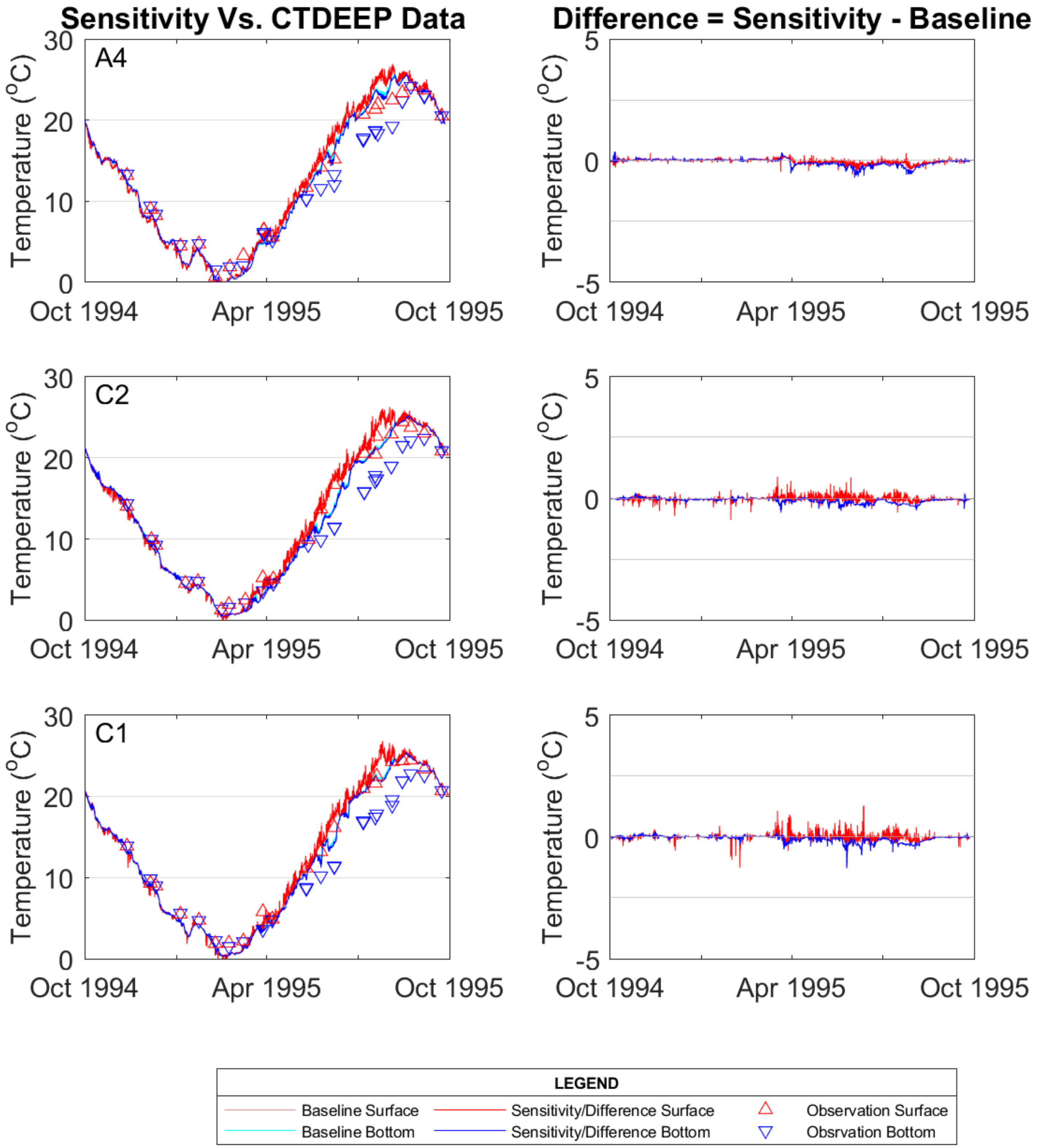
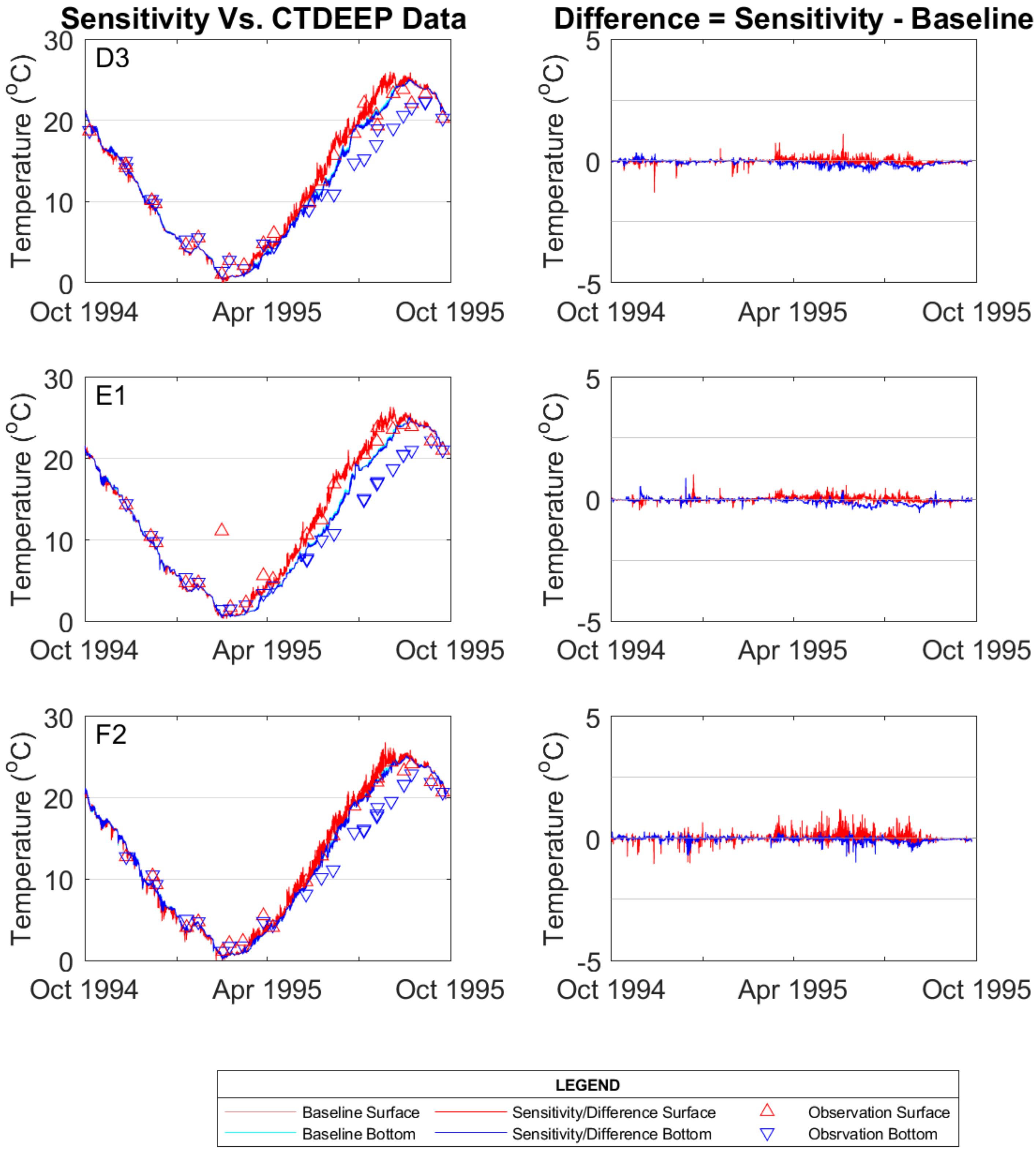
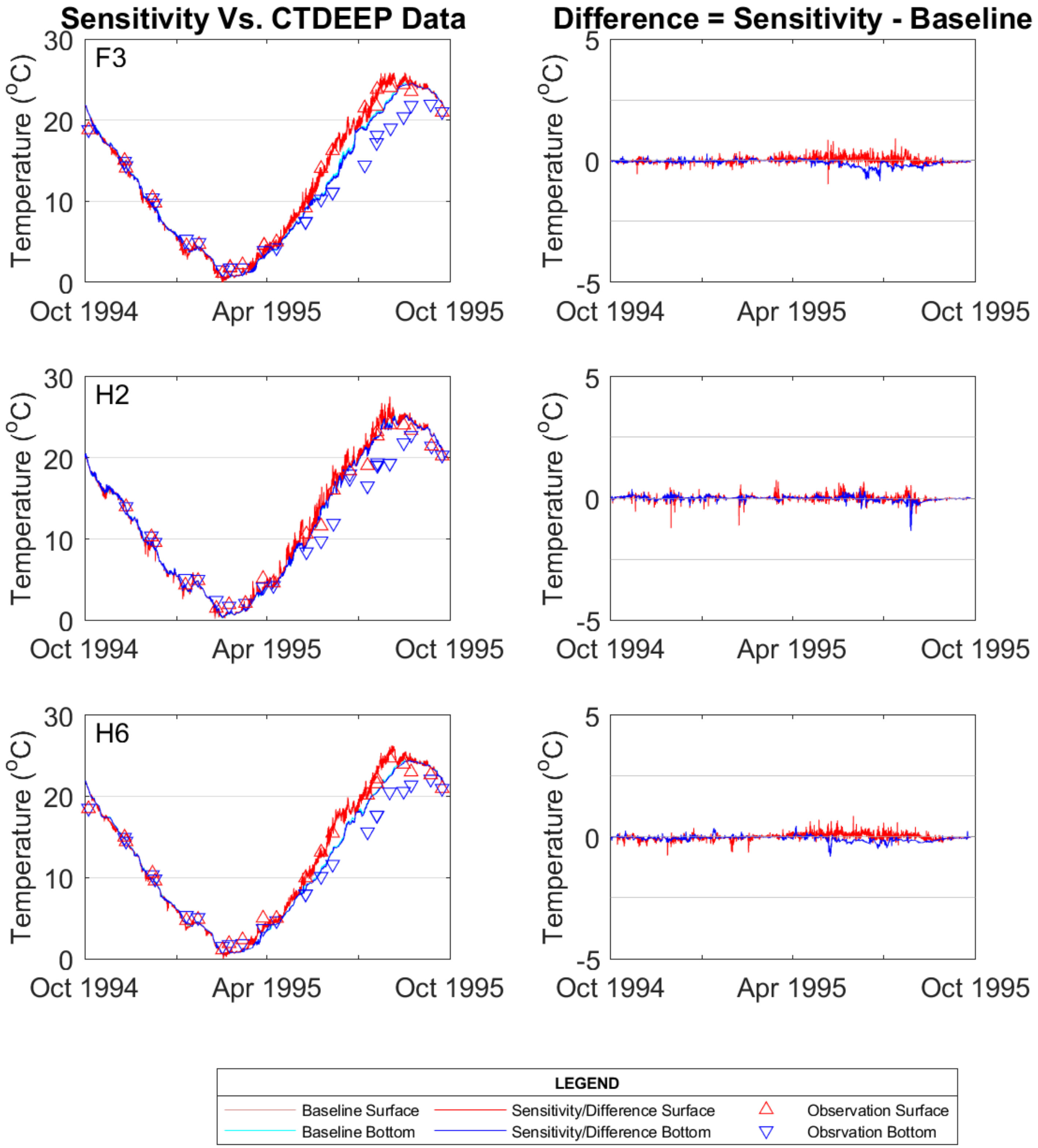


Baseline = k-epsilon Turbulent Closure

Sensitivity = Gen Turbulent Closure

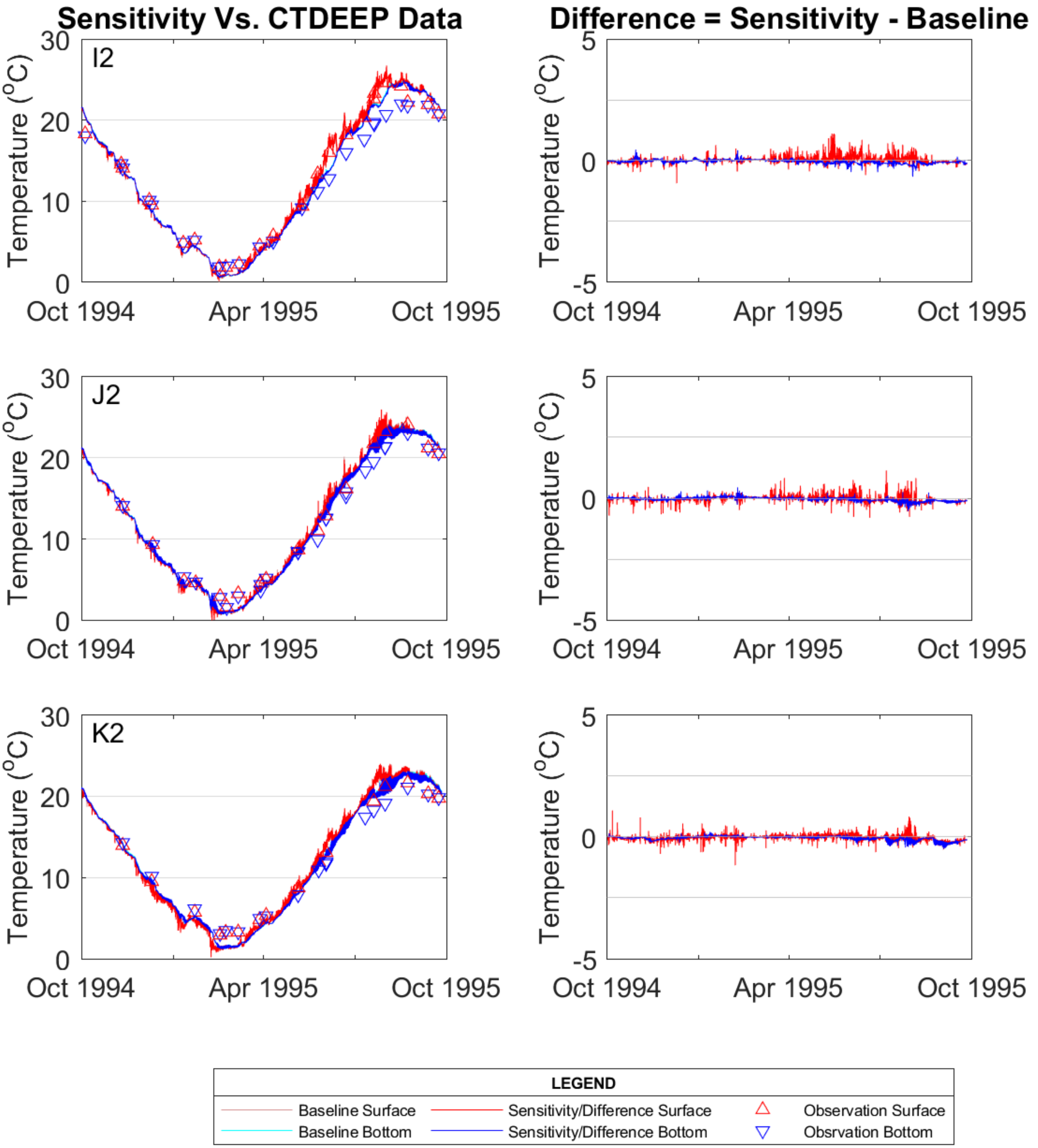


Baseline = k-epsilon Turbulent Closure
Sensitivity = Gen Turbulent Closure

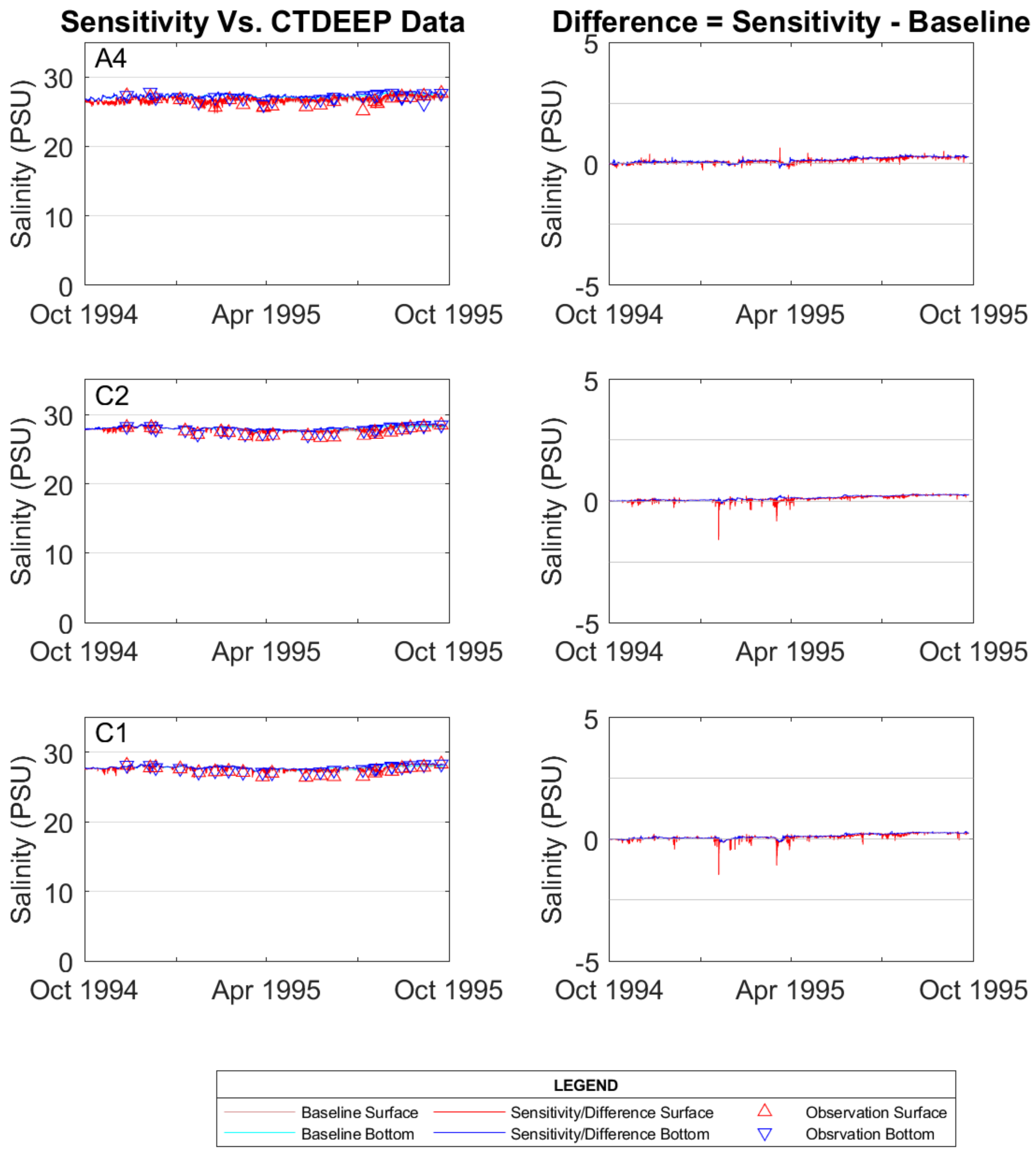


Baseline = k-epsilon Turbulent Closure

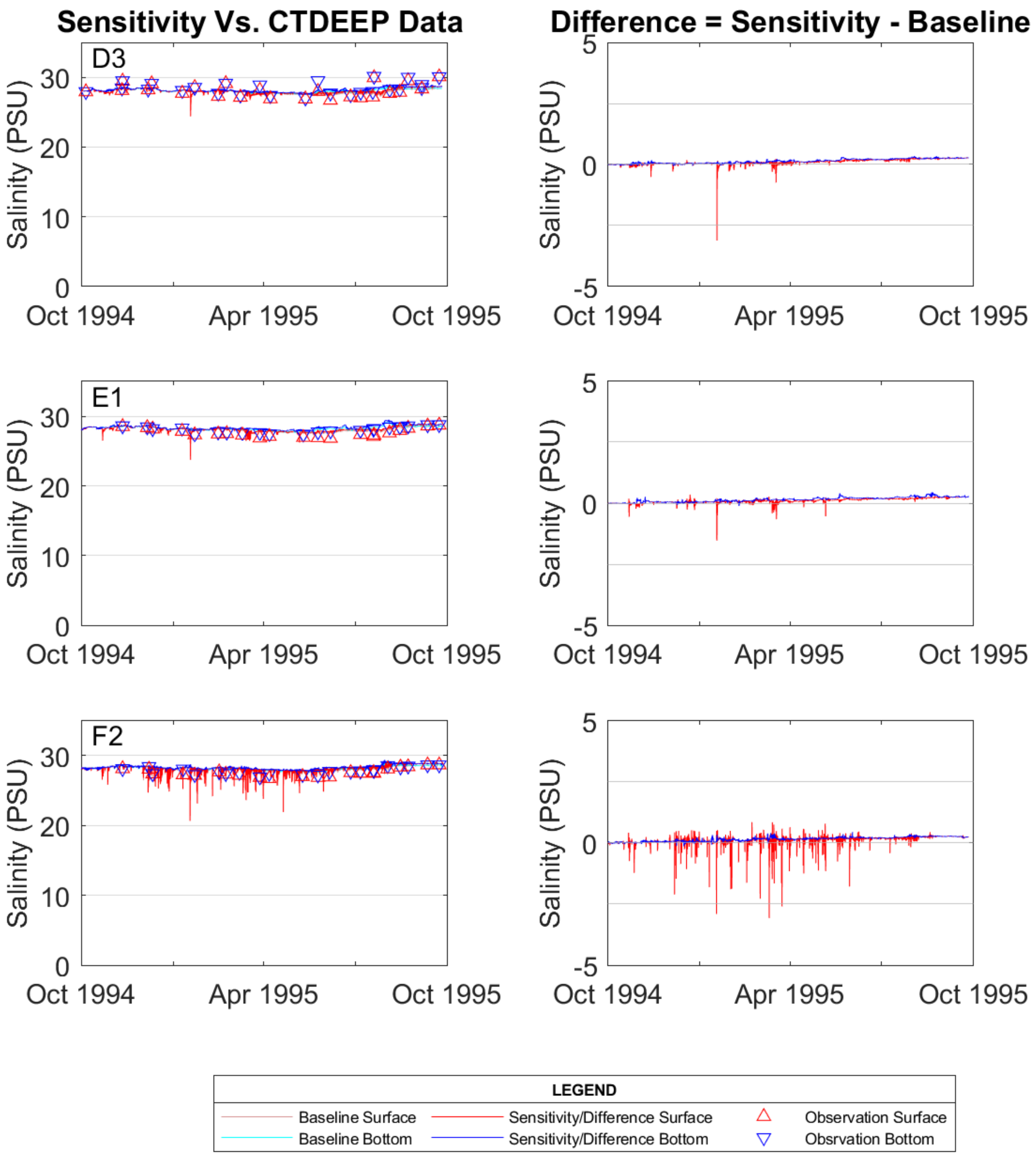
Sensitivity = Gen Turbulent Closure



Baseline = k-epsilon Turbulent Closure
Sensitivity = Gen Turbulent Closure

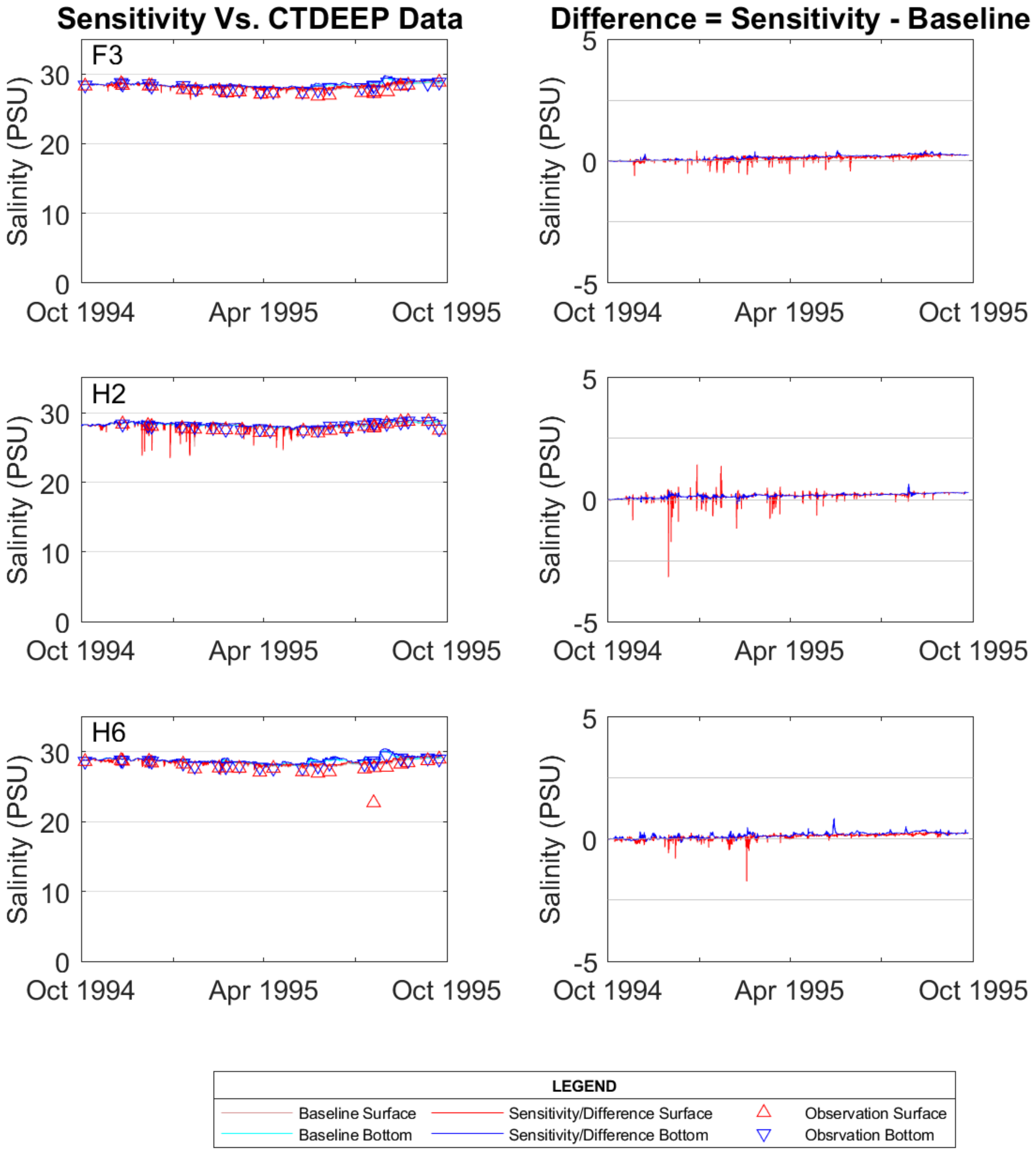


Baseline = k-epsilon Turbulent Closure
Sensitivity = Gen Turbulent Closure



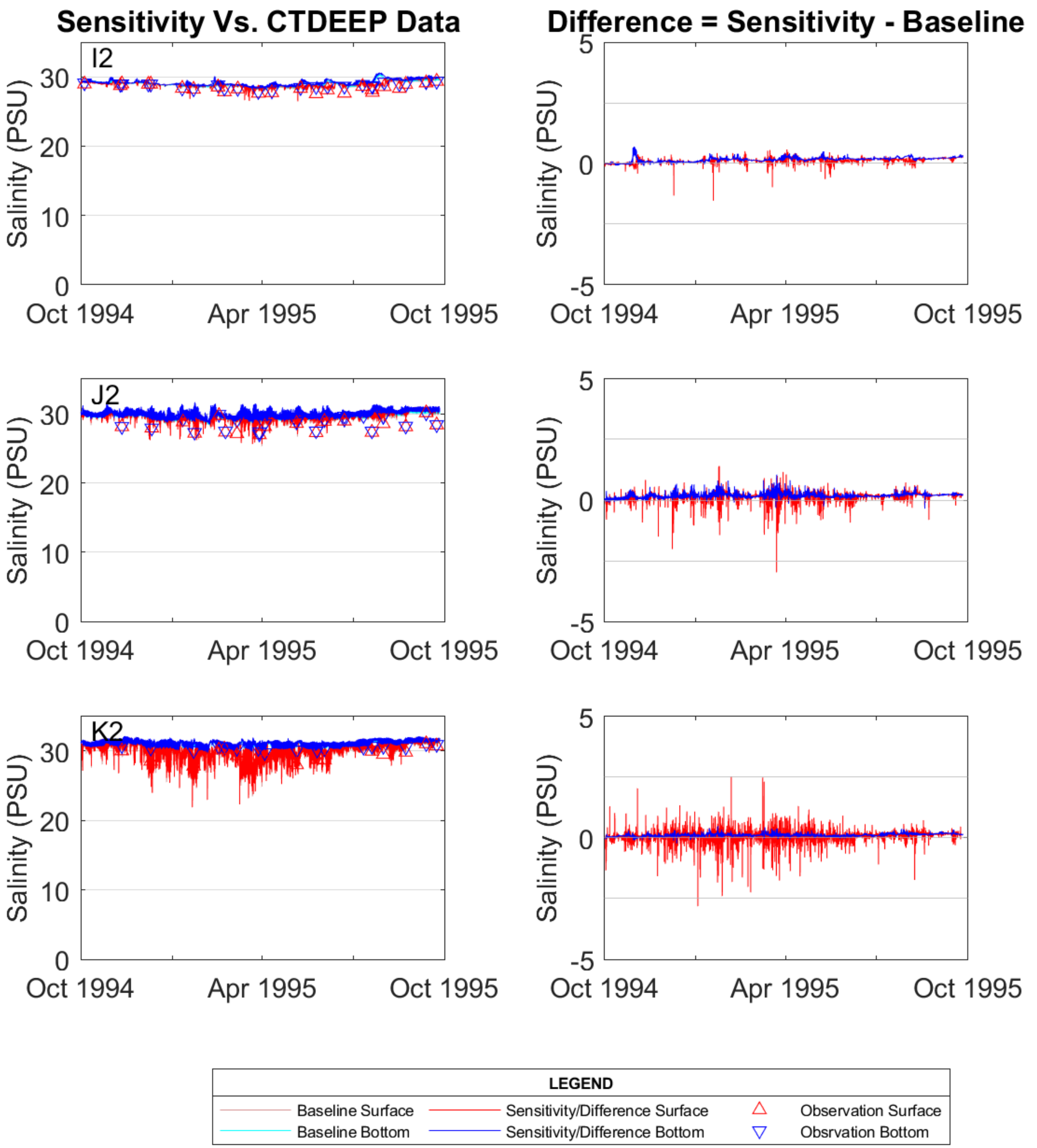
Baseline = k-epsilon Turbulent Closure

Sensitivity = Gen Turbulent Closure



Baseline = k-epsilon Turbulent Closure

Sensitivity = Gen Turbulent Closure



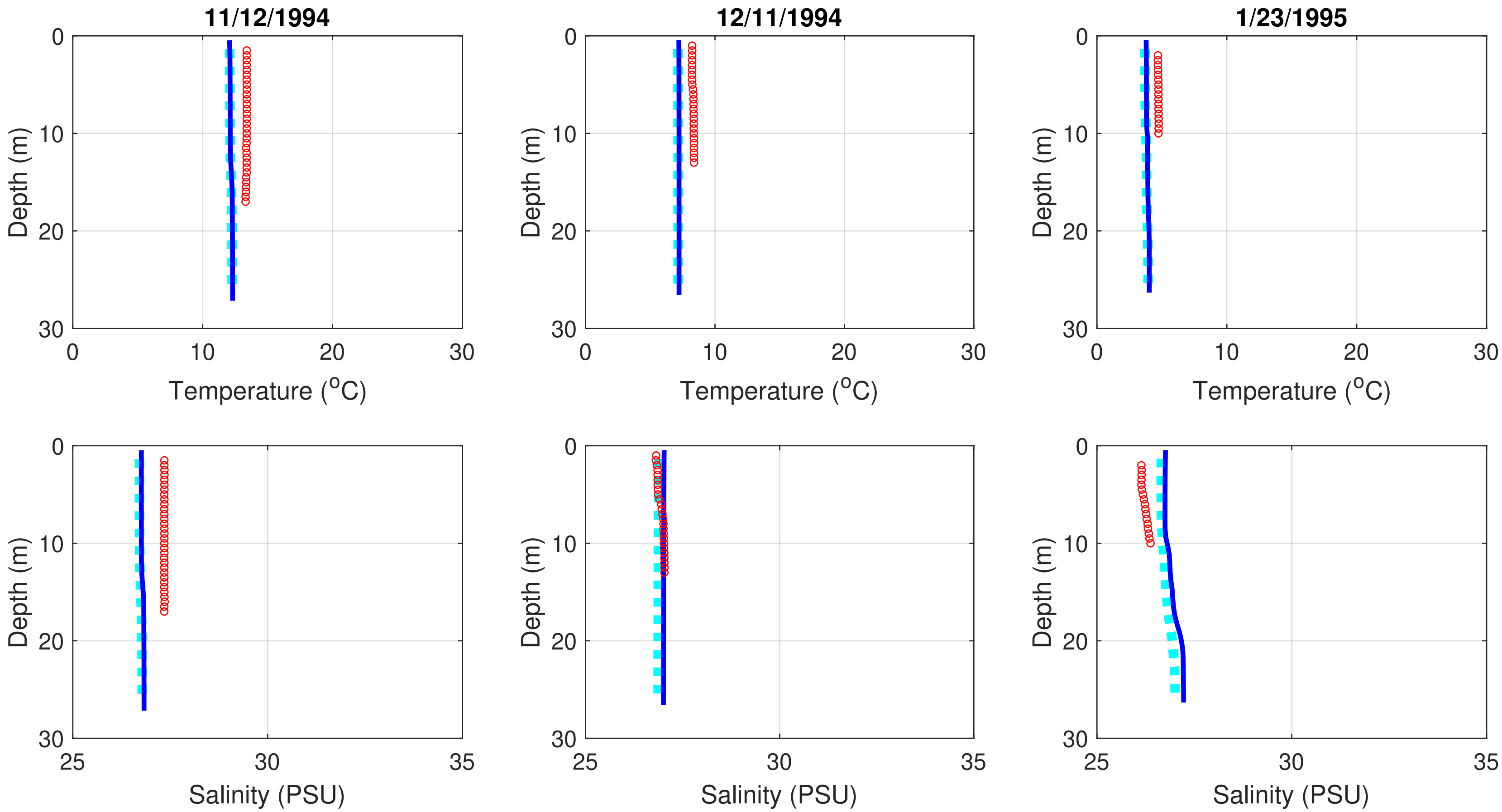
Baseline = k-epsilon Turbulent Closure
Sensitivity = Gen Turbulent Closure

7

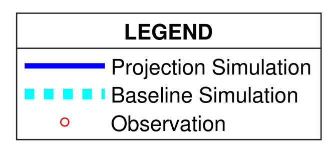
ROMS Vertical Layers Sensitivity

(10 vs. 30)

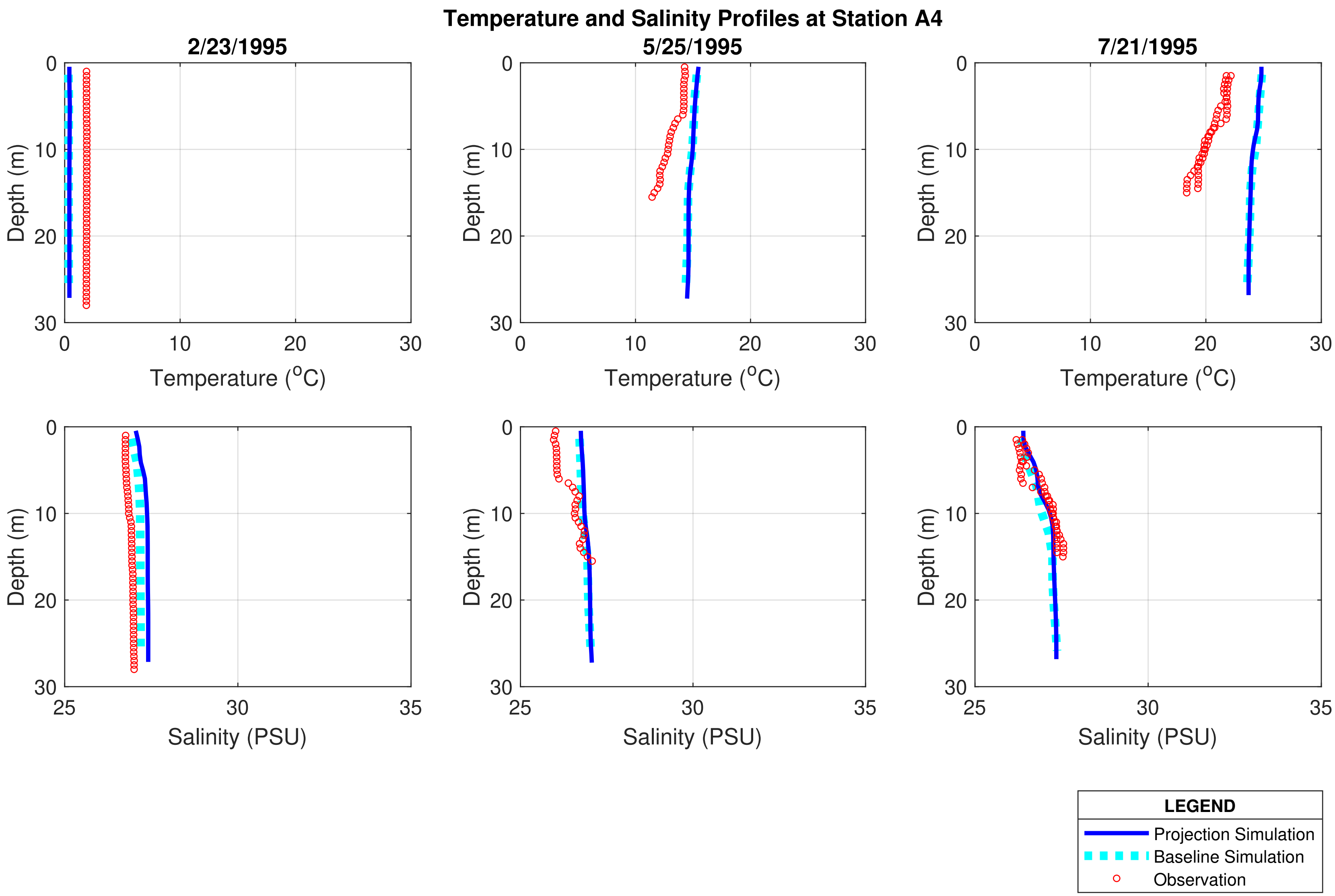
Temperature and Salinity Profiles at Station A4



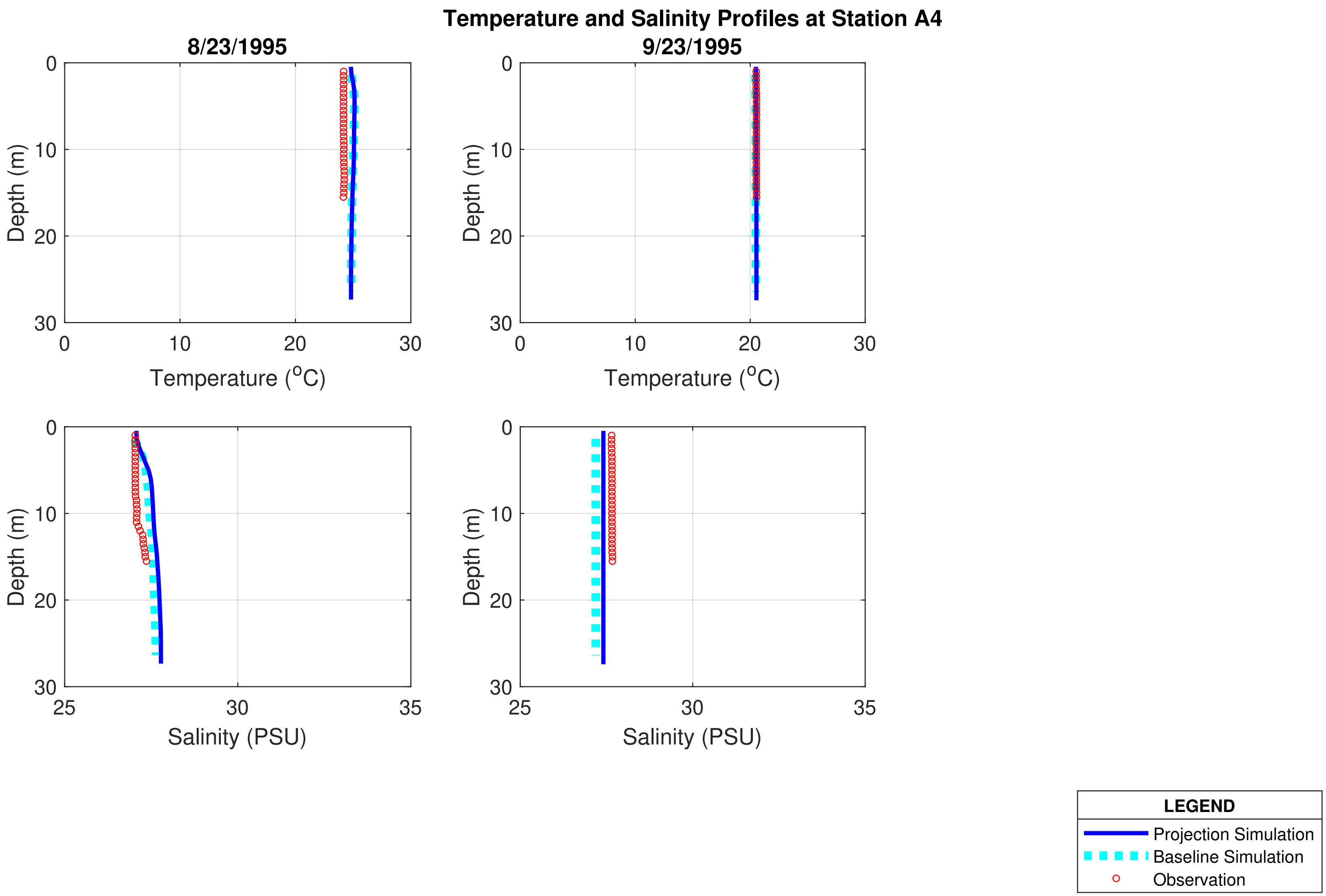
Data - Red Circles
Light Blue Dashed Line - Baseline Simulation
Dark Blue Solid Line - 30-Layer Simulation



LIS28 - 30 Layers

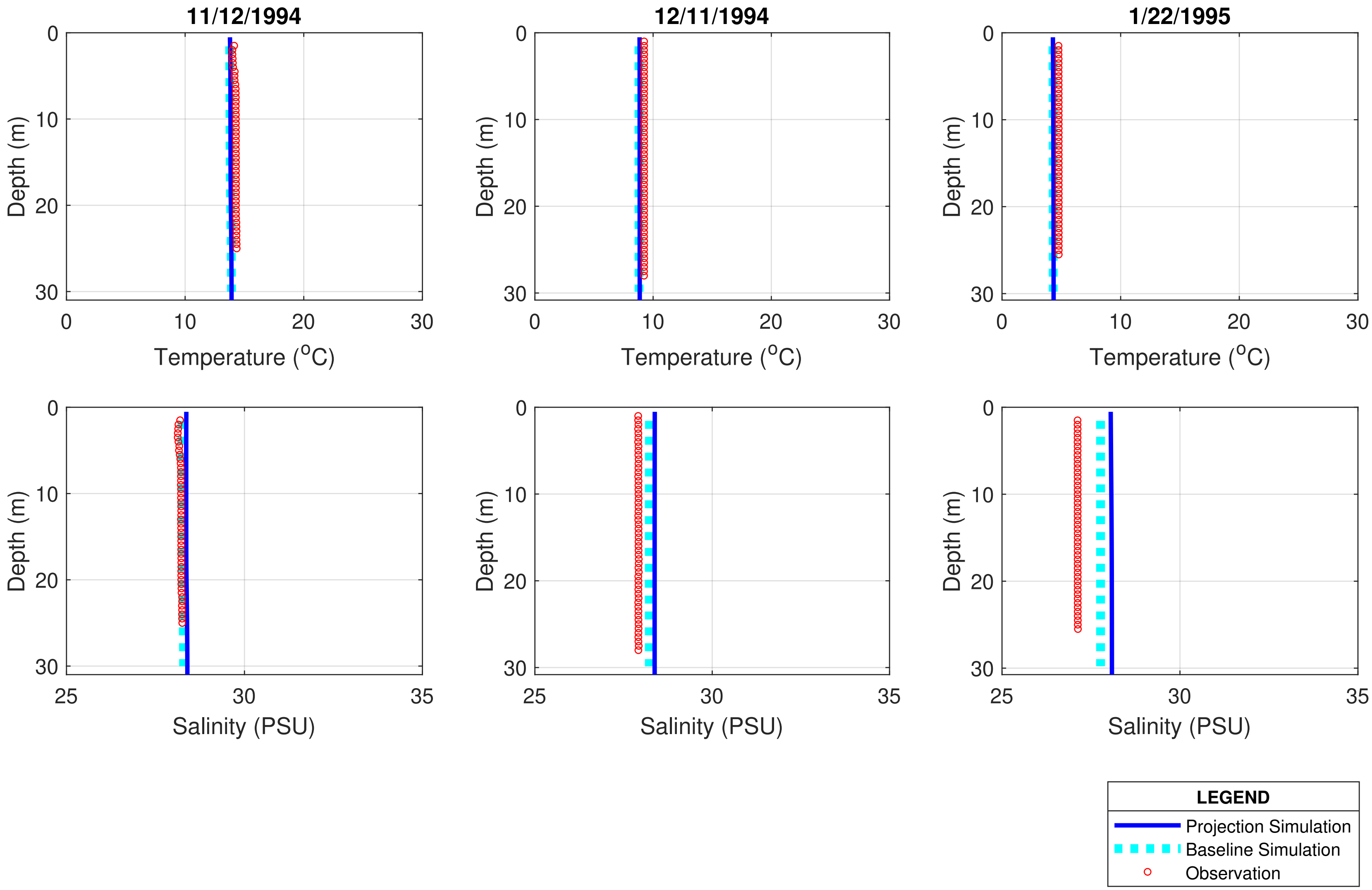


LIS28 - 30 Layers

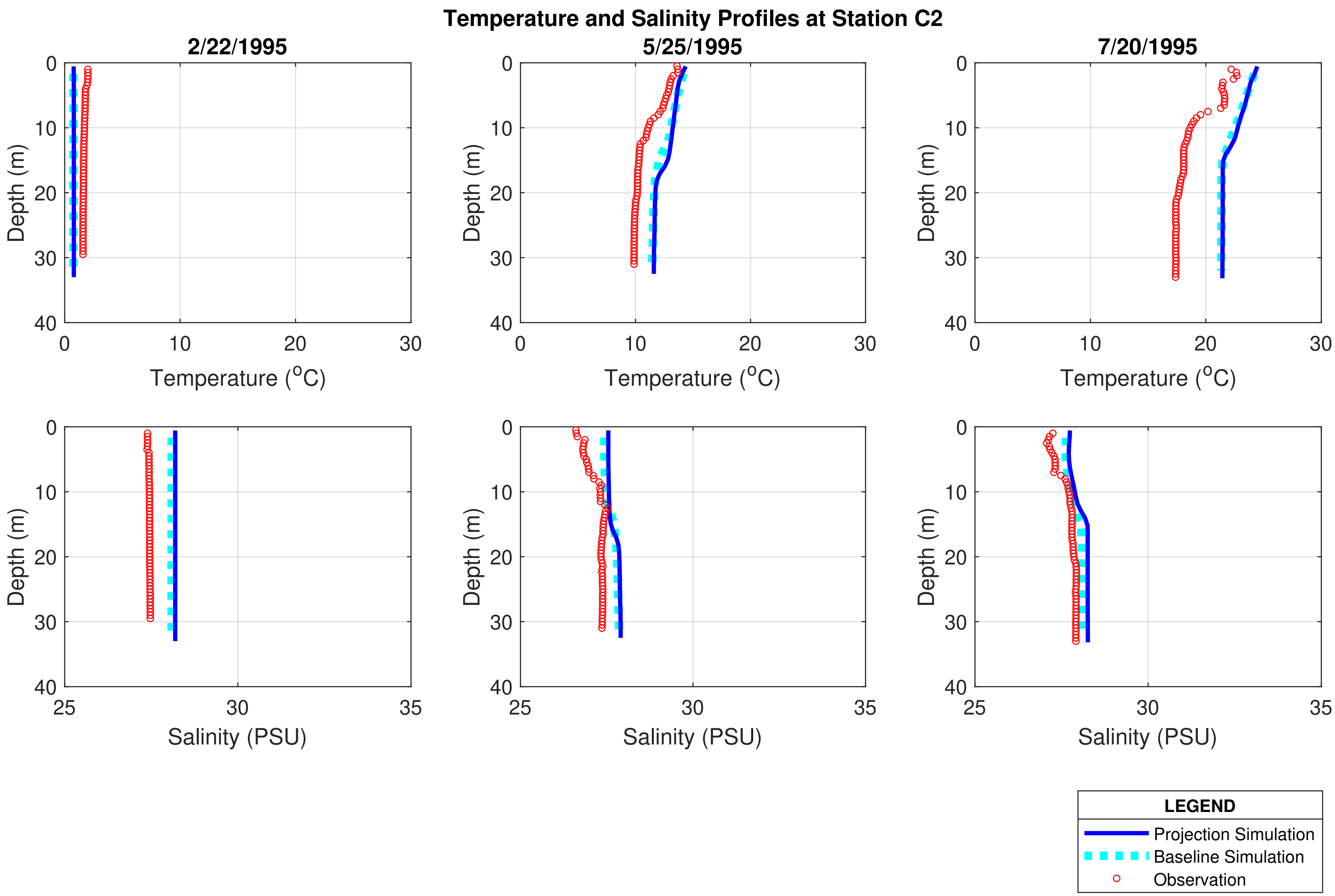


LIS28 - 30 Layers

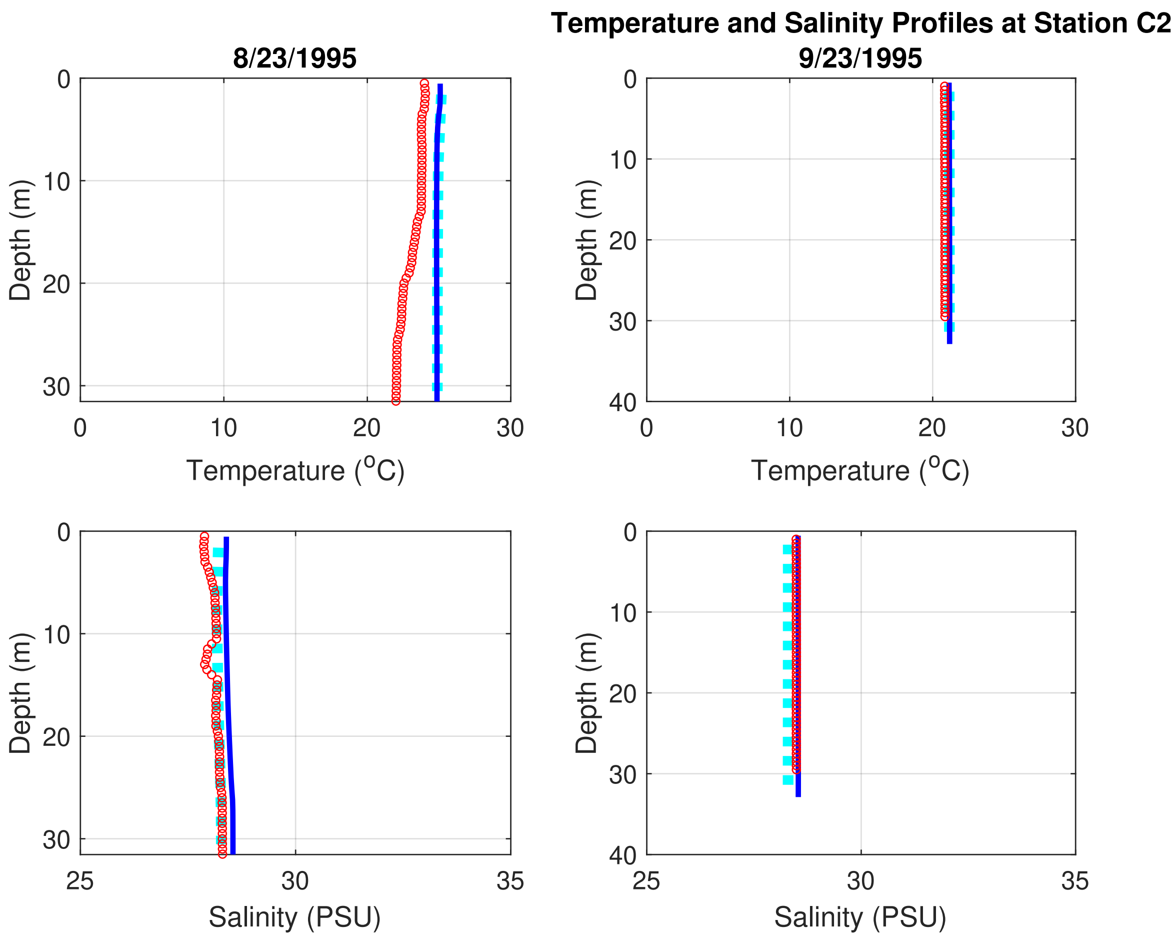
Temperature and Salinity Profiles at Station C2

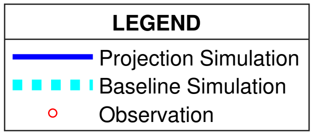


LIS28 - 30 Layers

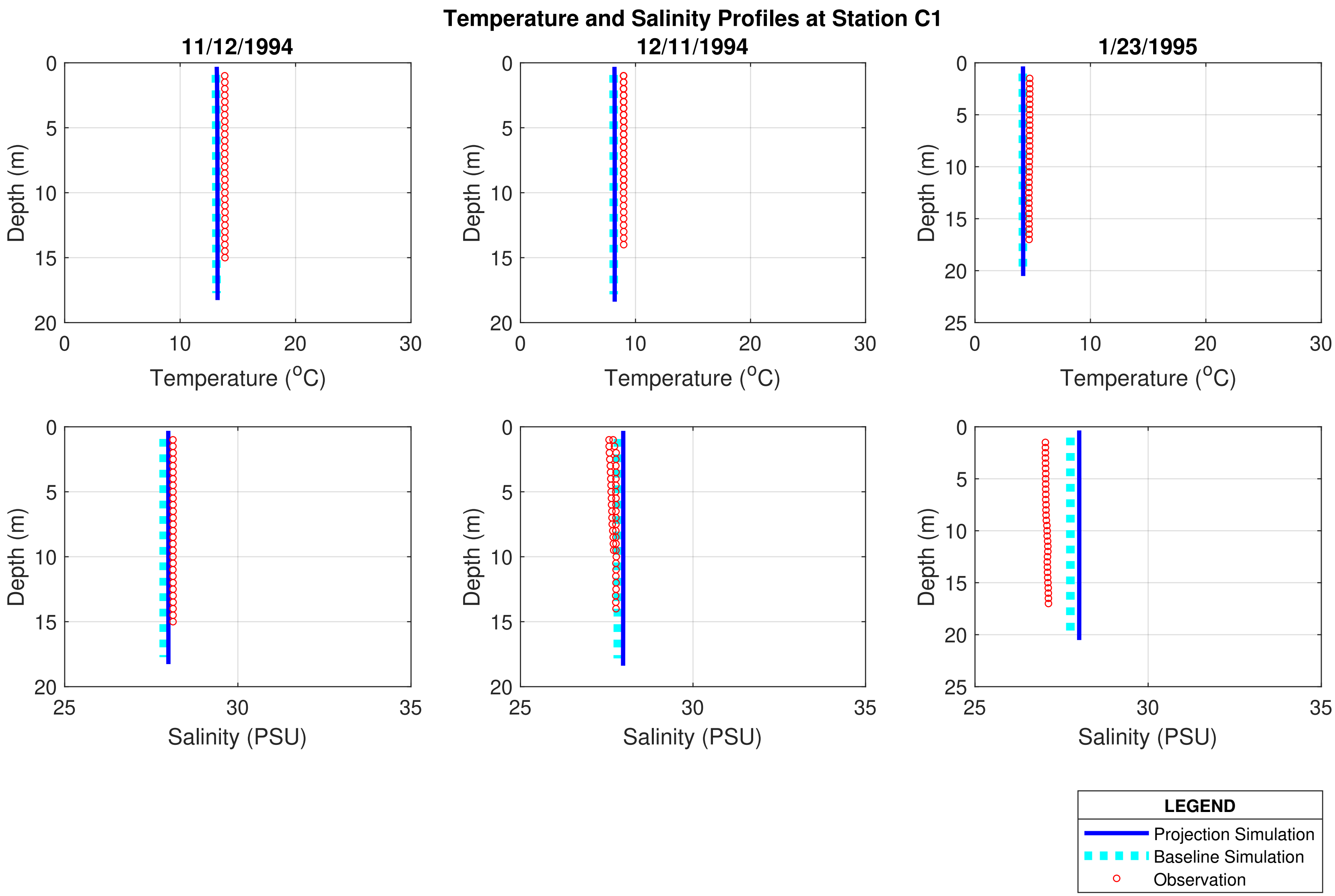


LIS28 - 30 Layers



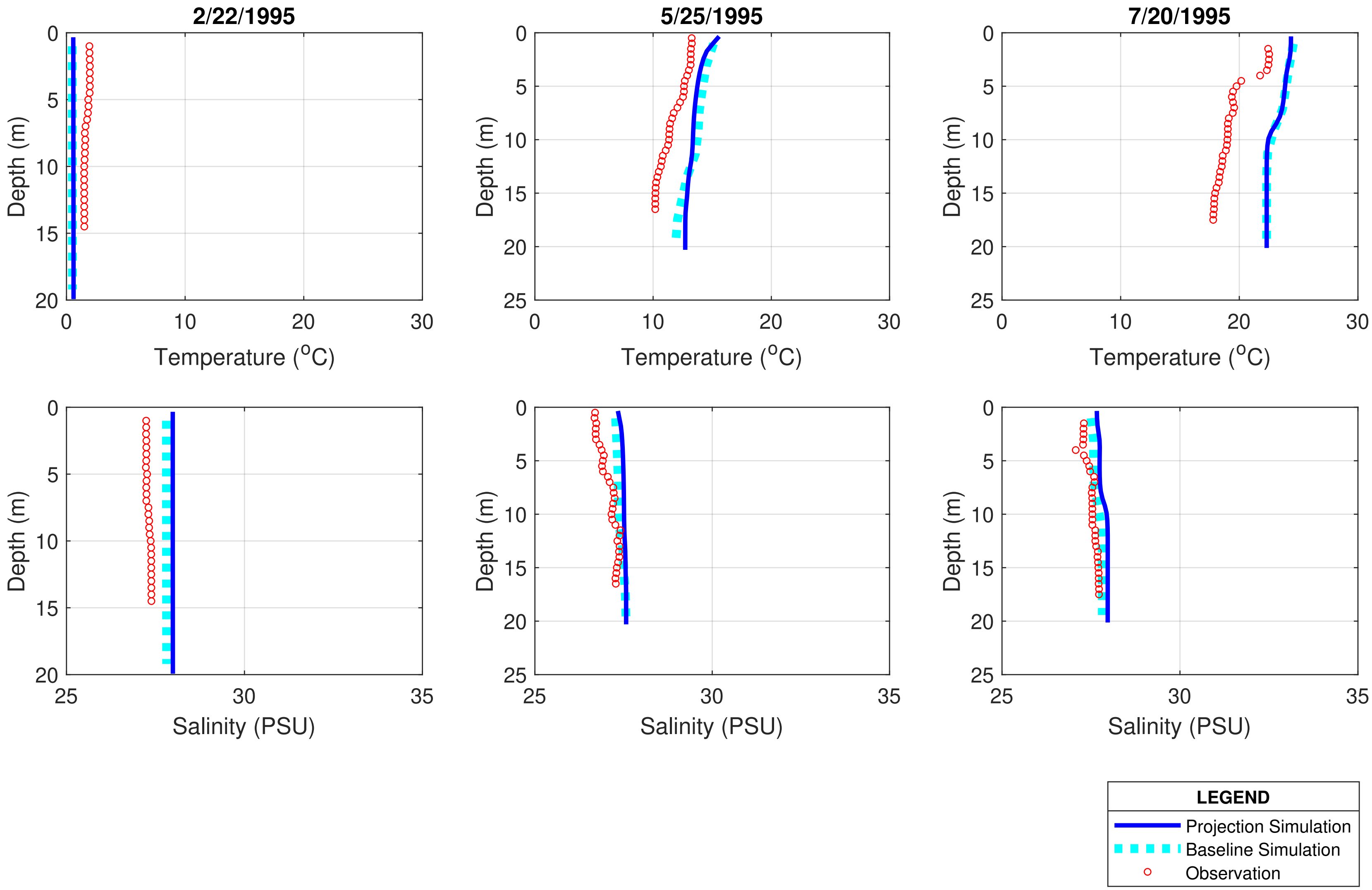


LIS28 - 30 Layers

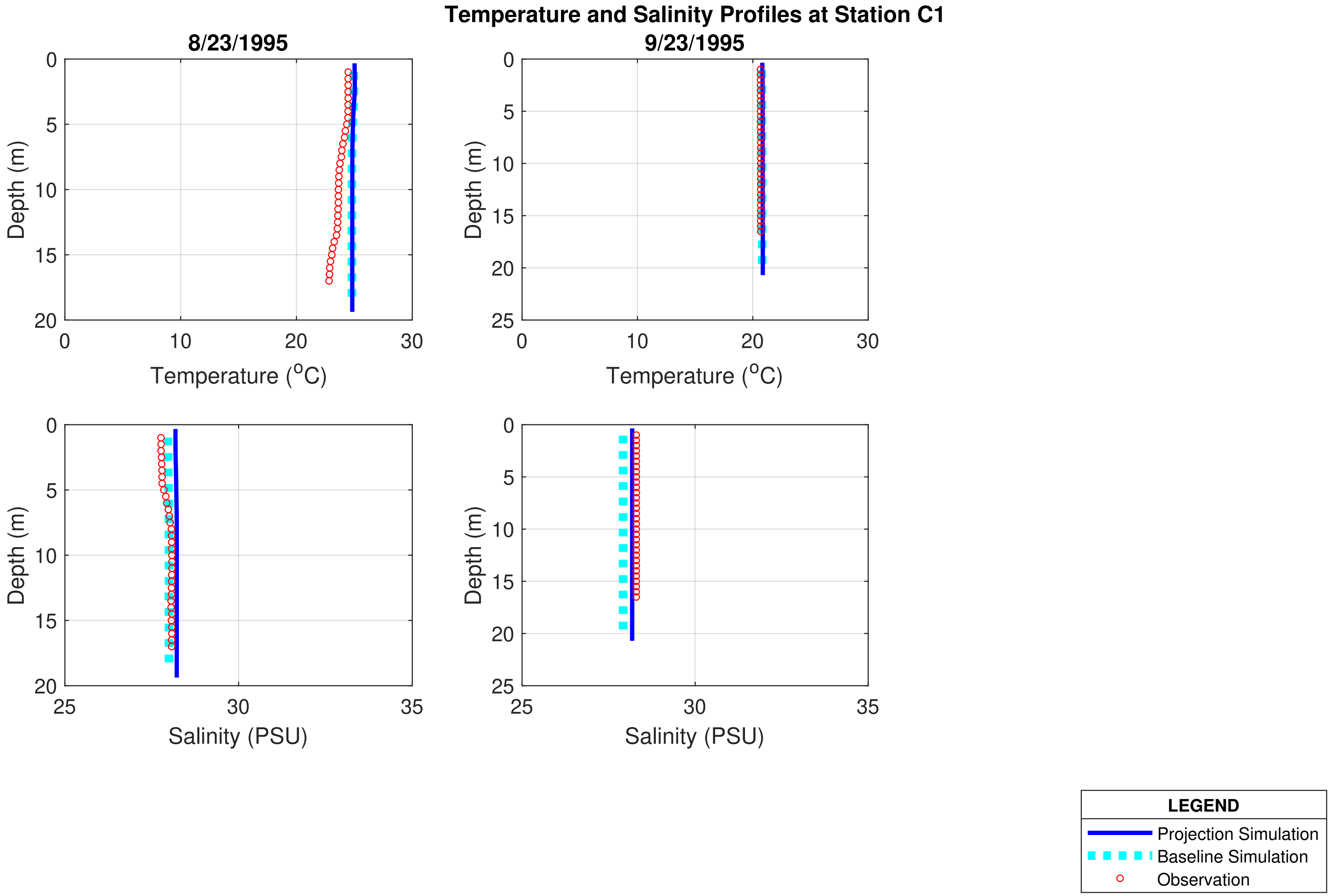


LIS28 - 30 Layers

Temperature and Salinity Profiles at Station C1



LIS28 - 30 Layers



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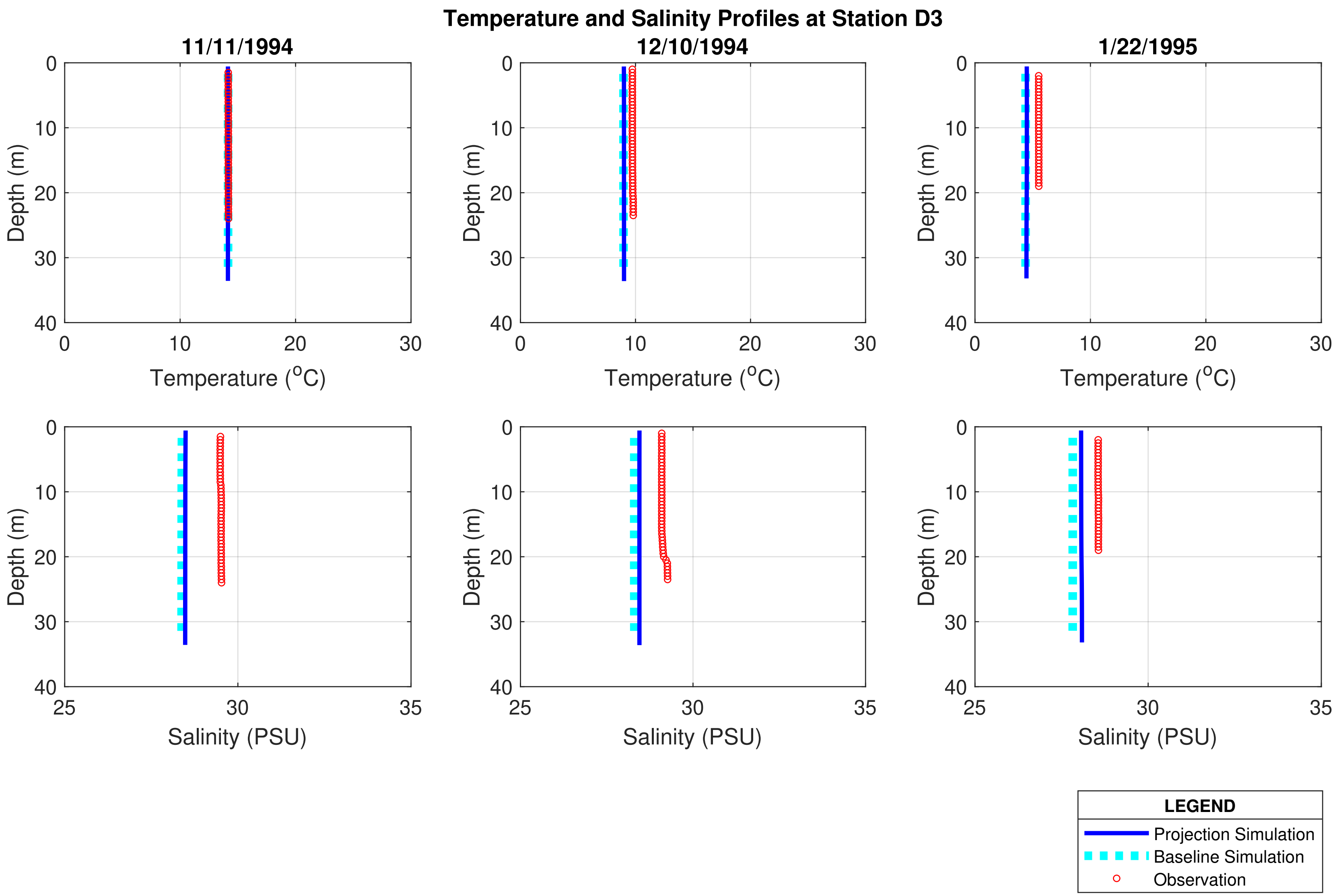
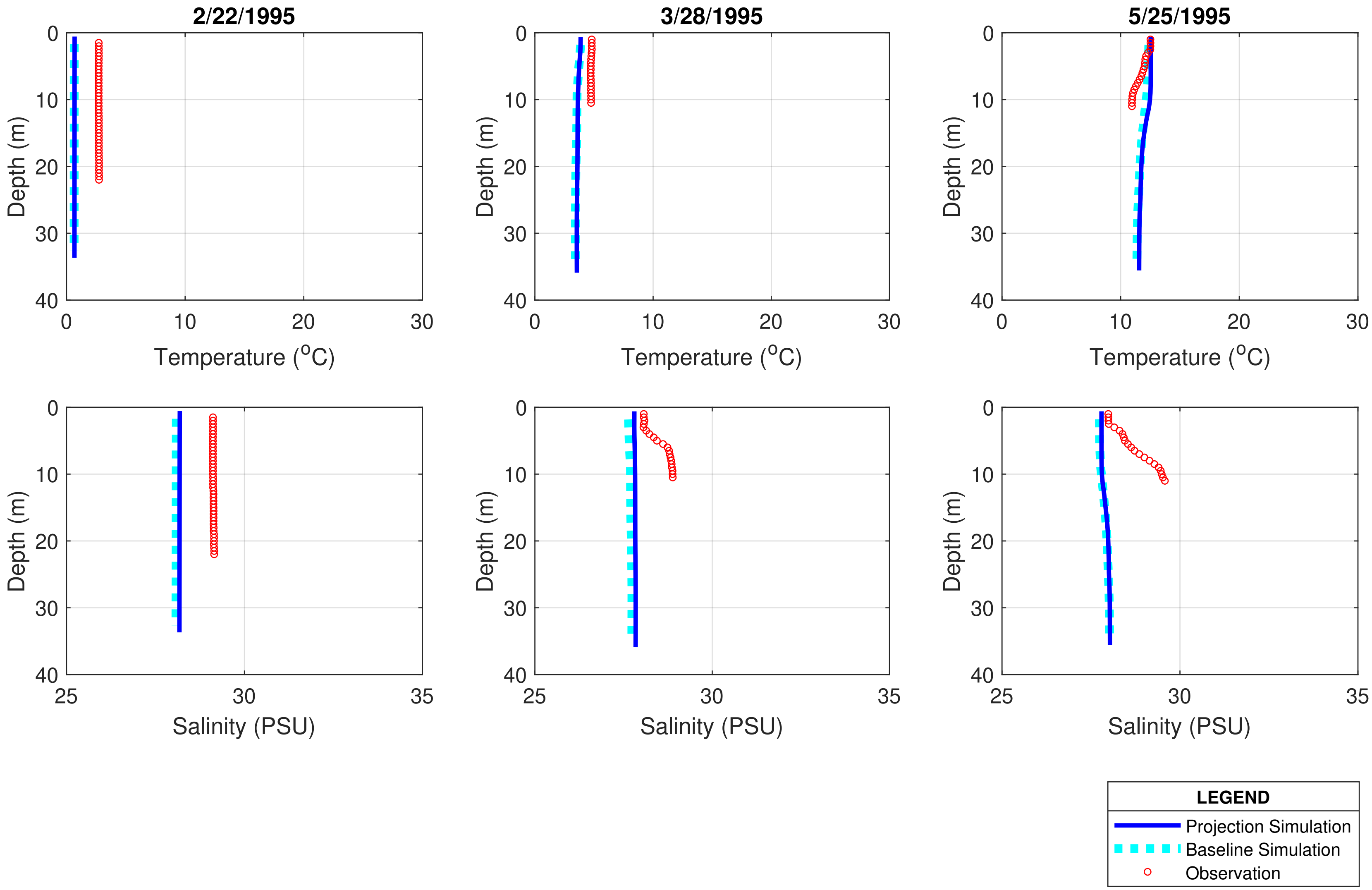
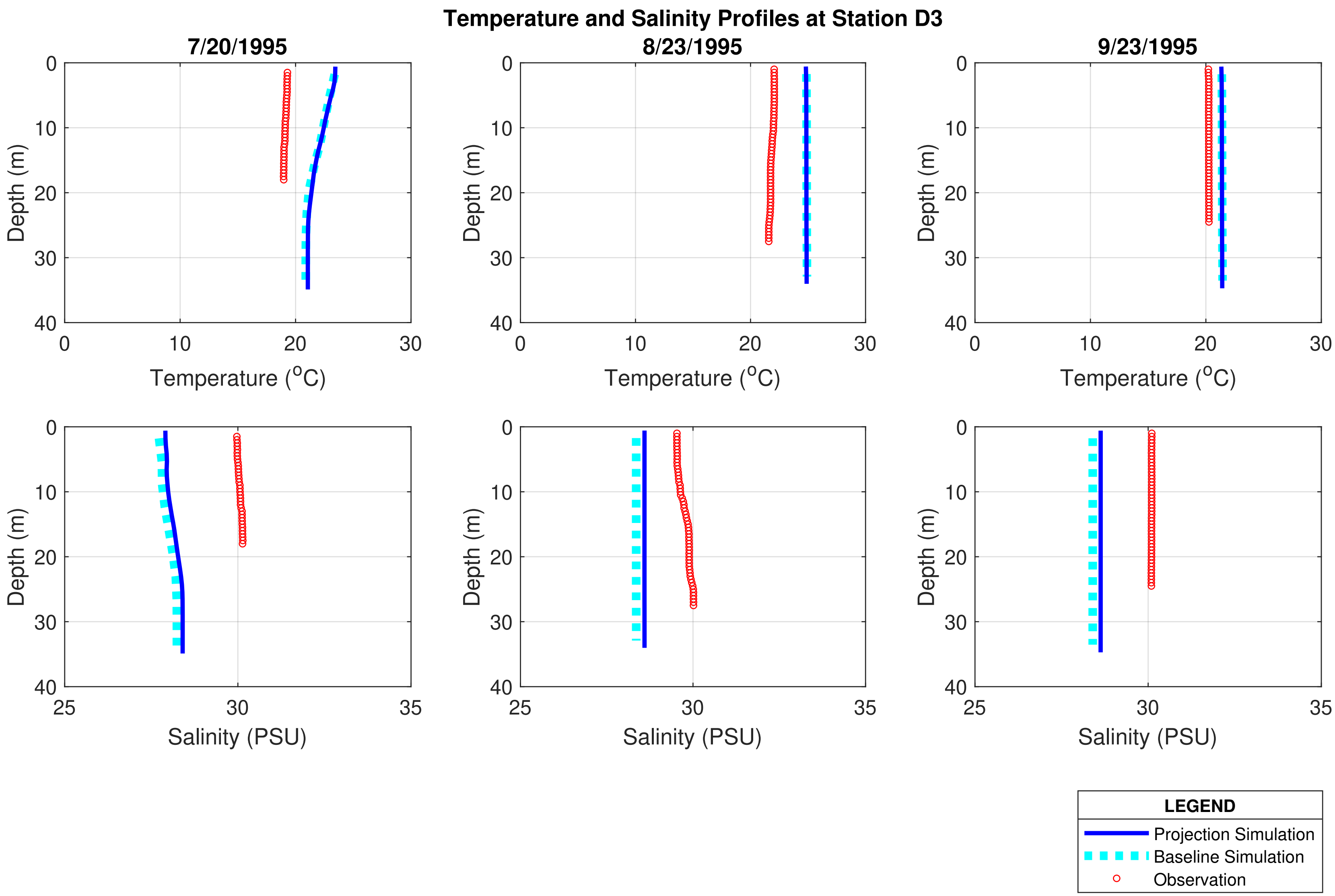


LIS28 - 30 Layers

Temperature and Salinity Profiles at Station D3



LIS28 - 30 Layers



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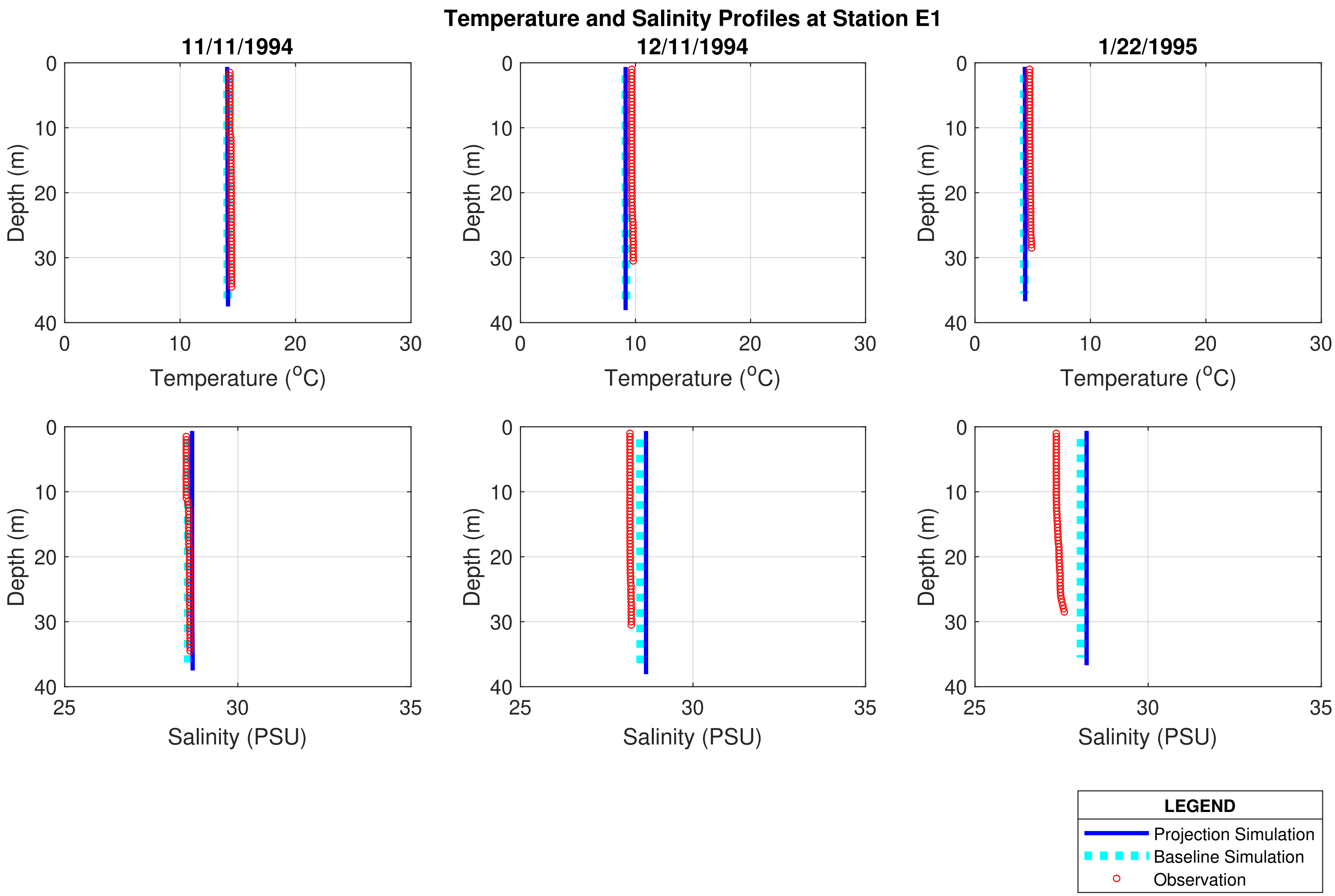
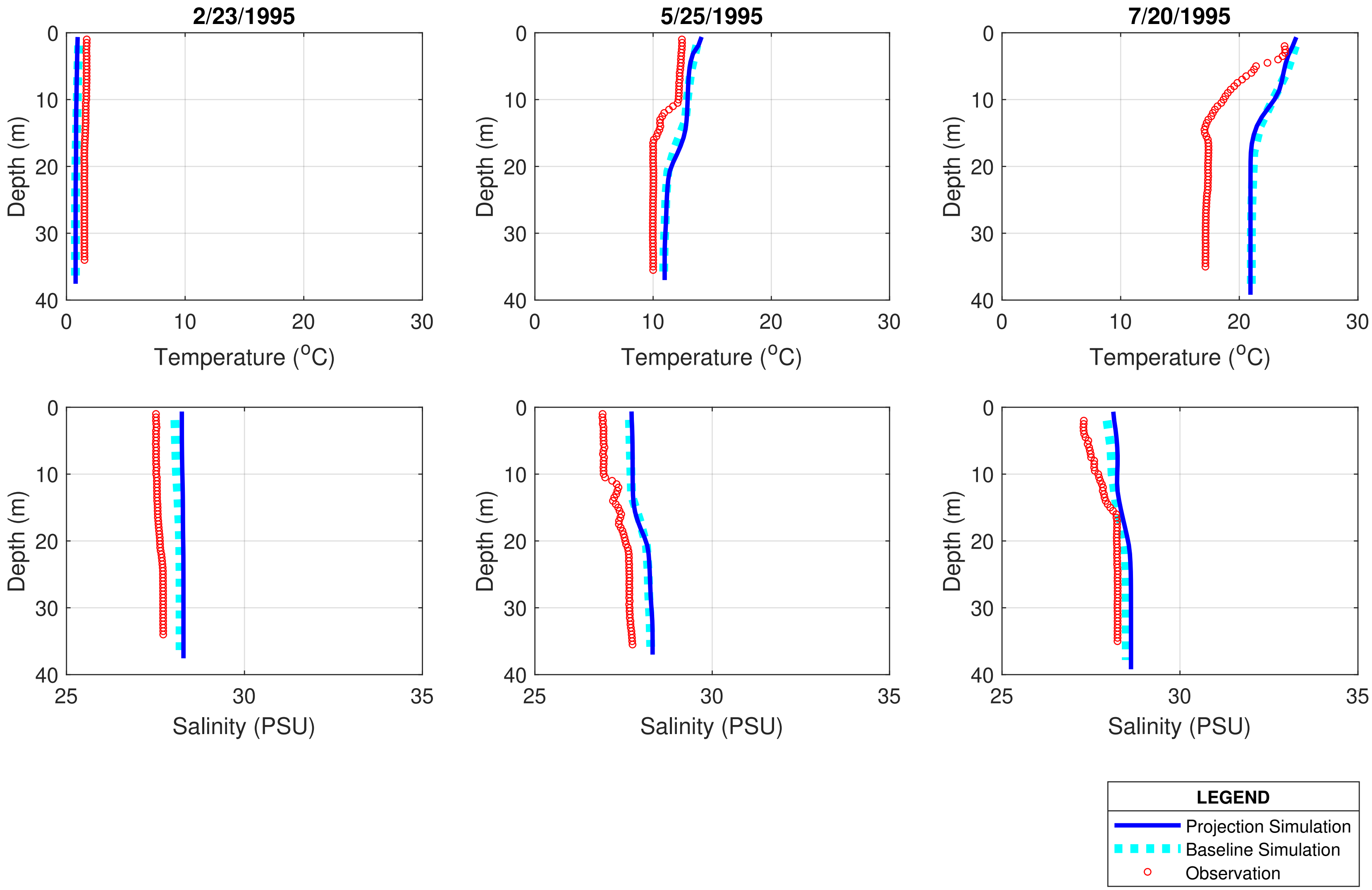


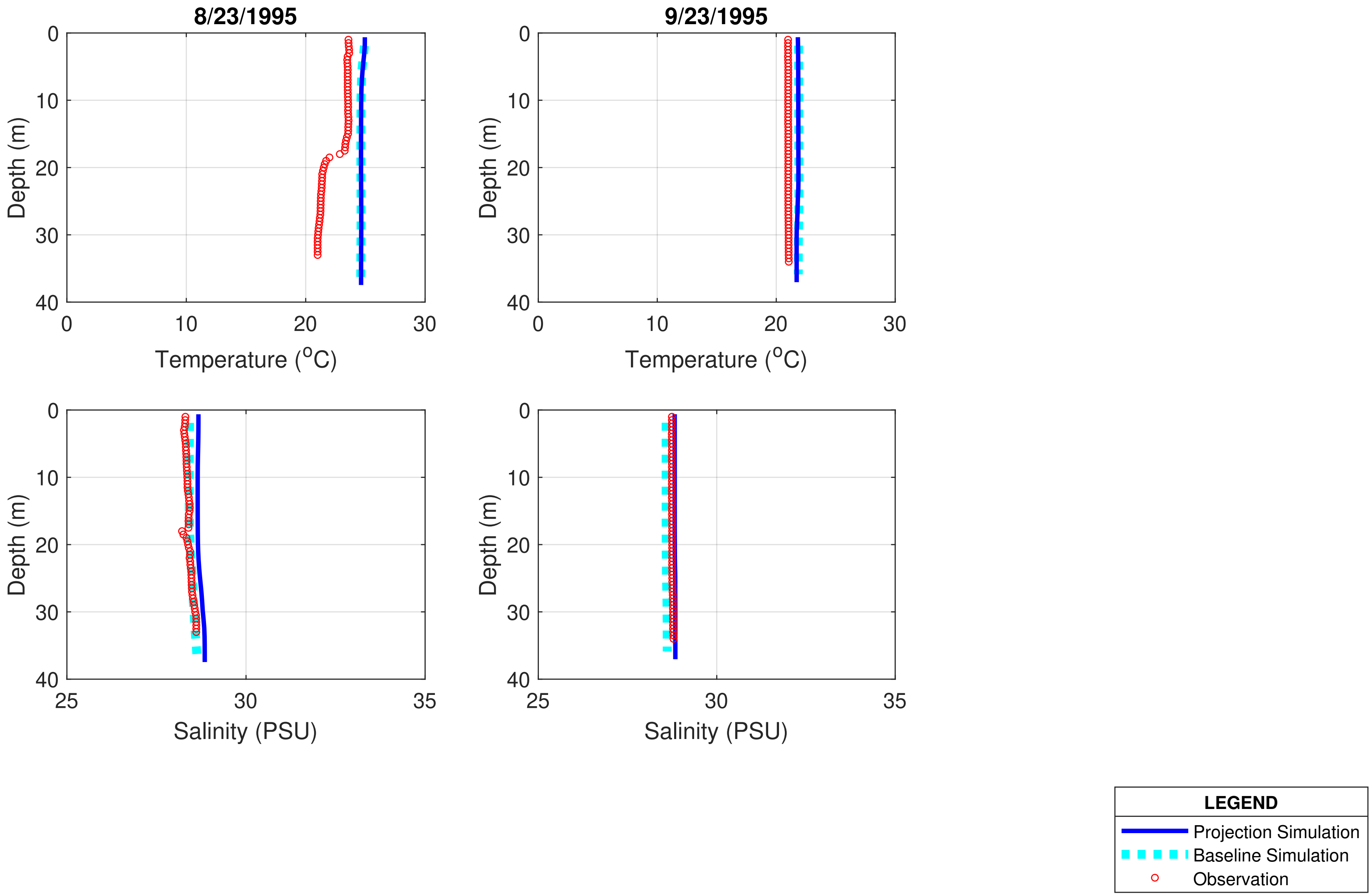
LIS28 - 30 Layers

Temperature and Salinity Profiles at Station E1



LIS28 - 30 Layers

Temperature and Salinity Profiles at Station E1



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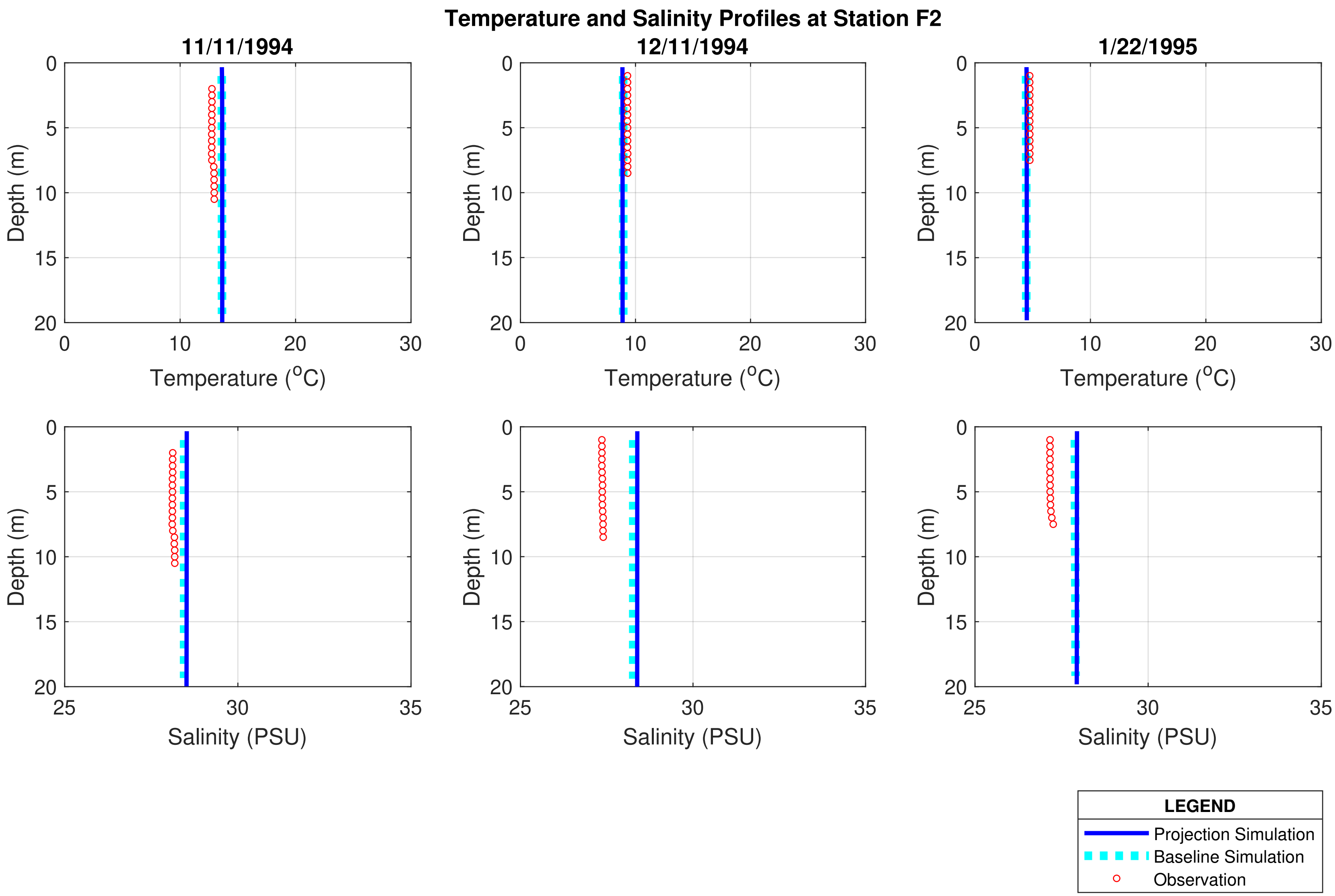

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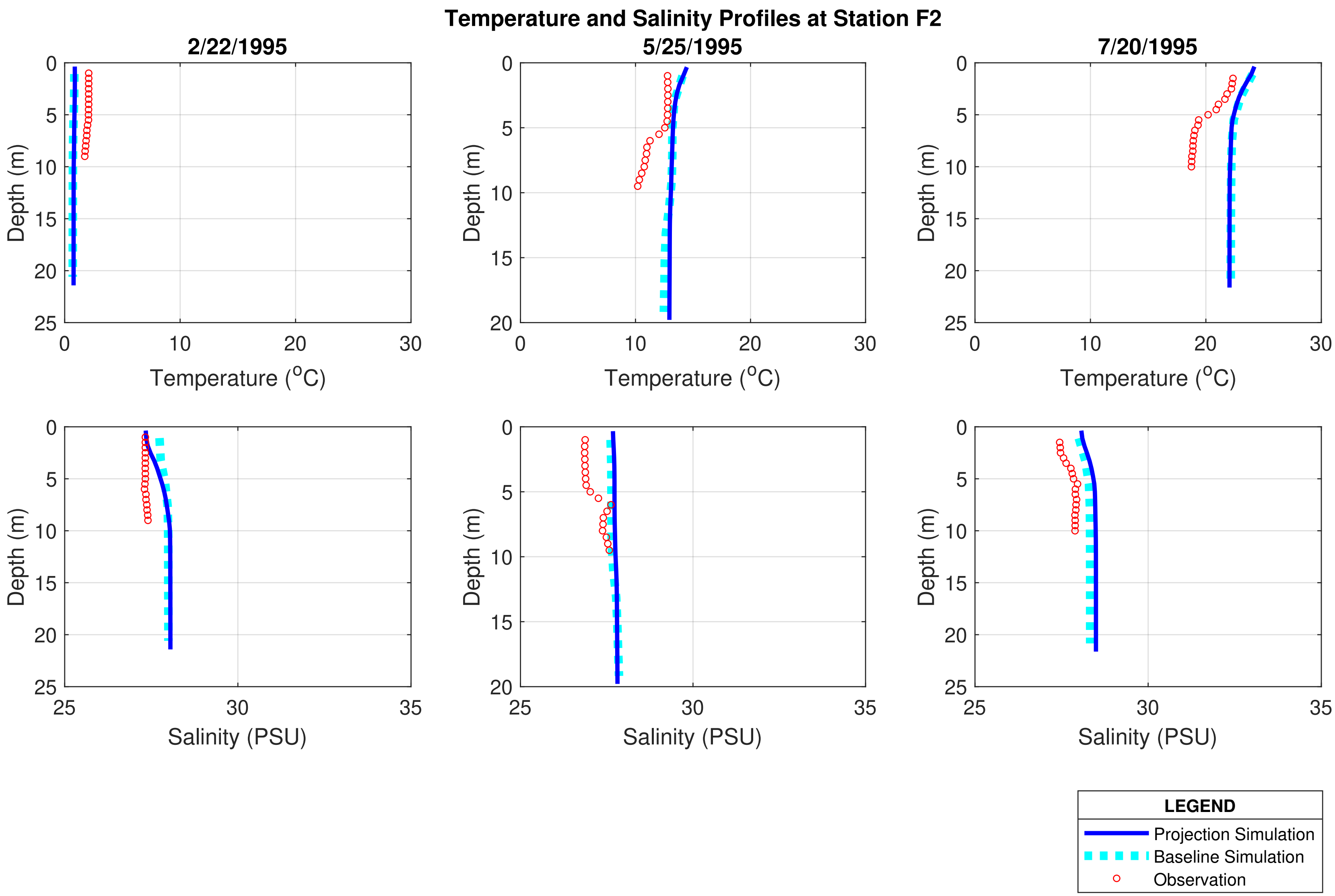

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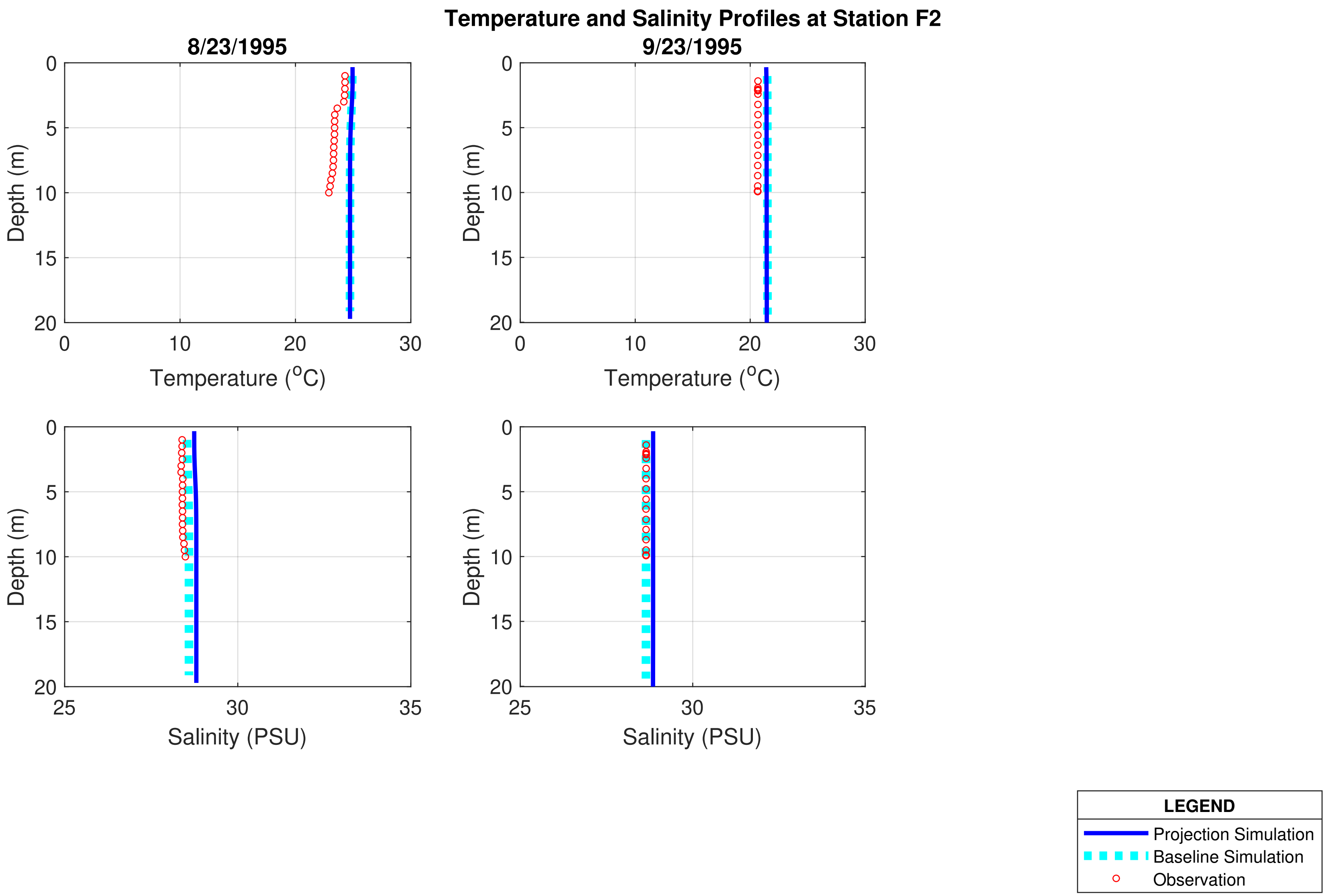

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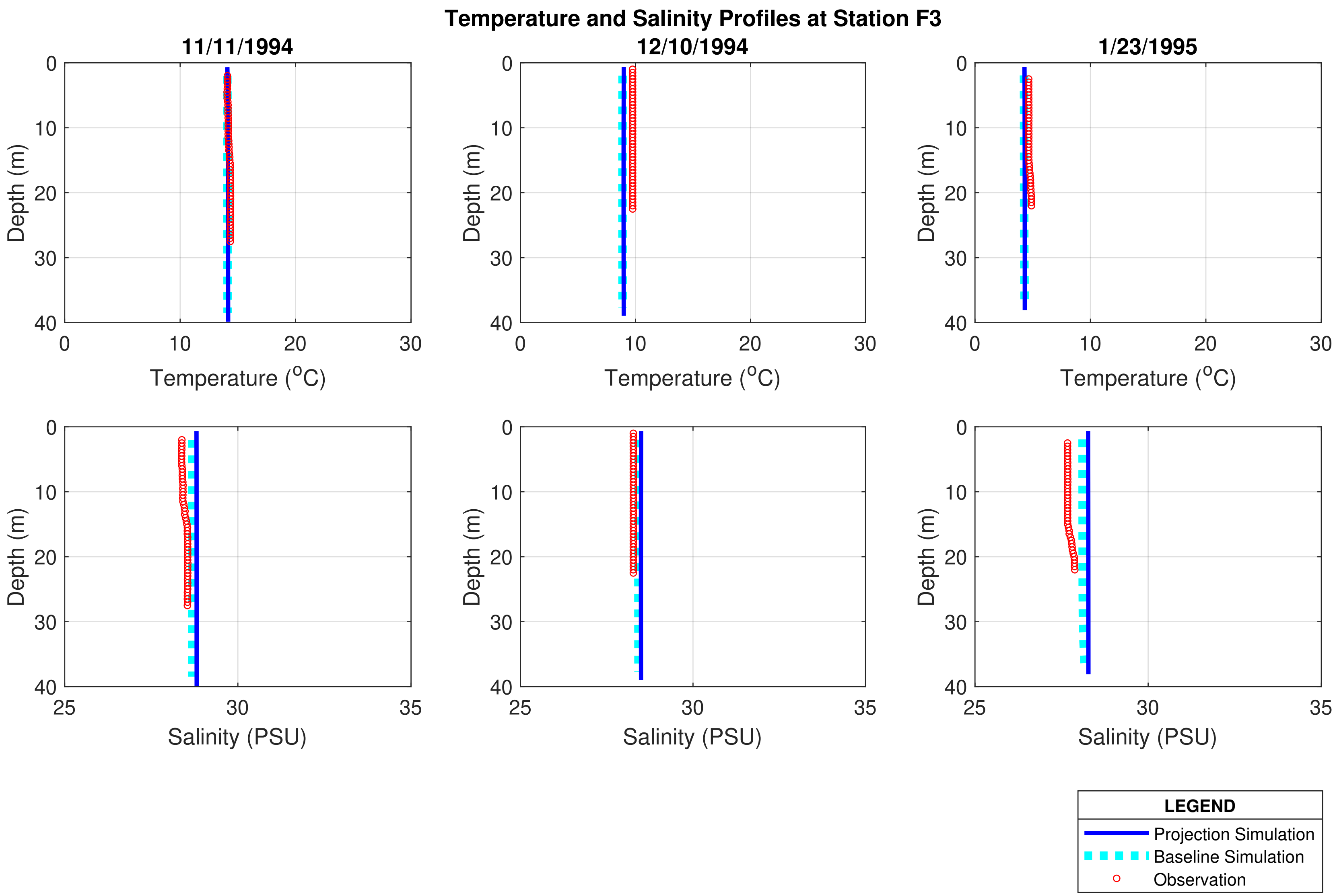

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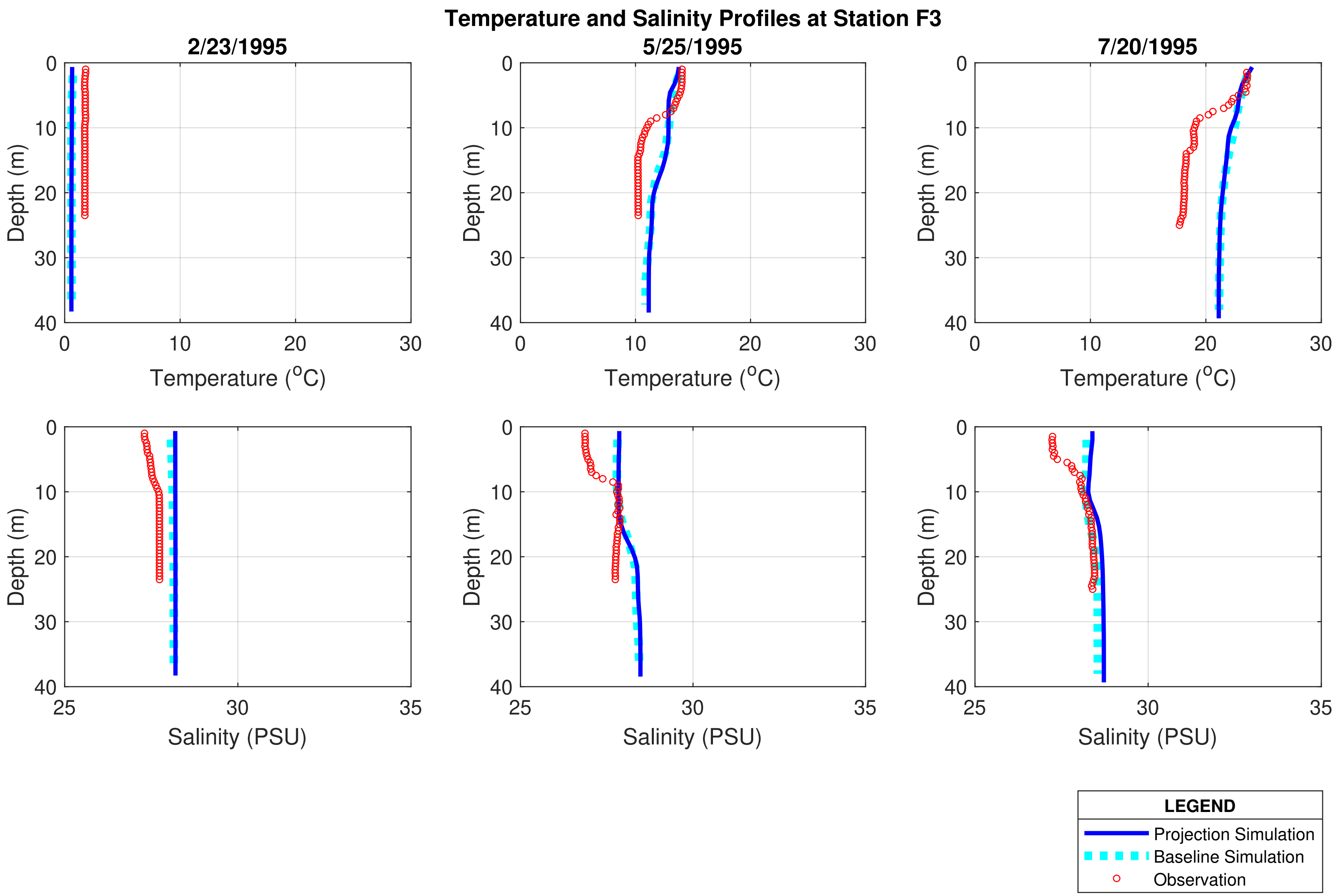

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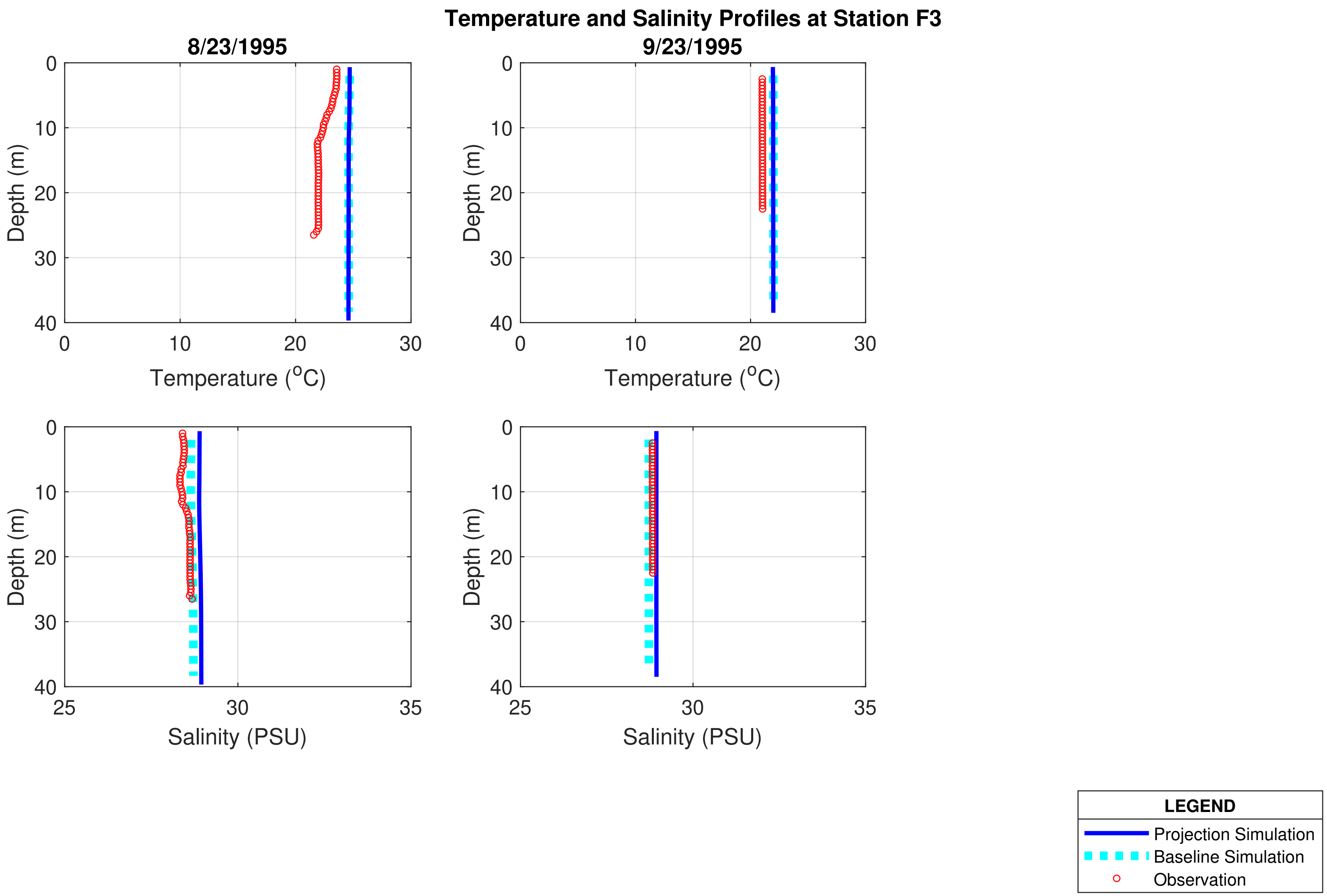

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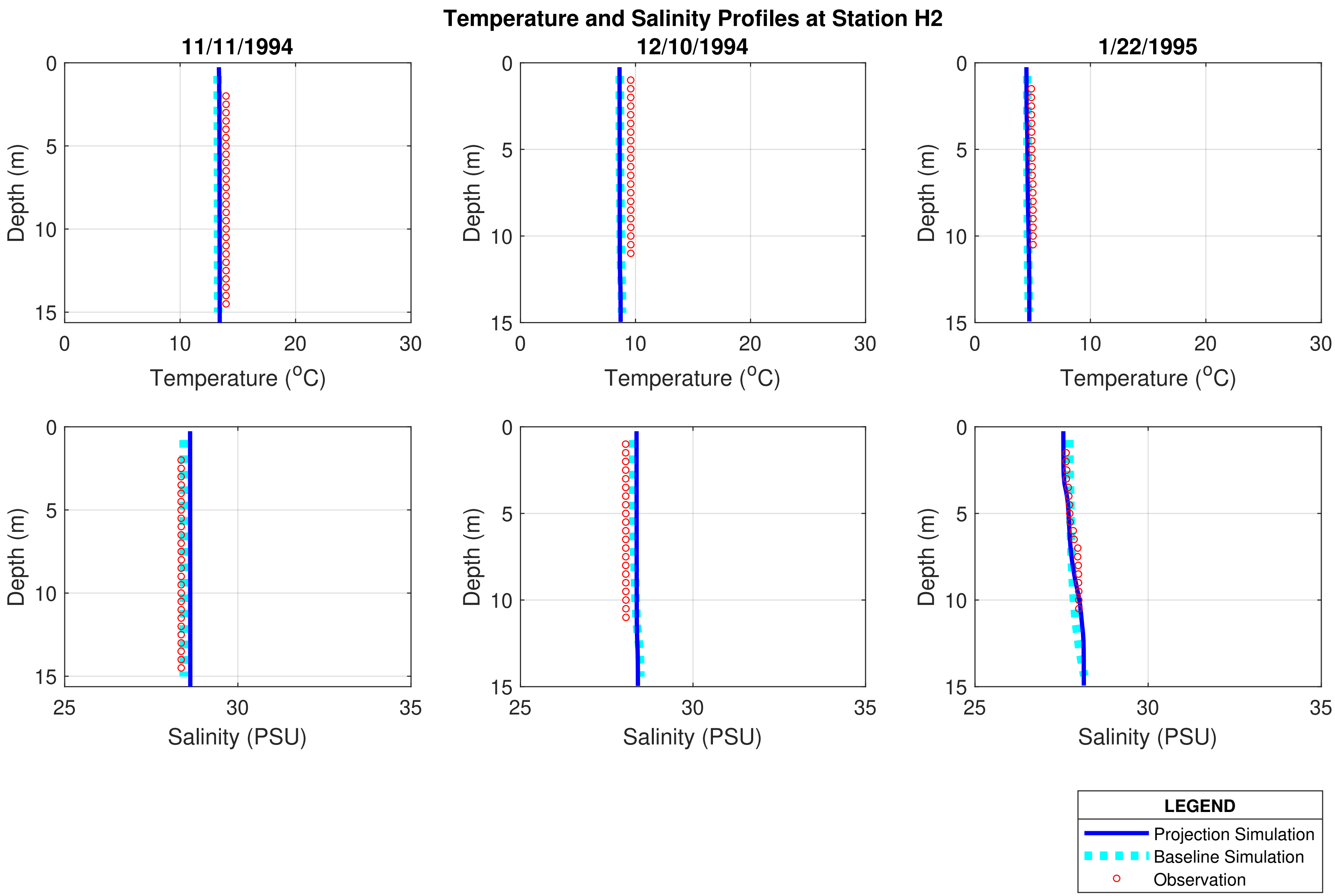

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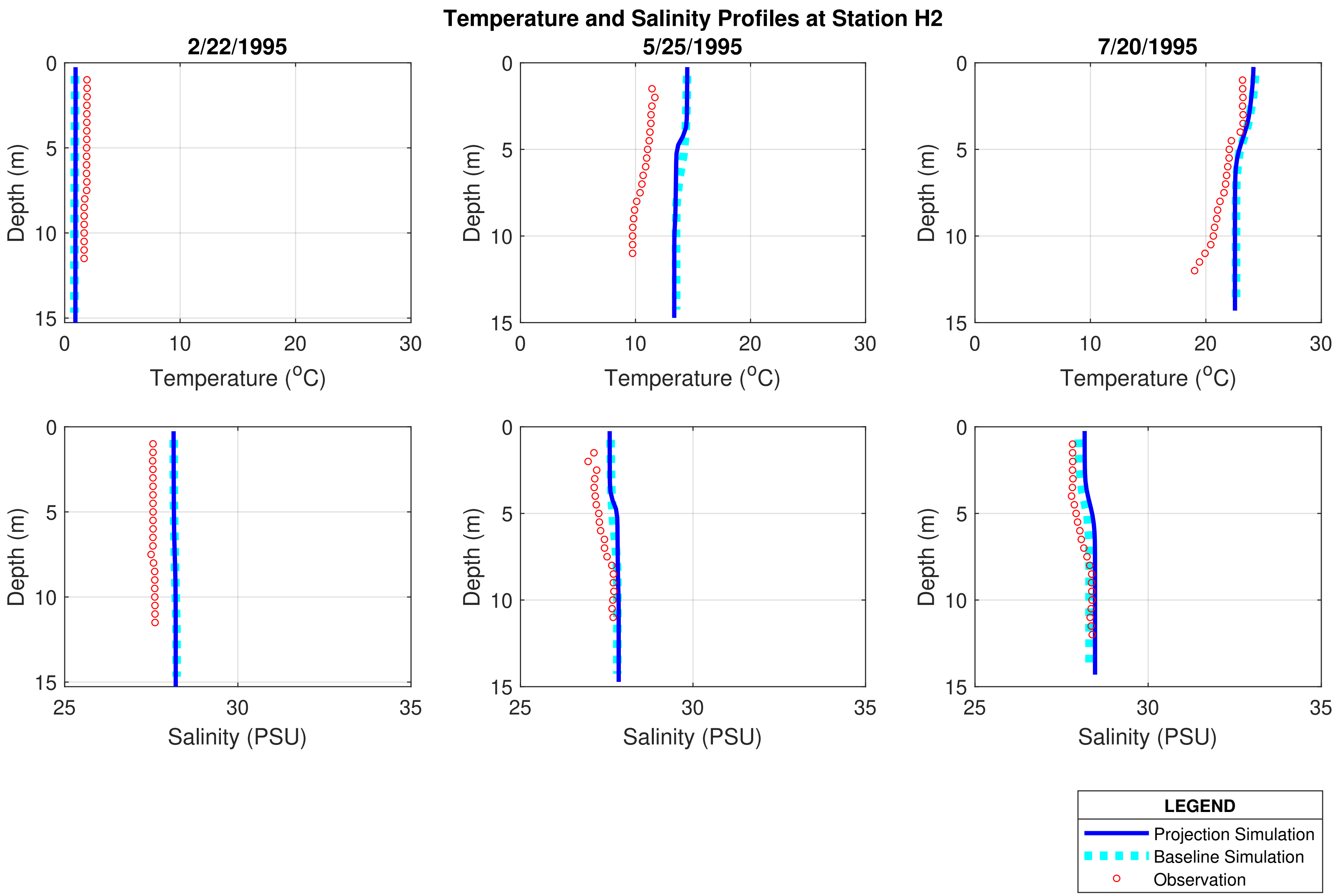

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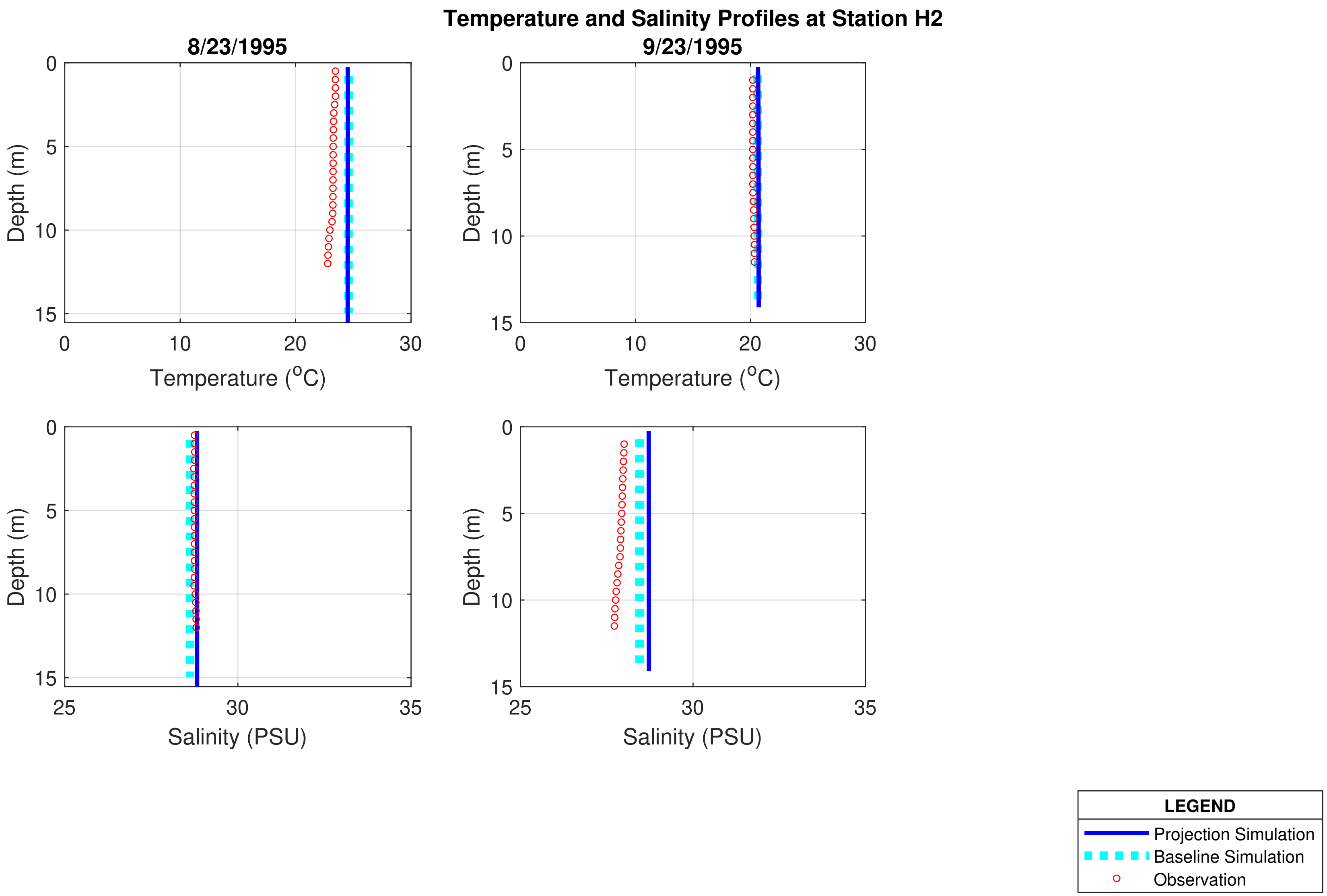

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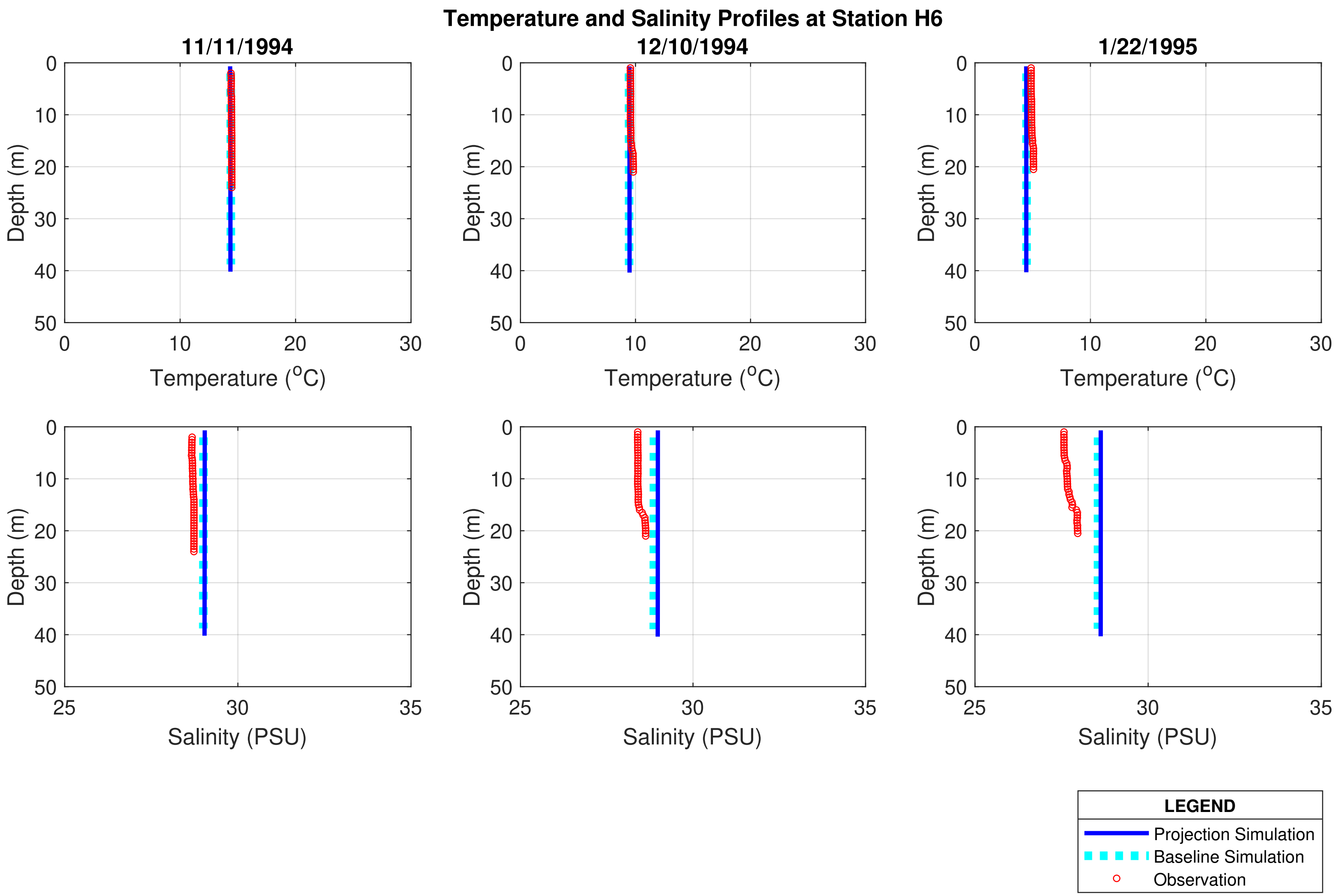

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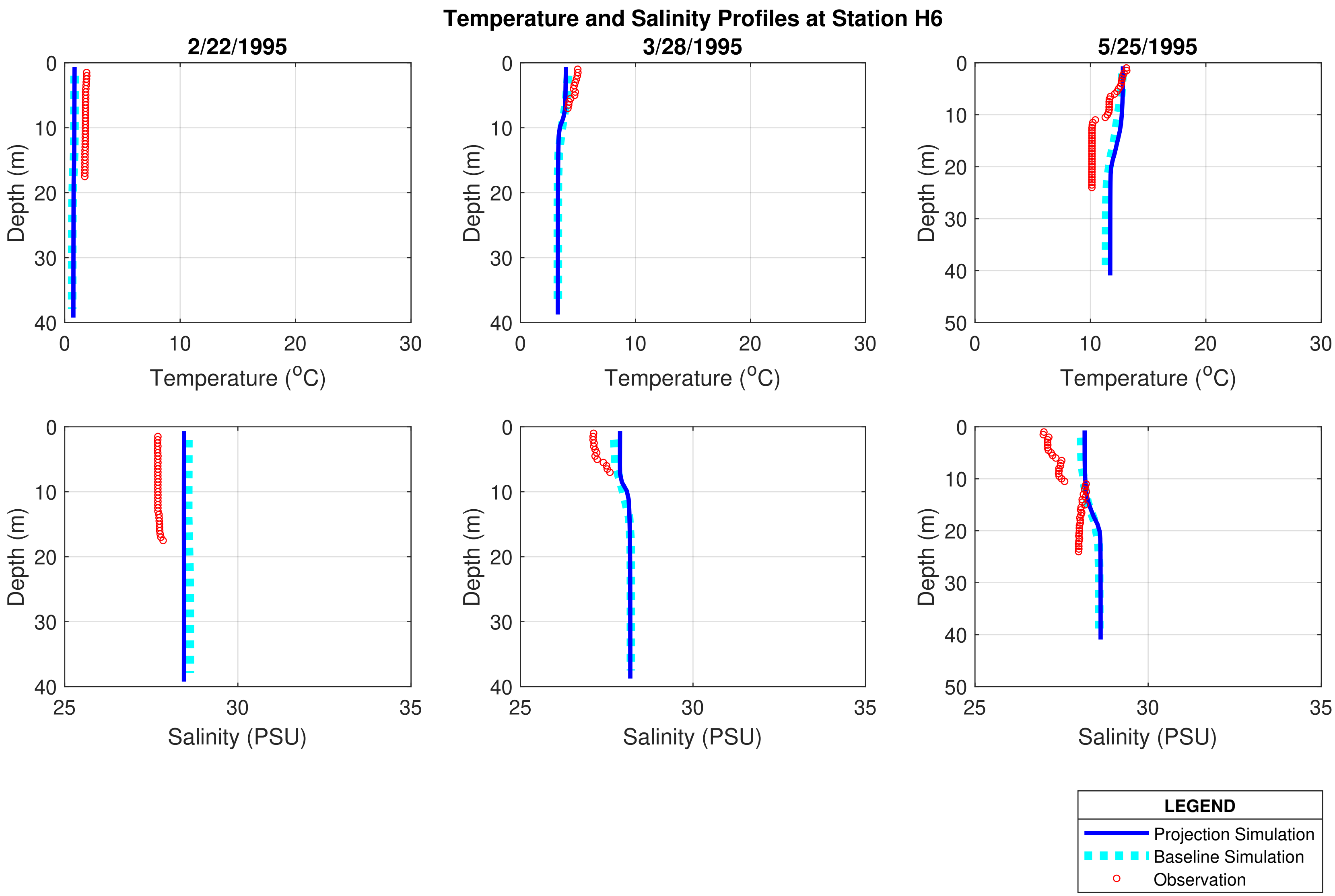

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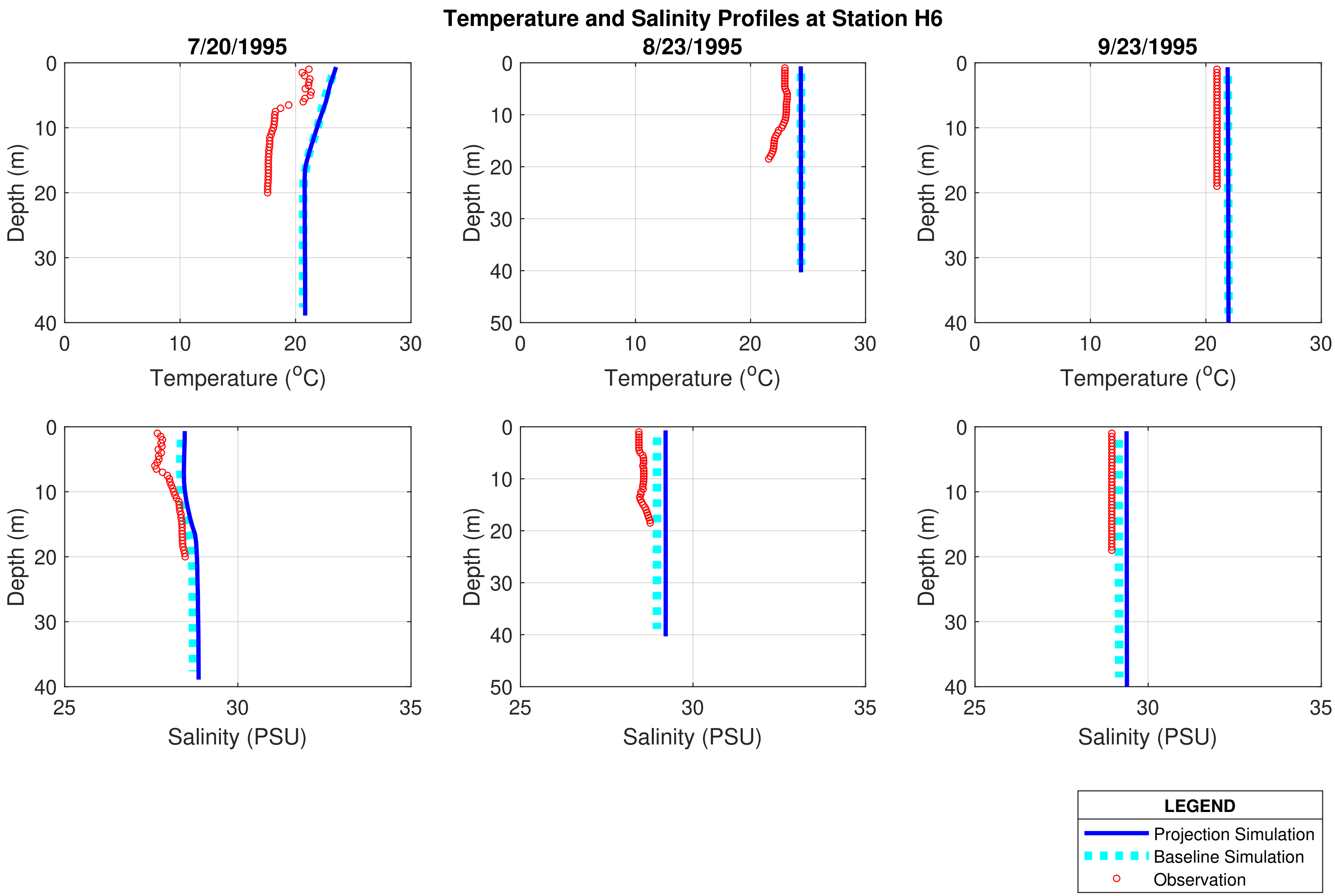

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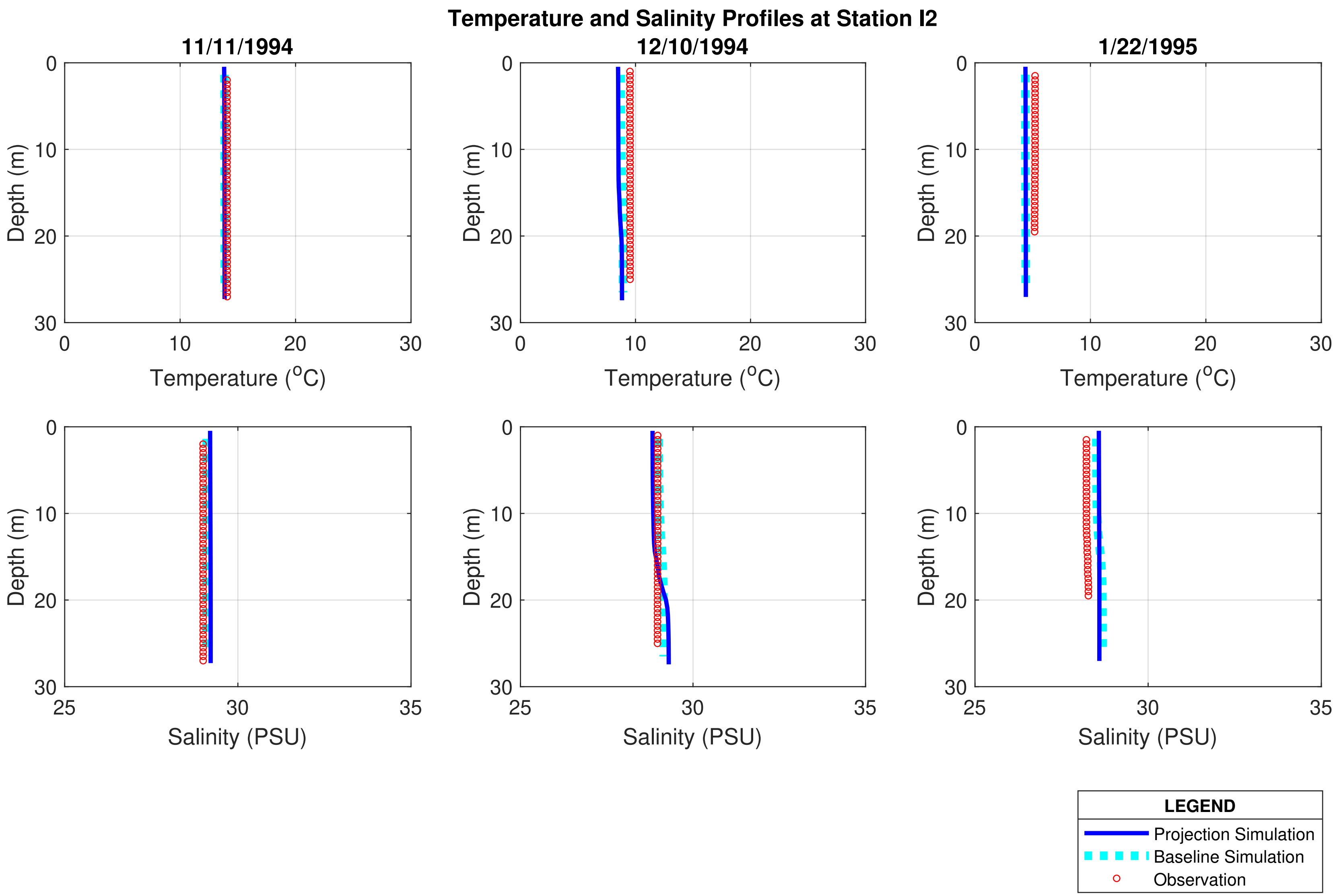

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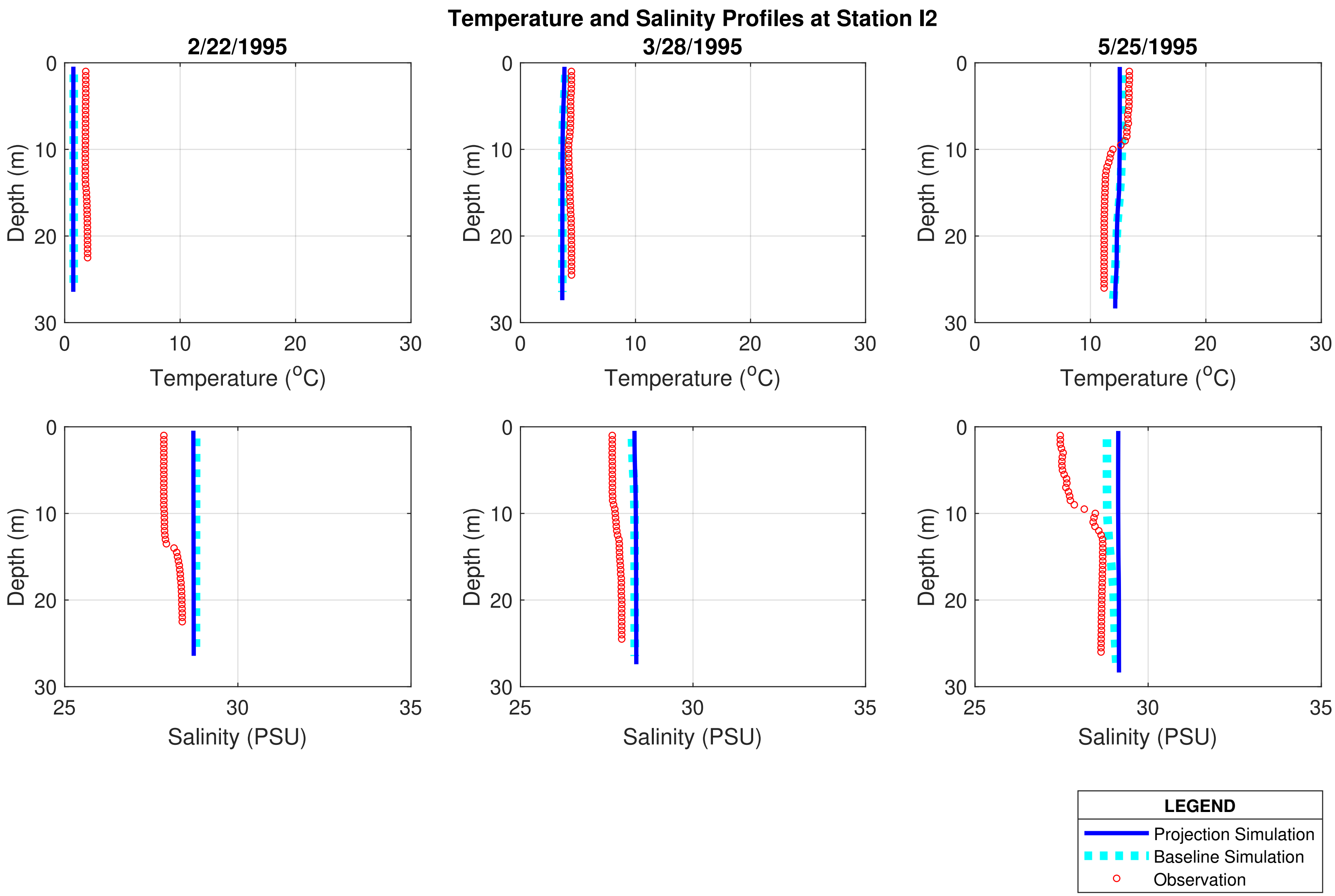

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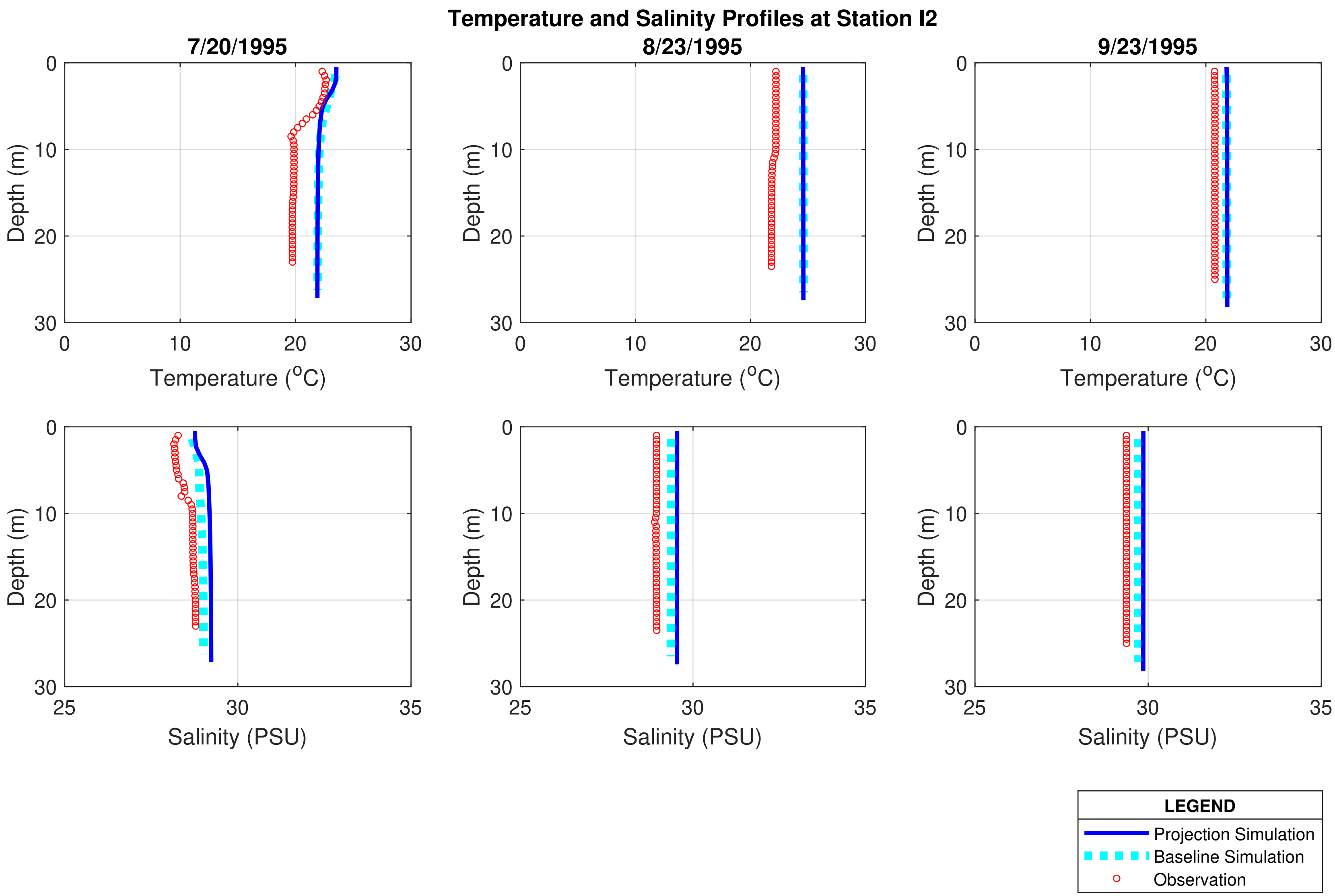

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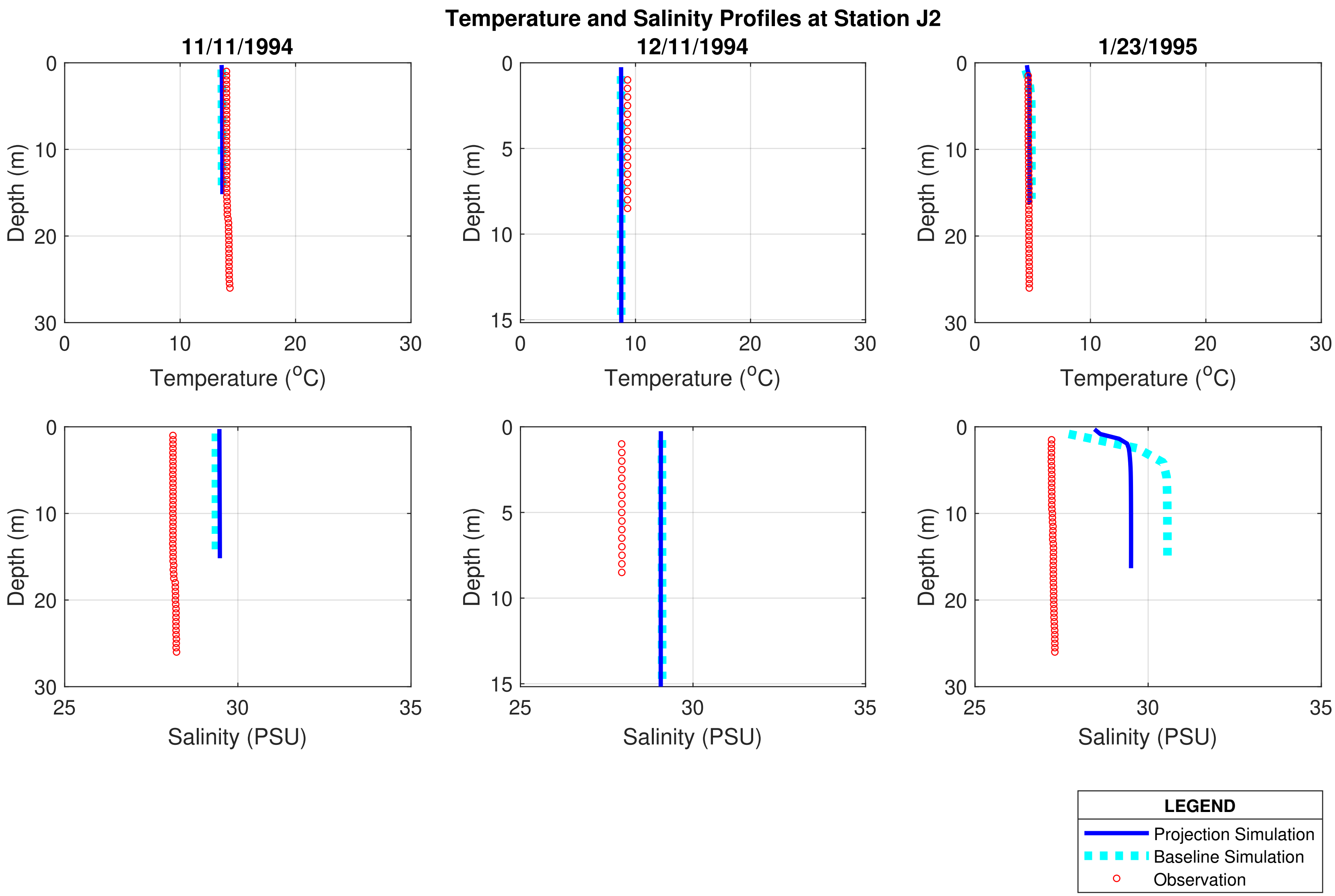

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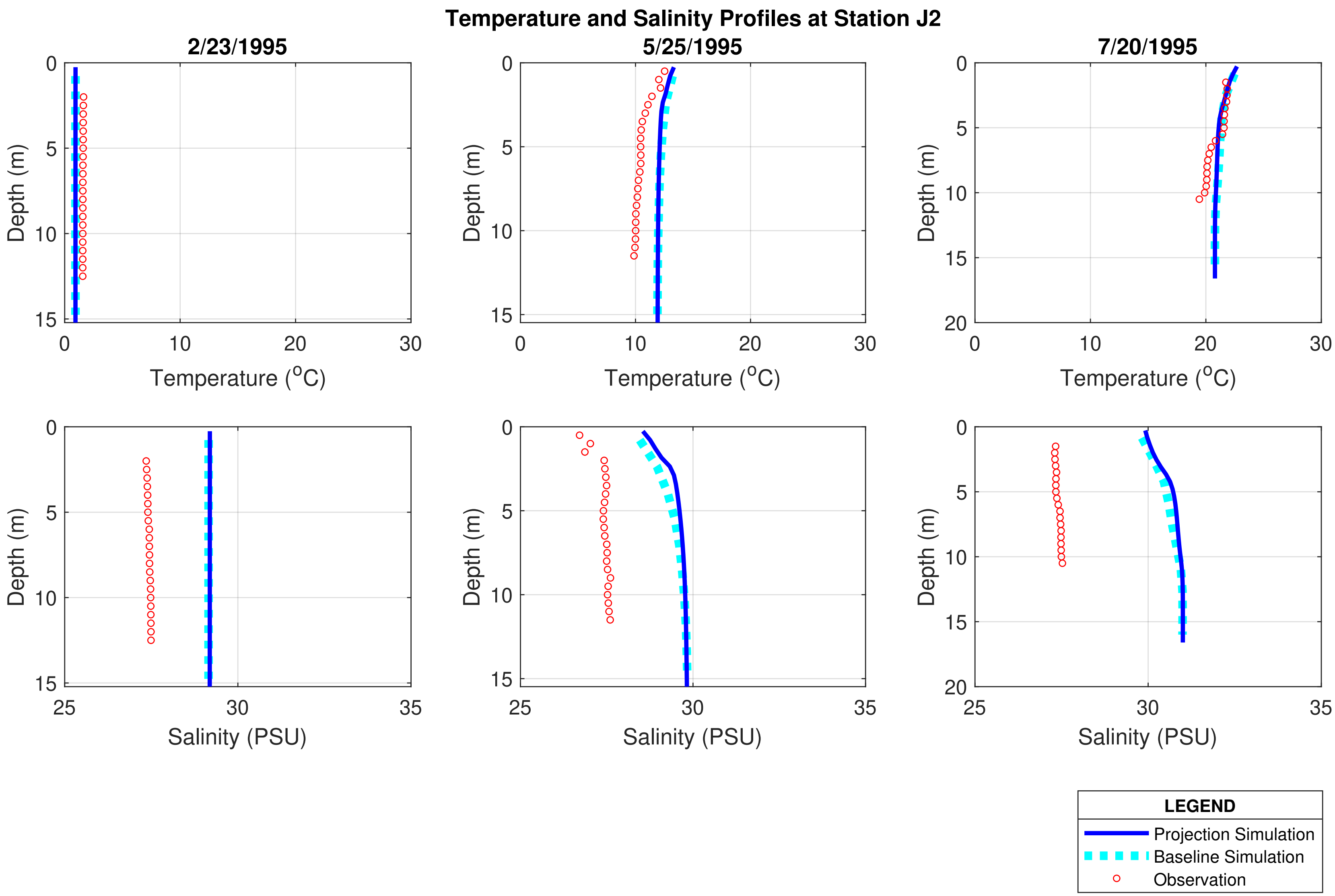

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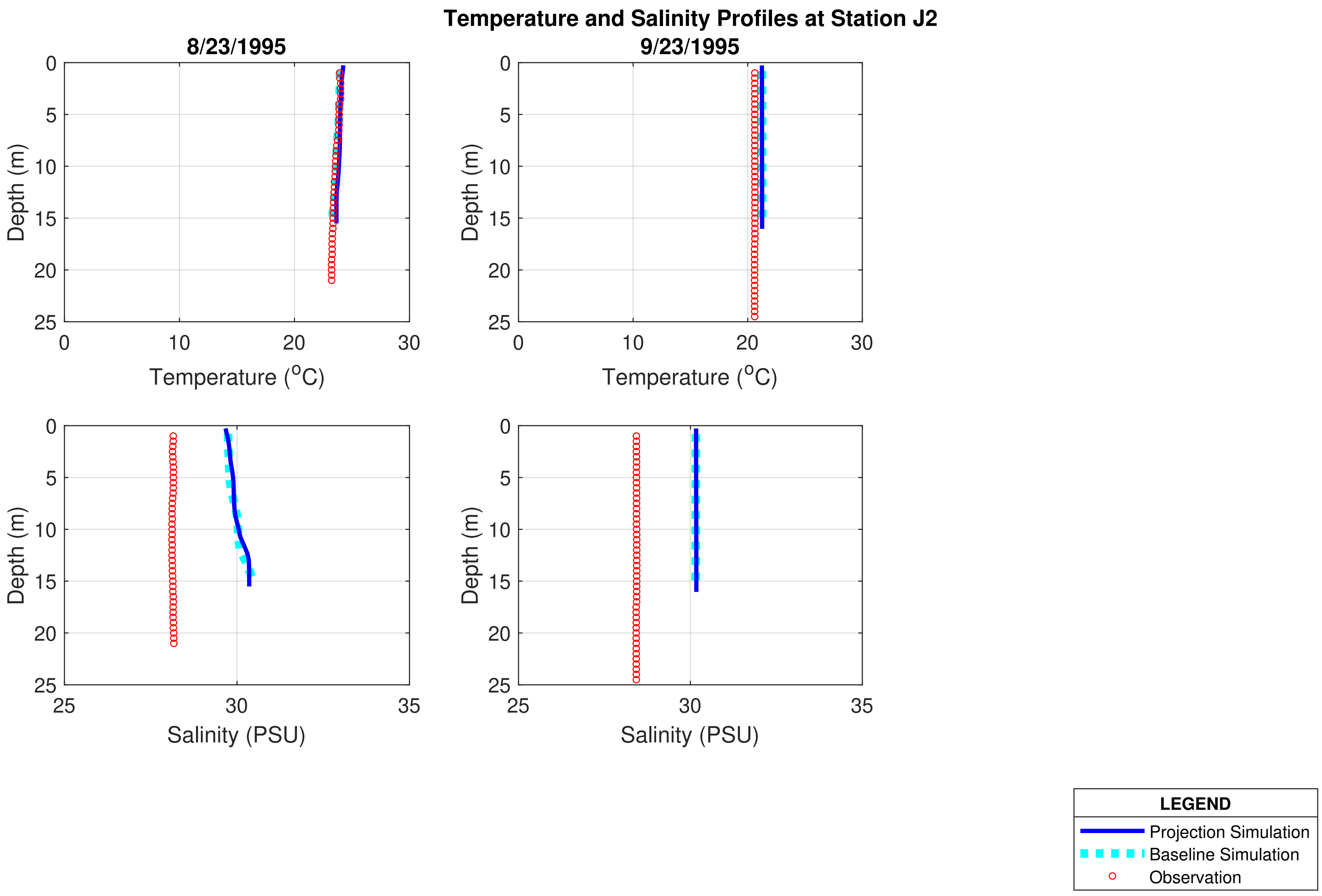

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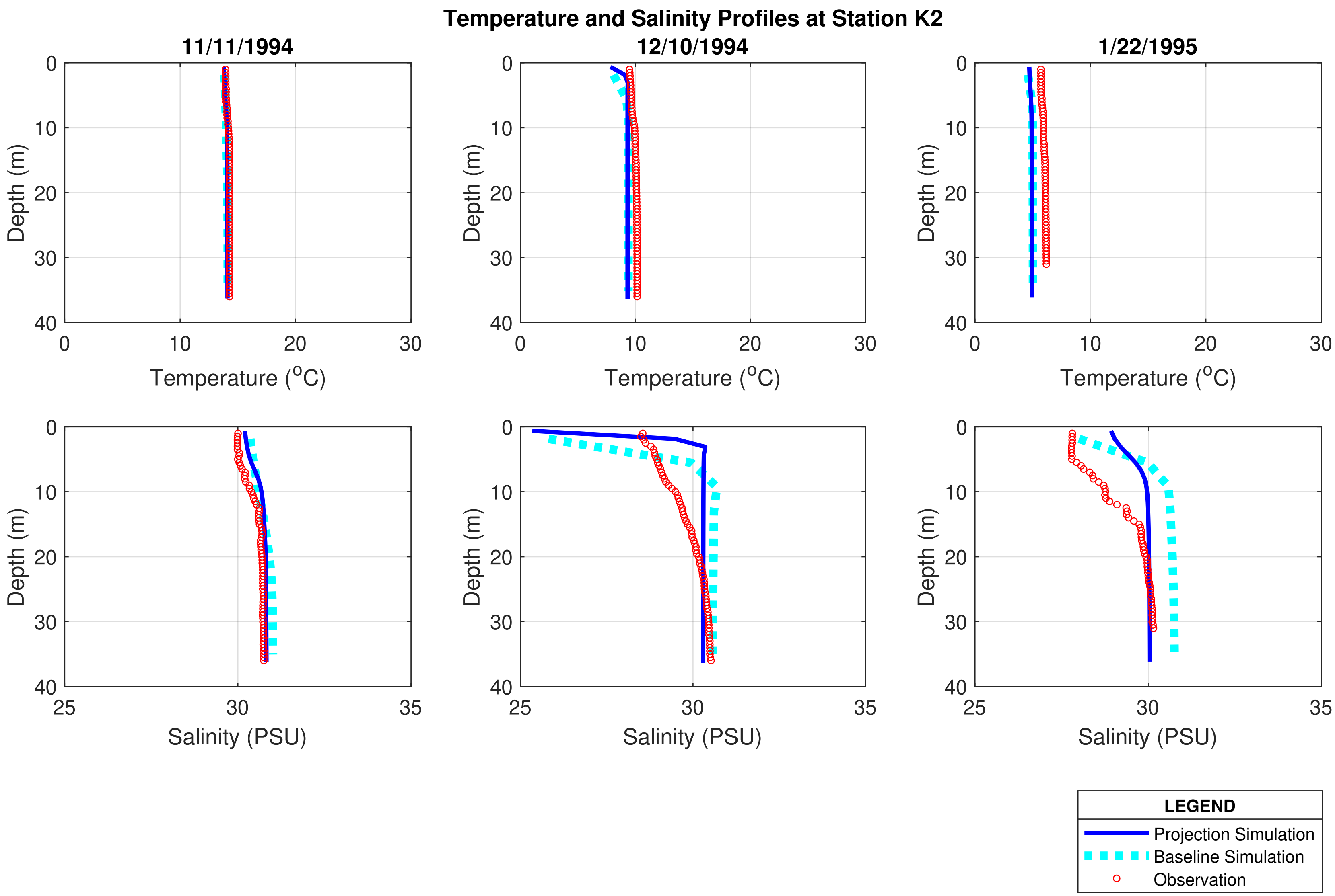

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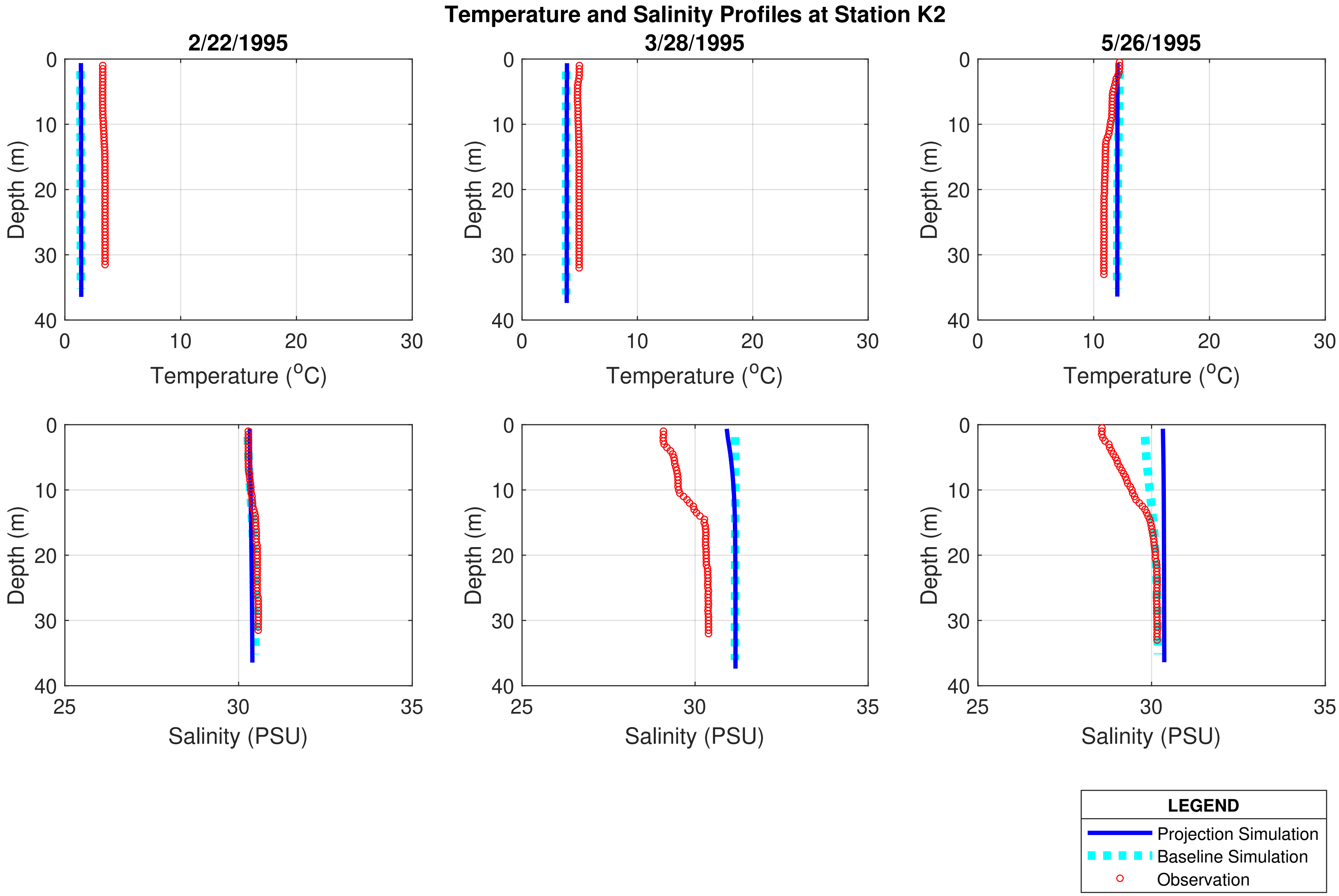

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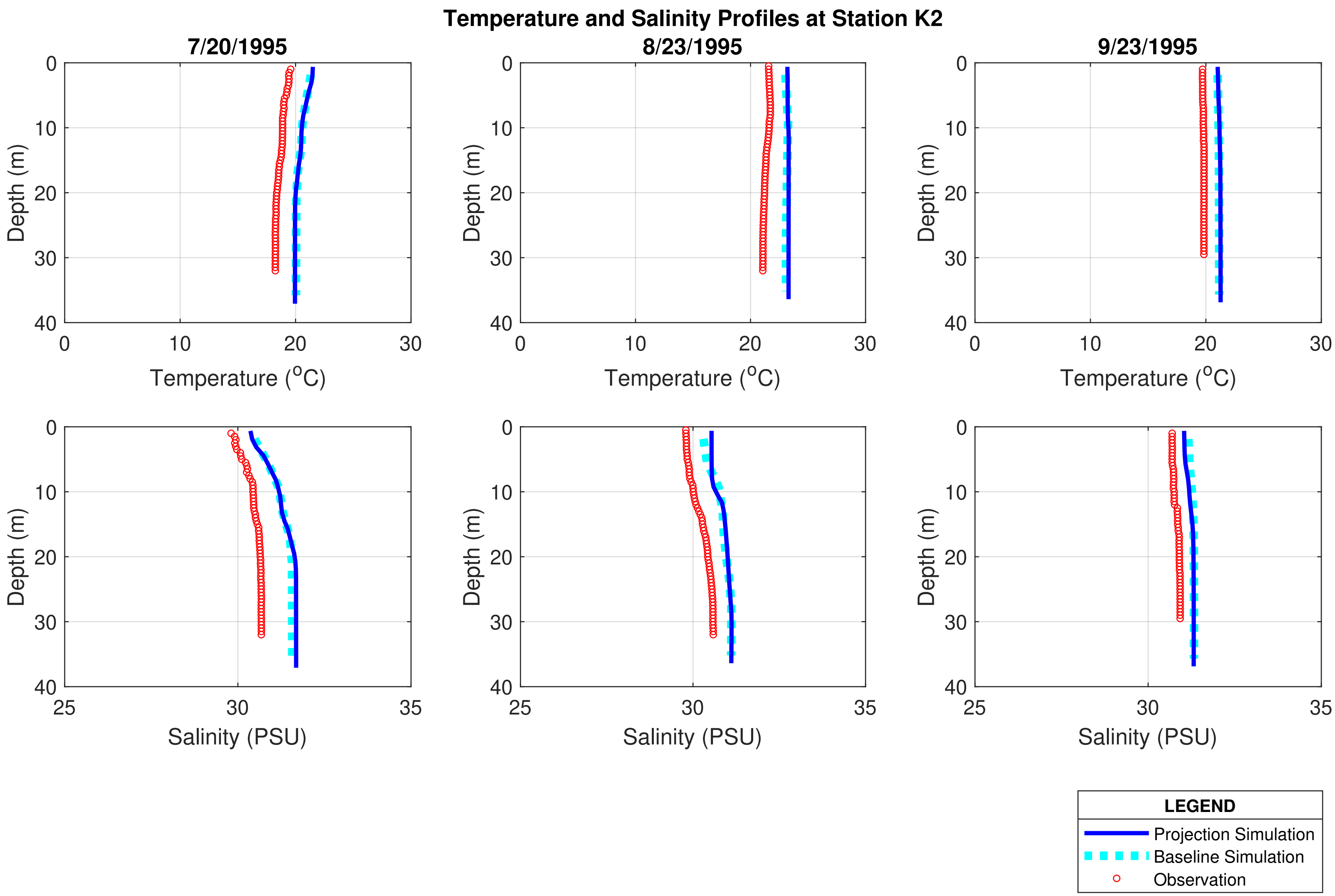

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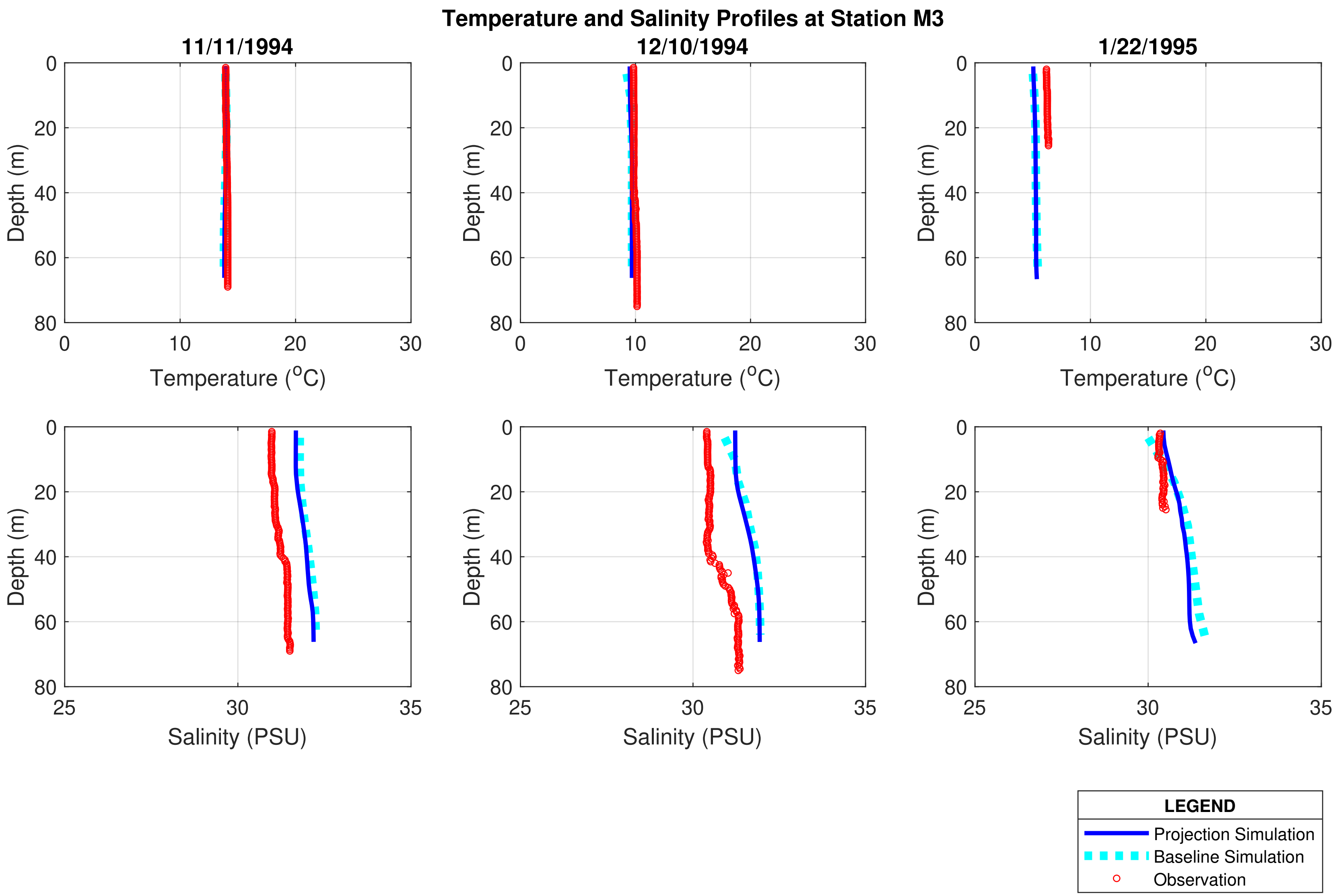

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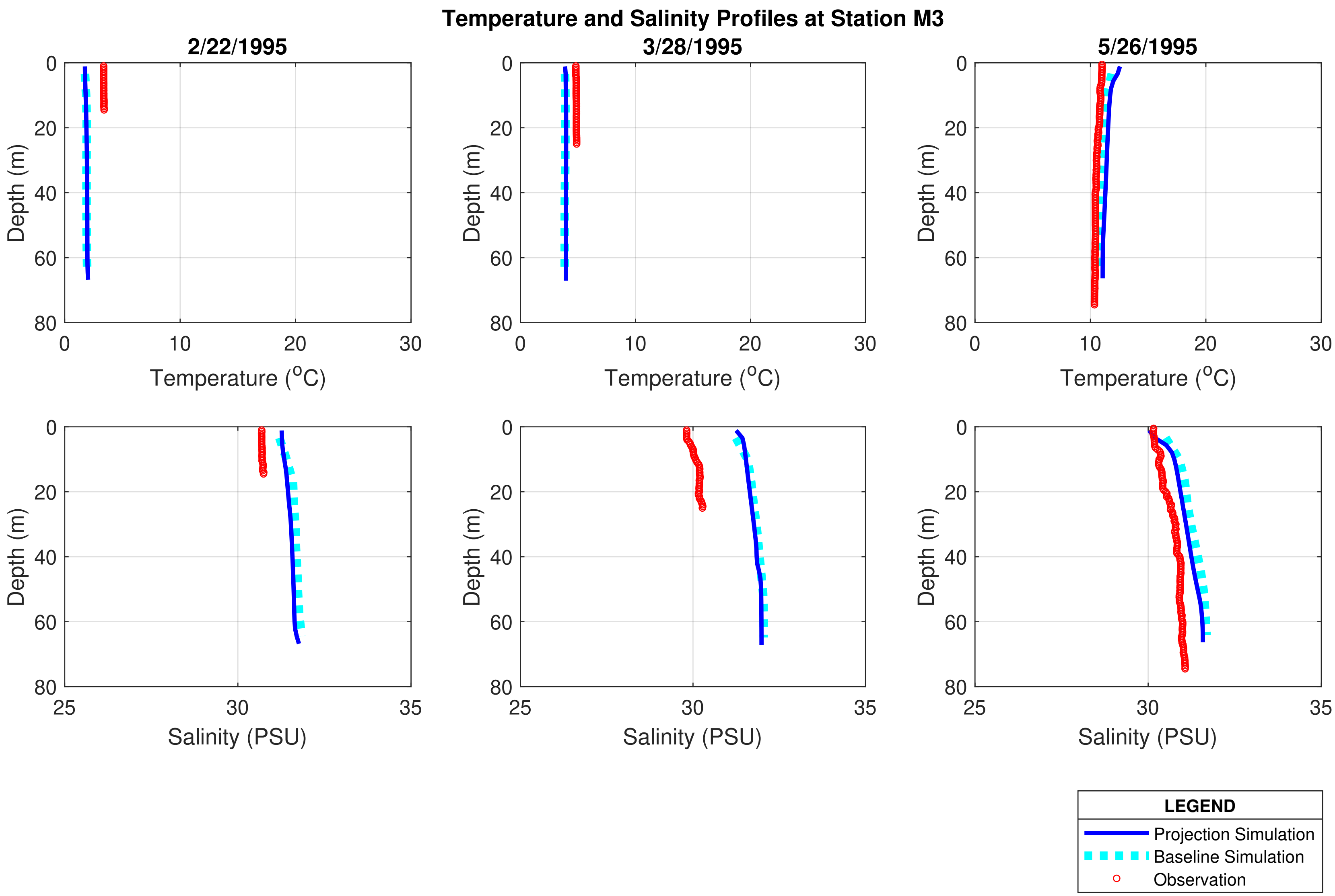

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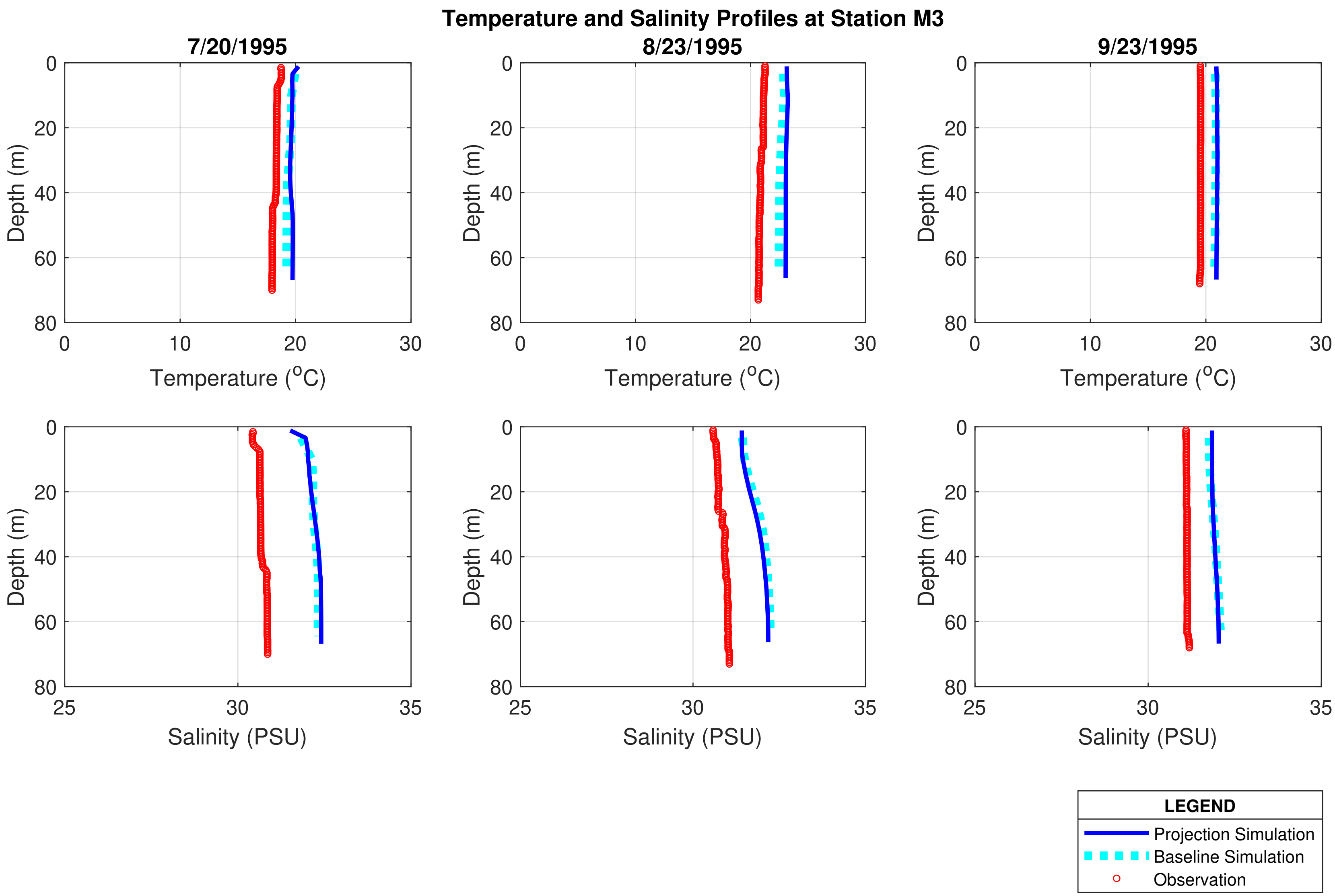
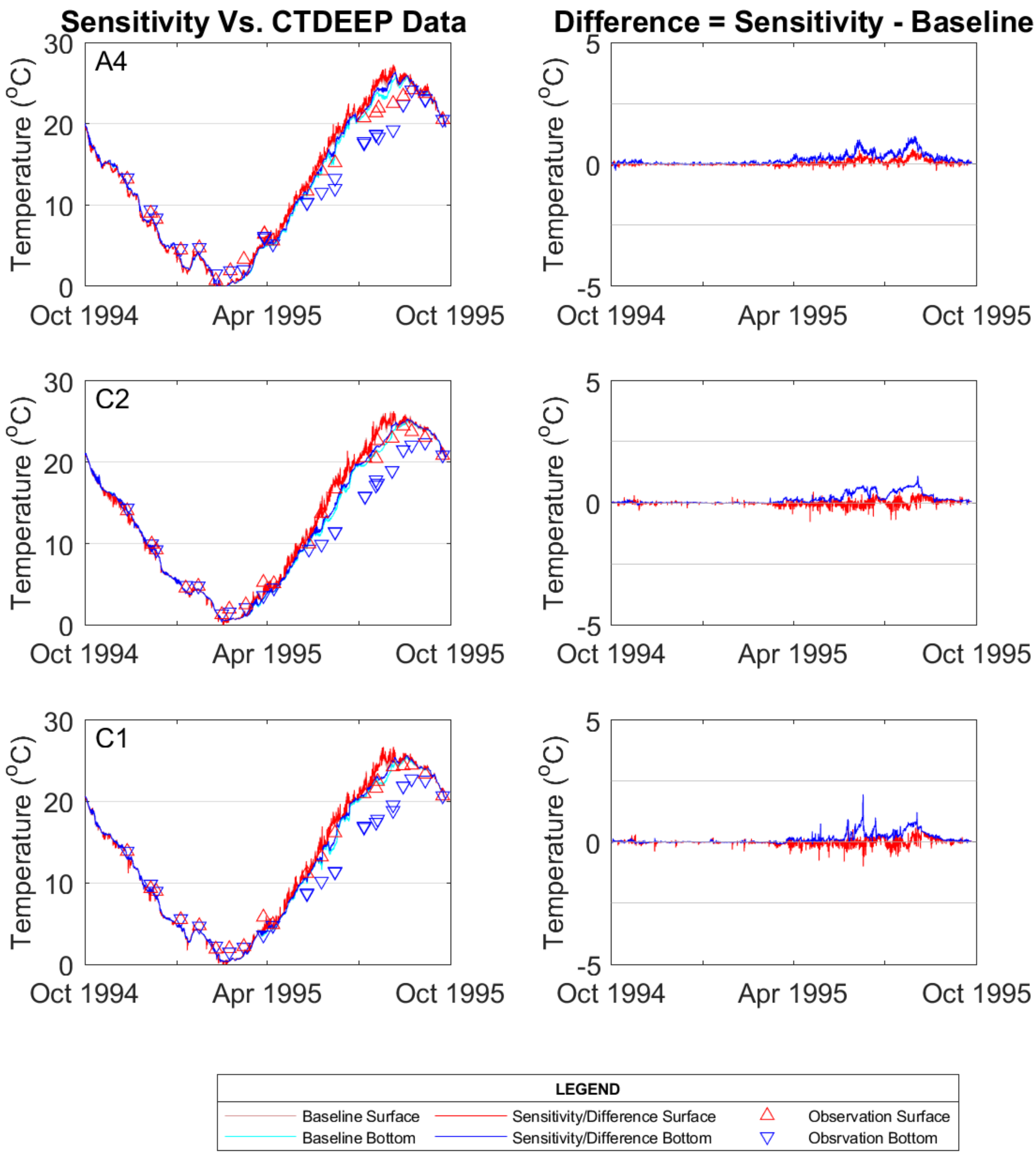


LIS28 - 30 Layers

8

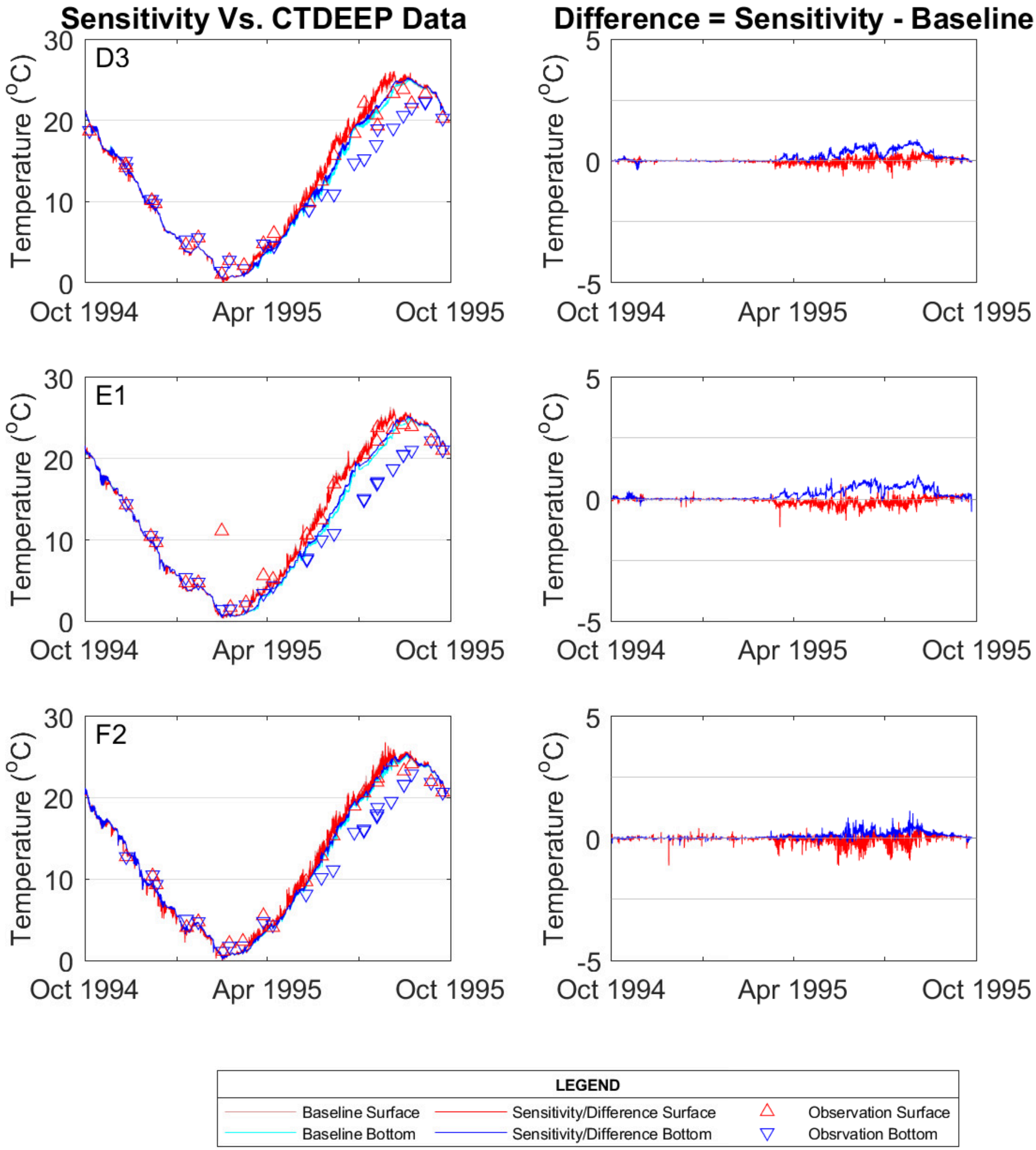
ROMS Jerlov Water Type Sensitivity

(Type III vs. Type I)



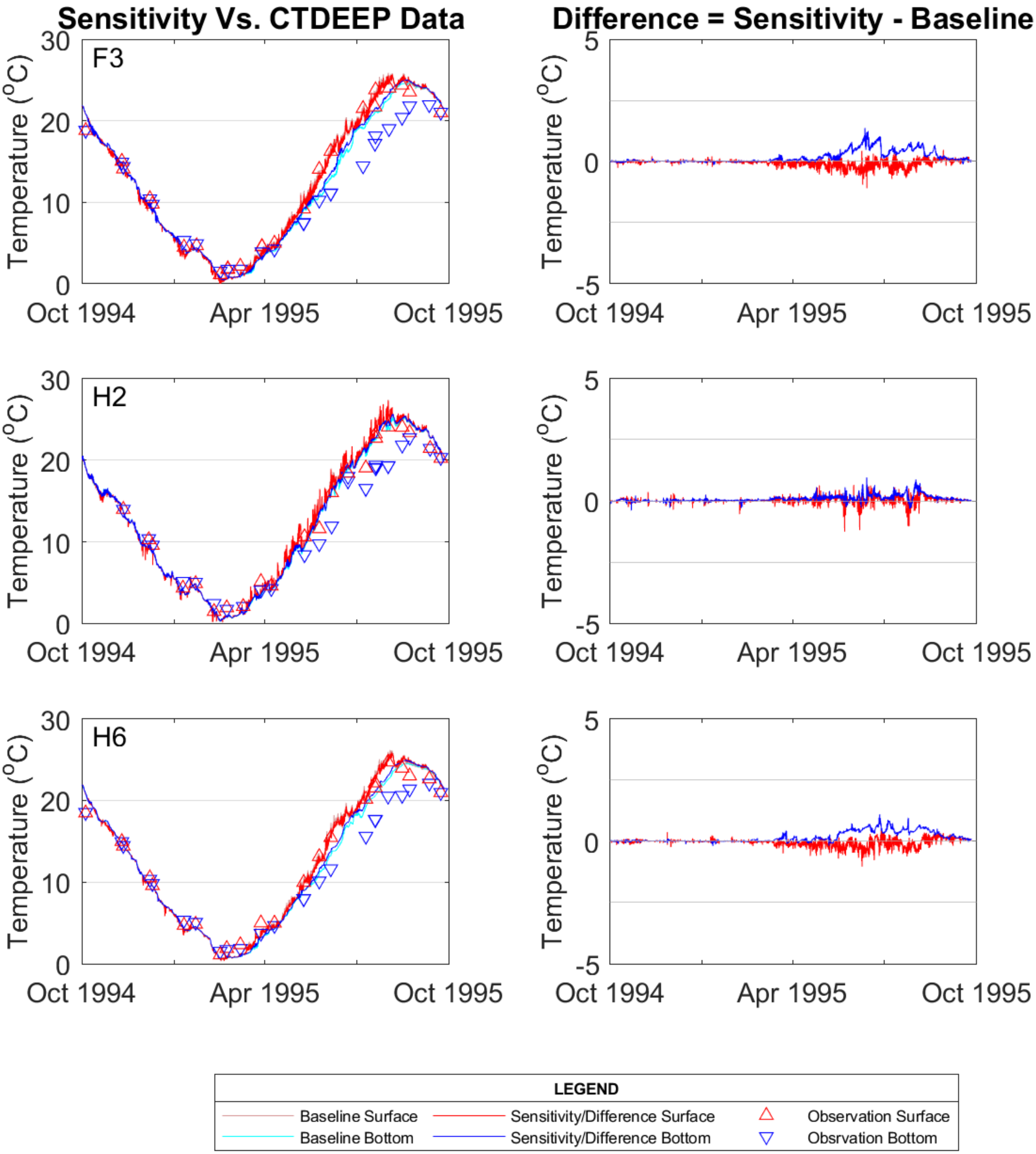
Baseline = Water Type III

Sensitivity = Water Type I



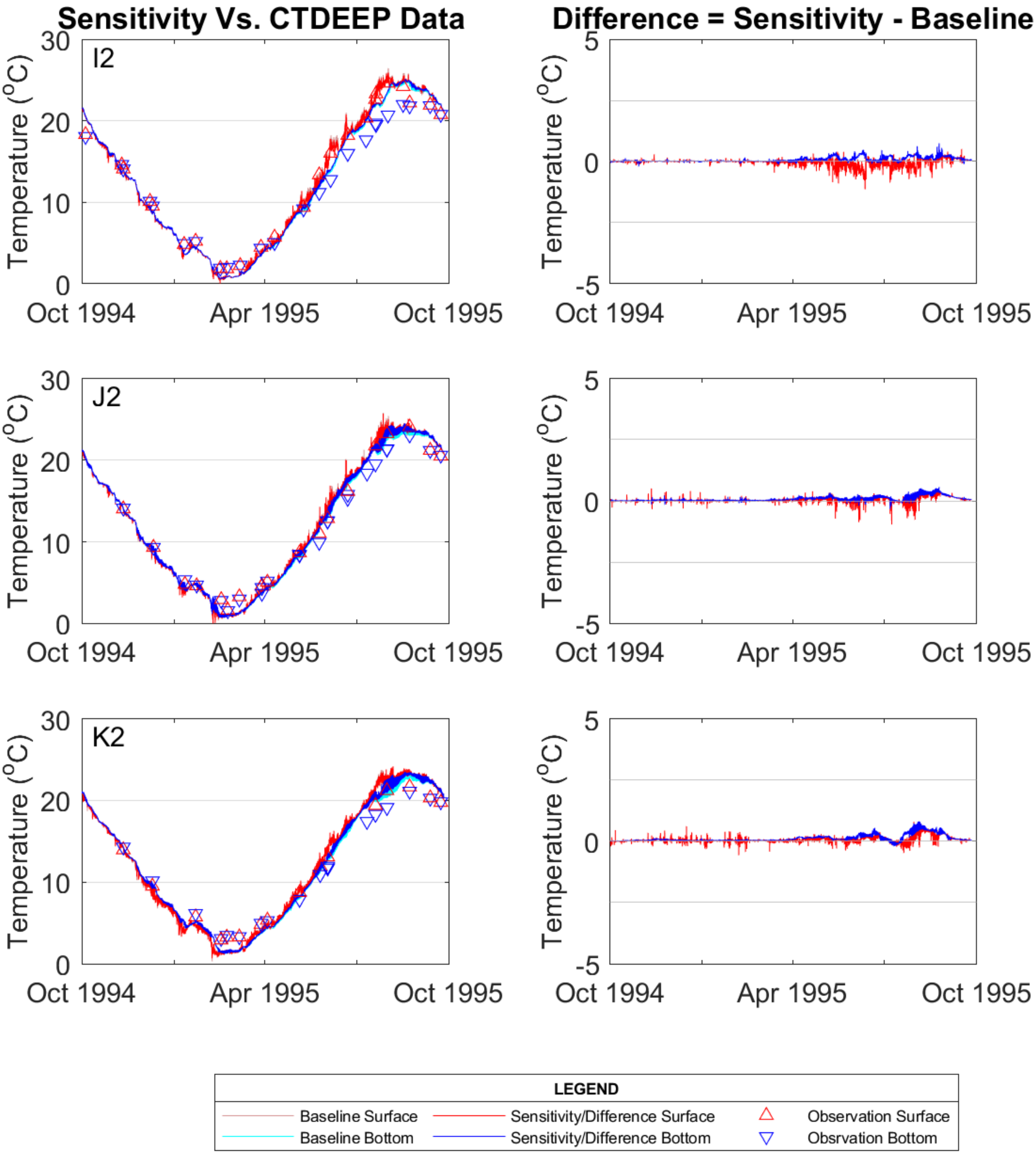
Baseline = Water Type III

Sensitivity = Water Type I

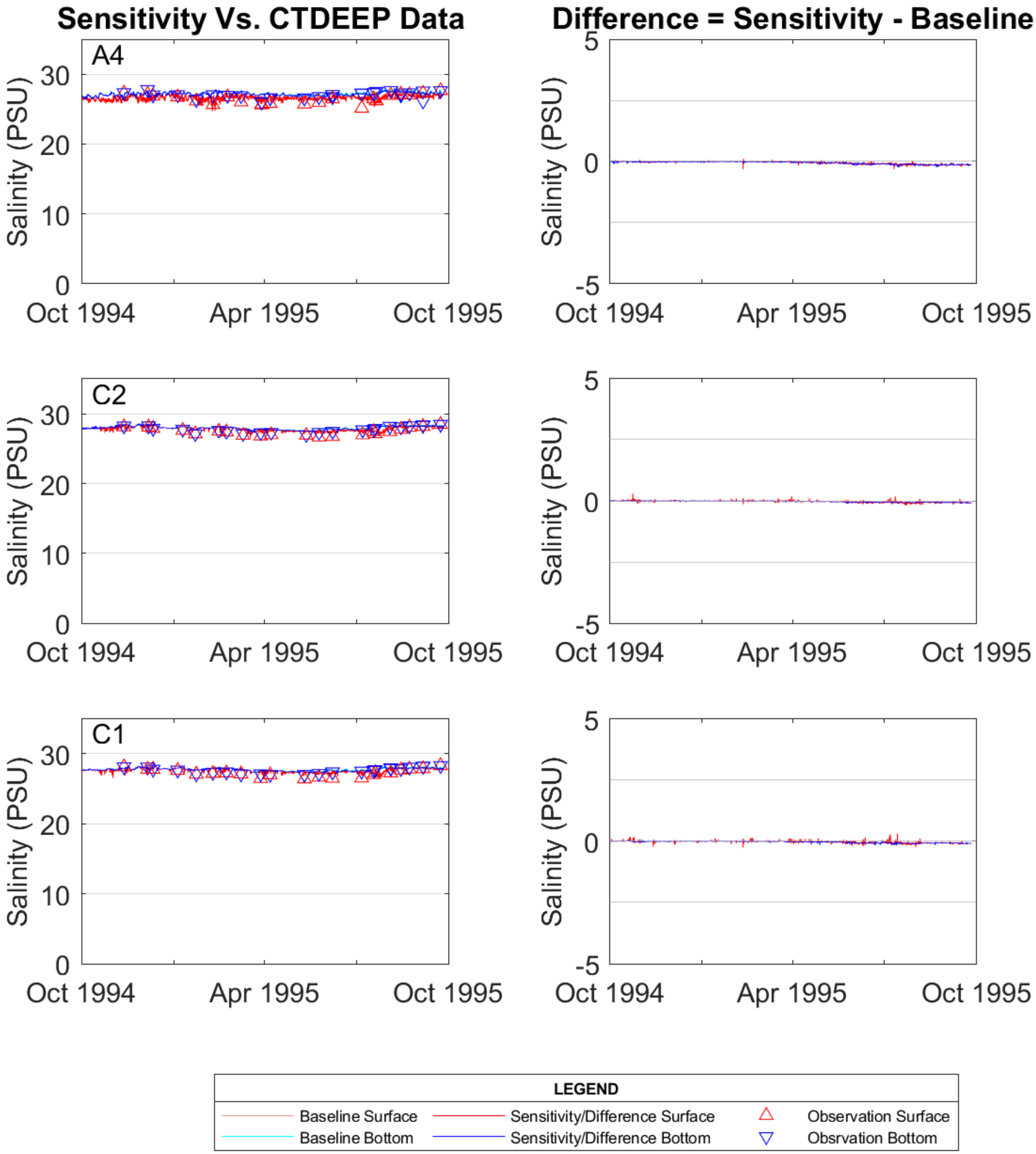


Baseline = Water Type III

Sensitivity = Water Type I

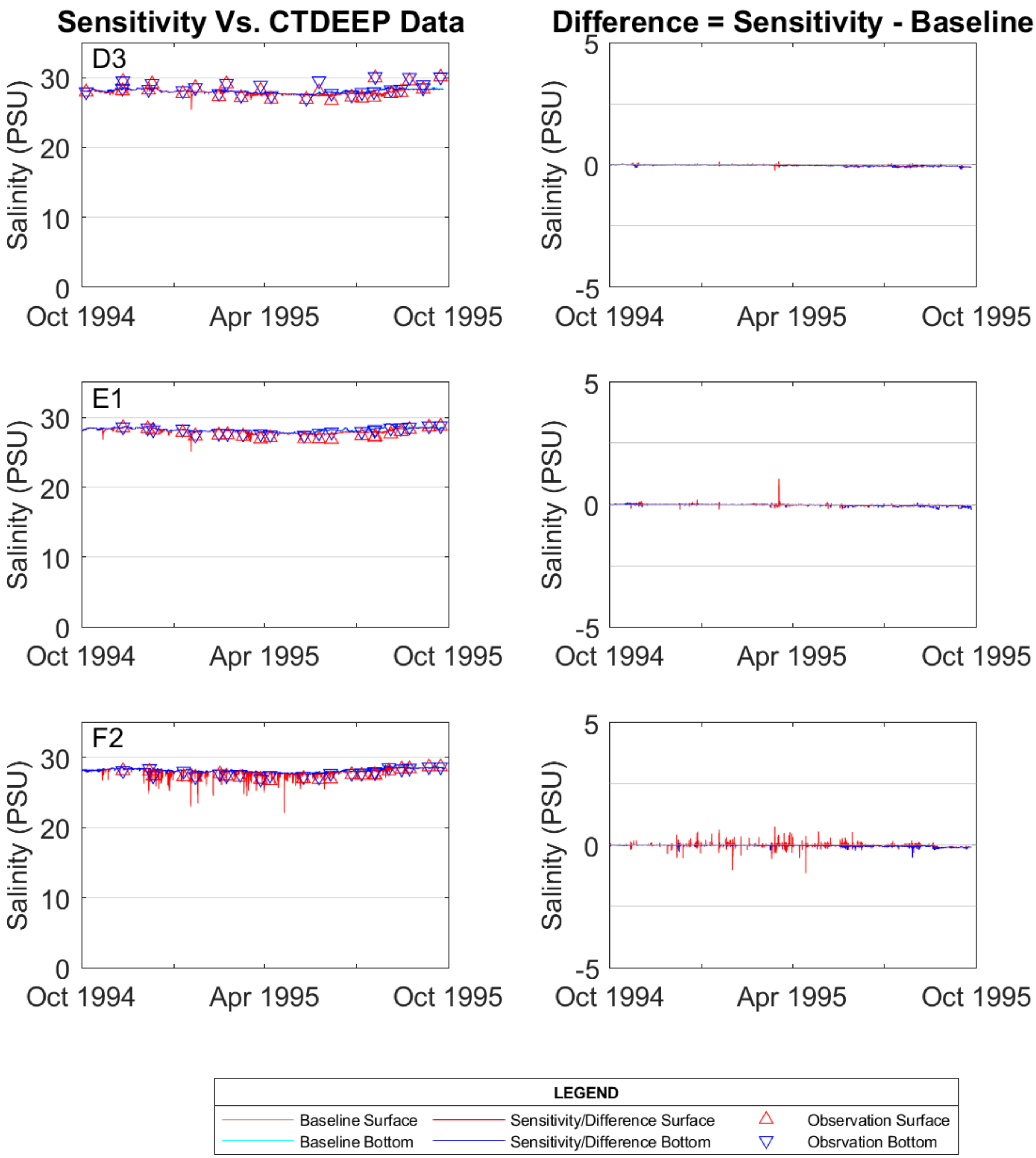


Baseline = Water Type III
Sensitivity = Water Type I



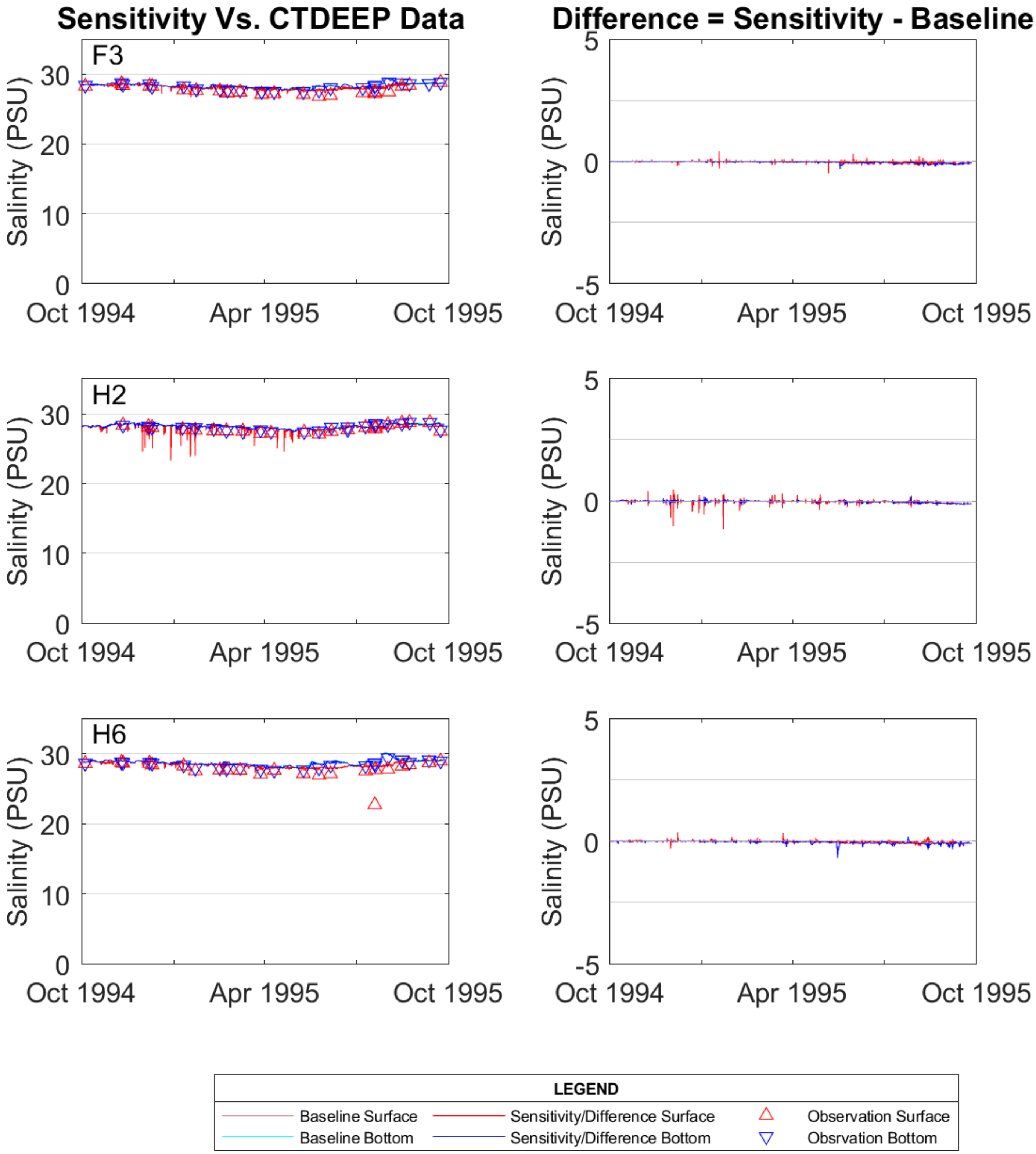
Baseline = Water Type III

Sensitivity = Water Type I

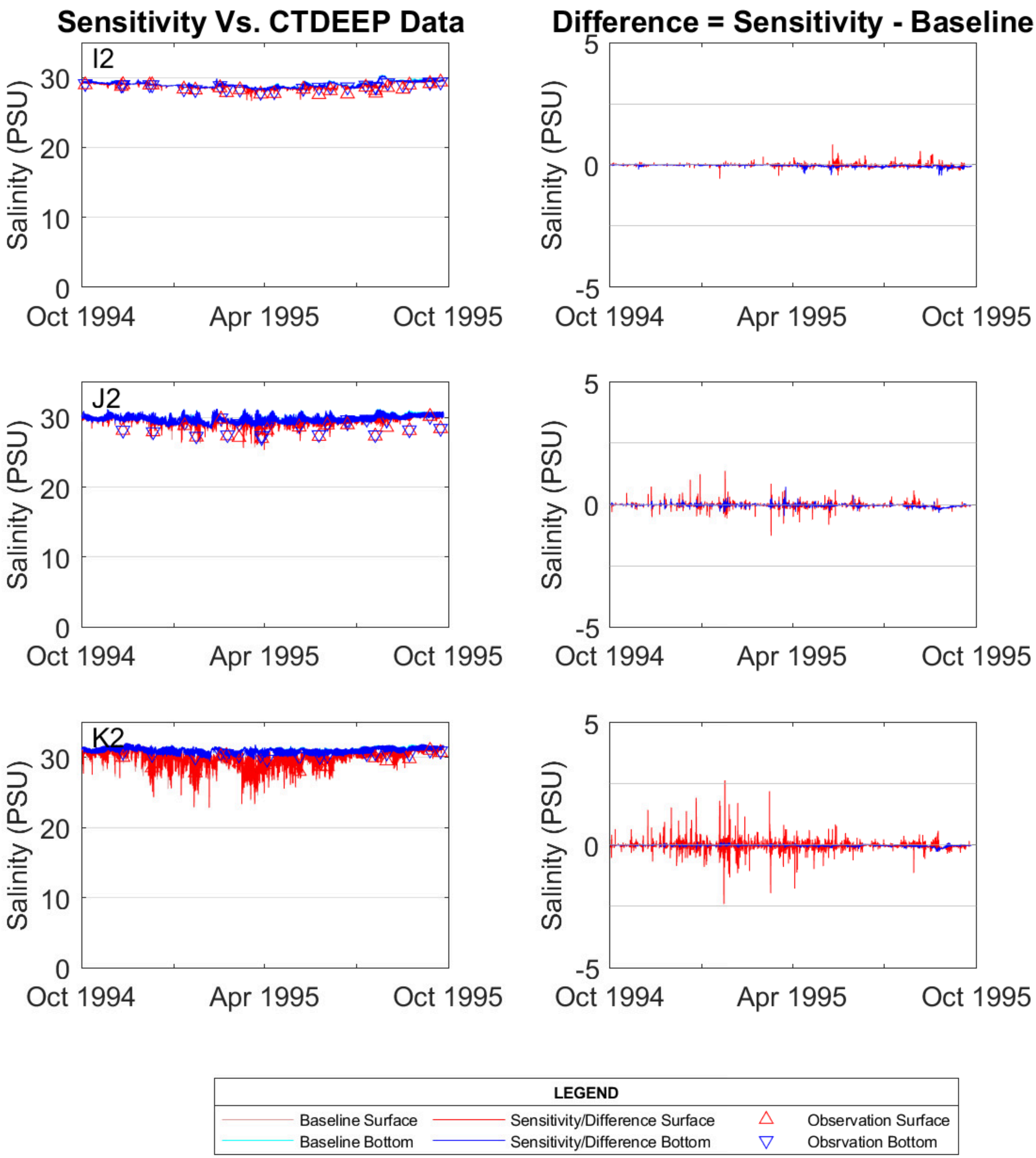


Baseline = Water Type III

Sensitivity = Water Type I



Baseline = Water Type III
Sensitivity = Water Type I



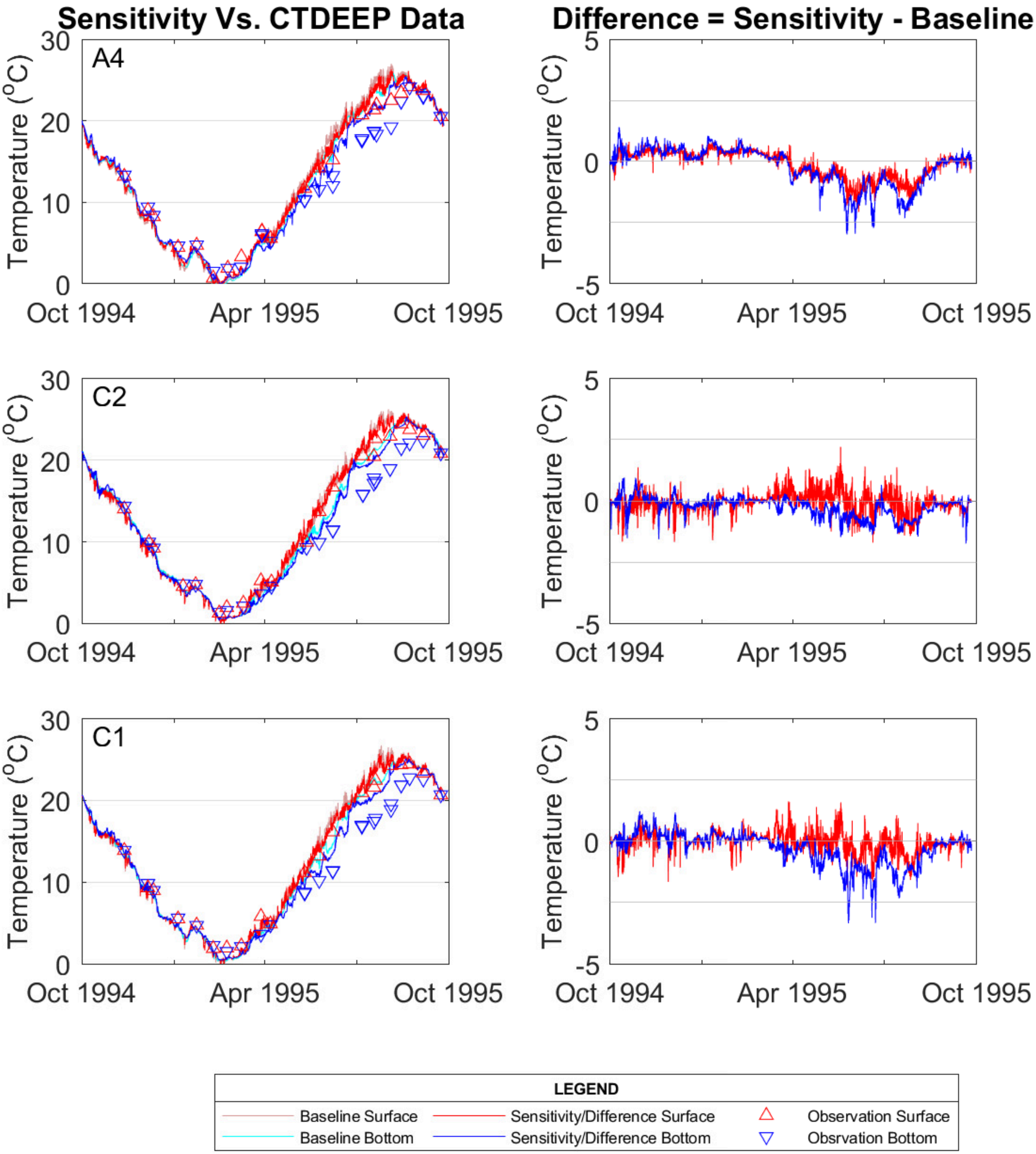
Baseline = Water Type III

Sensitivity = Water Type I

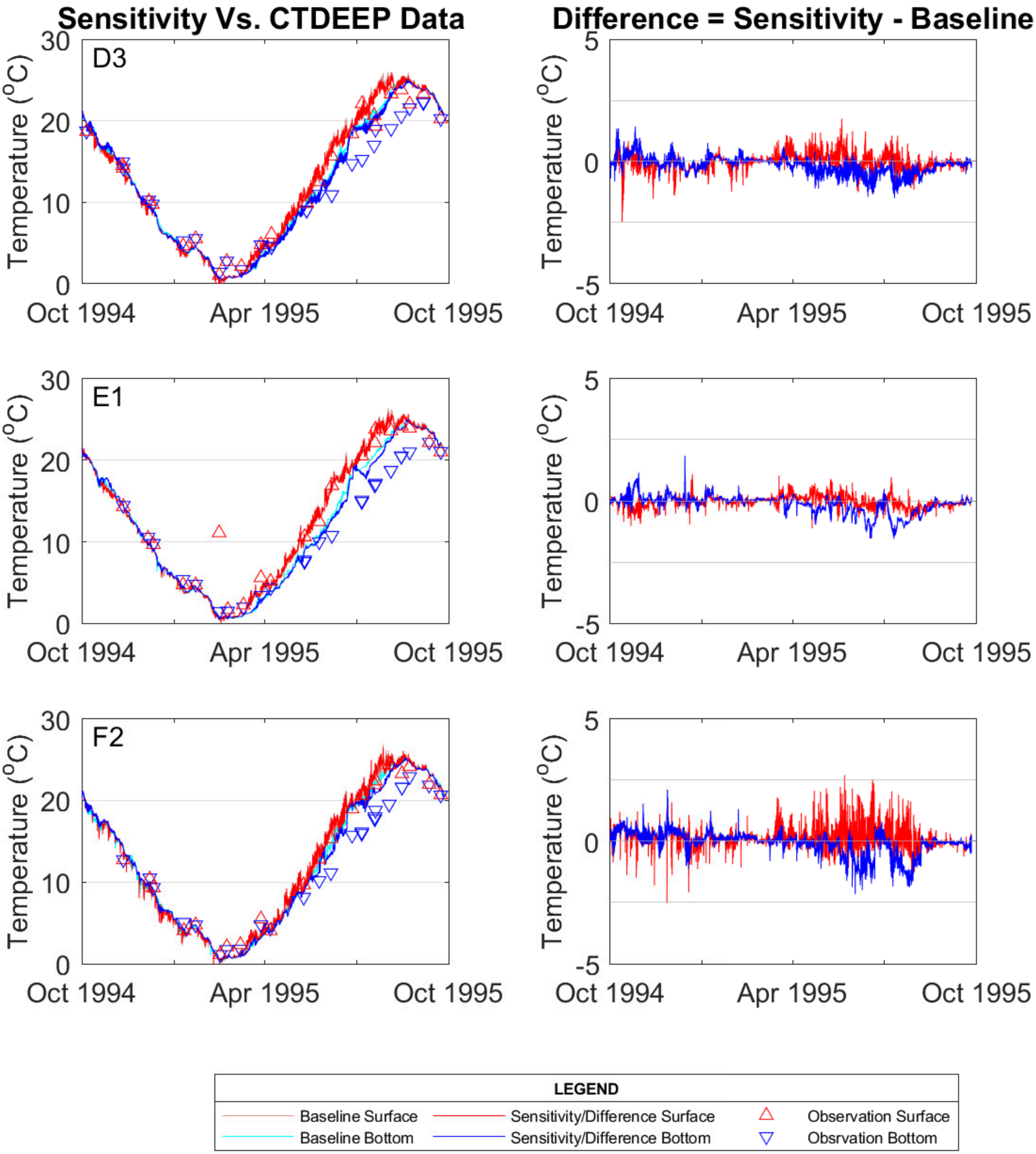
9

ROMS Bottom Friction Sensitivity

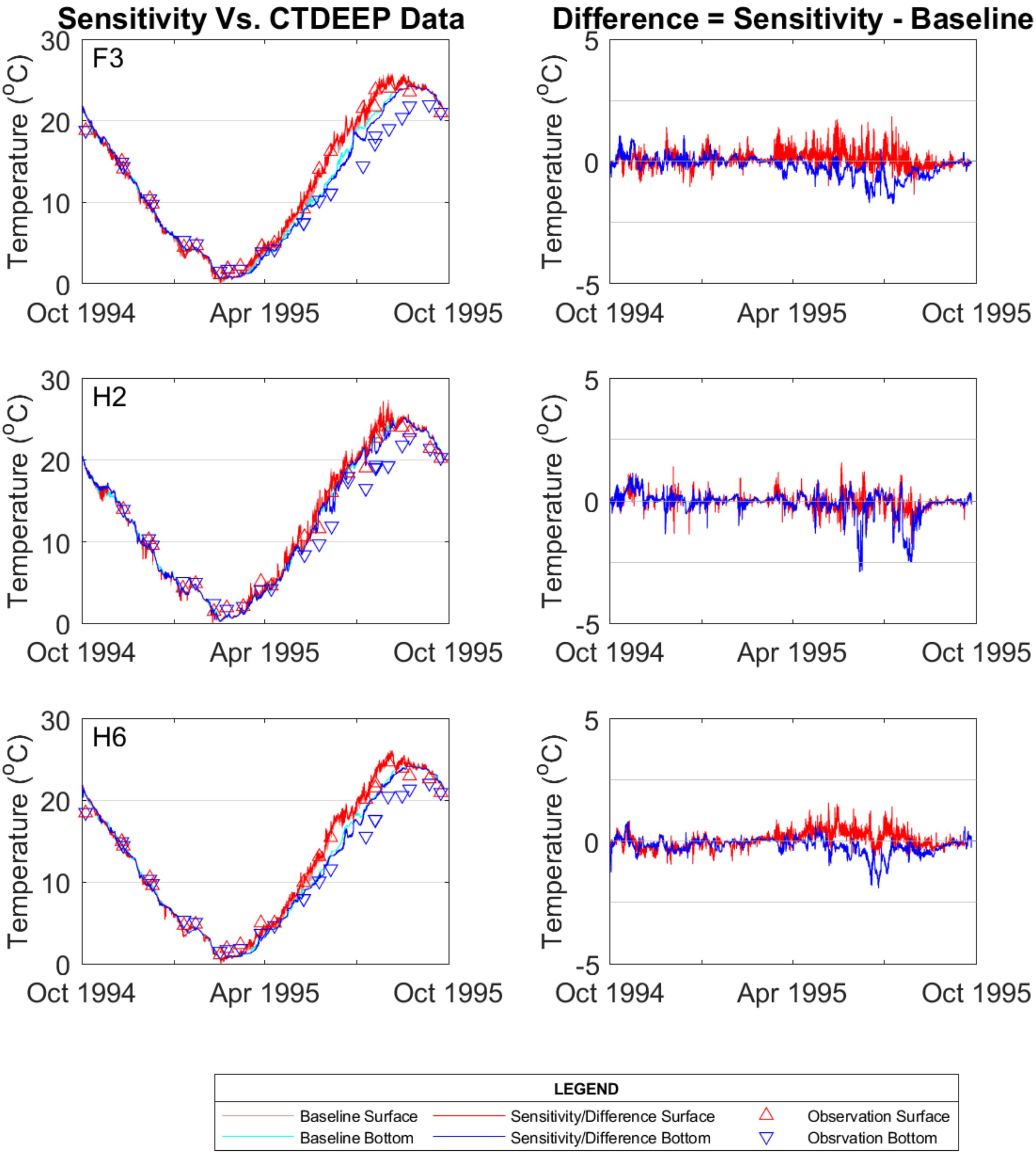
(Variable vs. Constant)



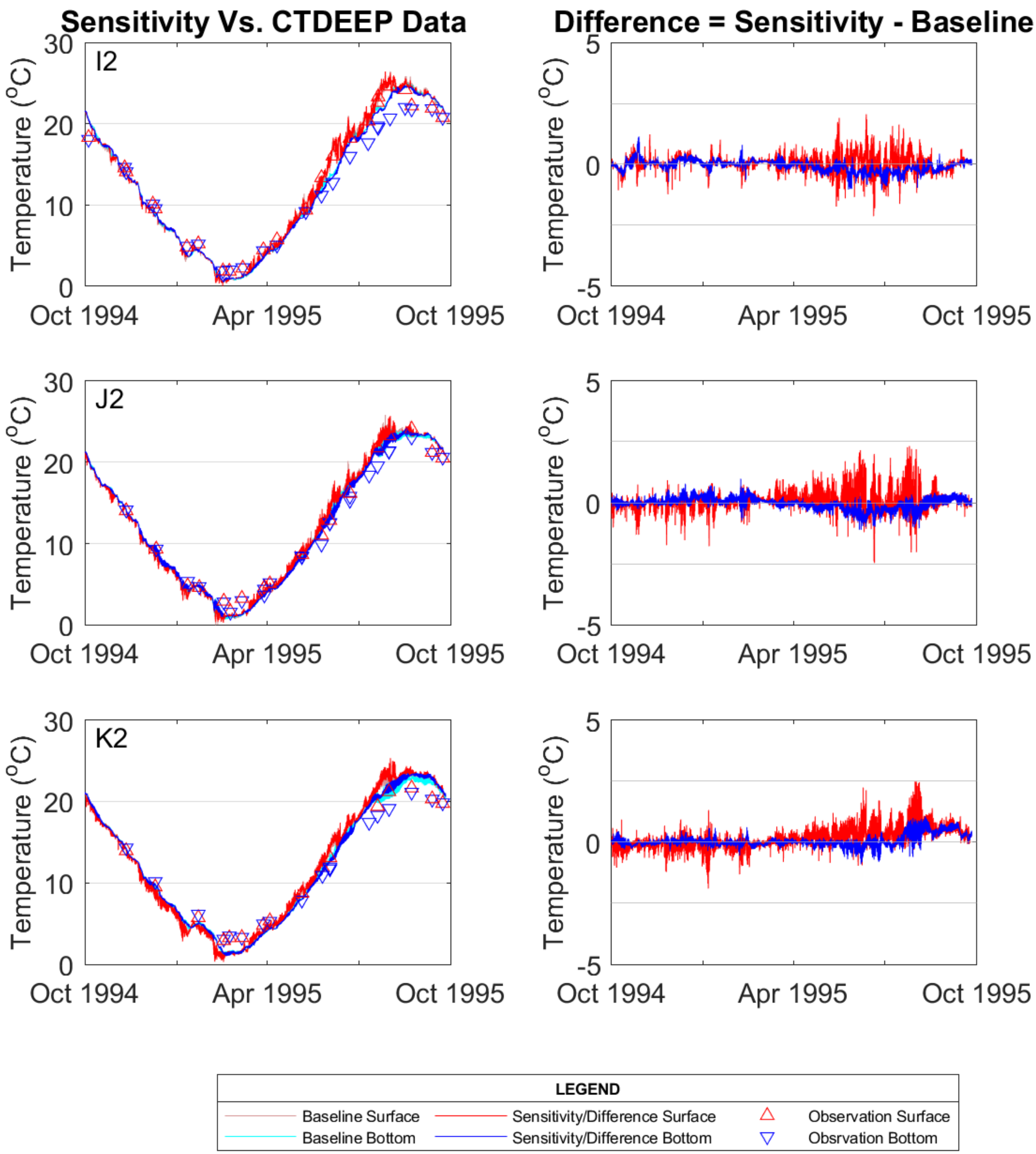
Baseline = Spatially Variable Bottom Friction
Sensitivity = Uniform Bottom Friction



Baseline = Spatially Variable Bottom Friction
Sensitivity = Uniform Bottom Friction

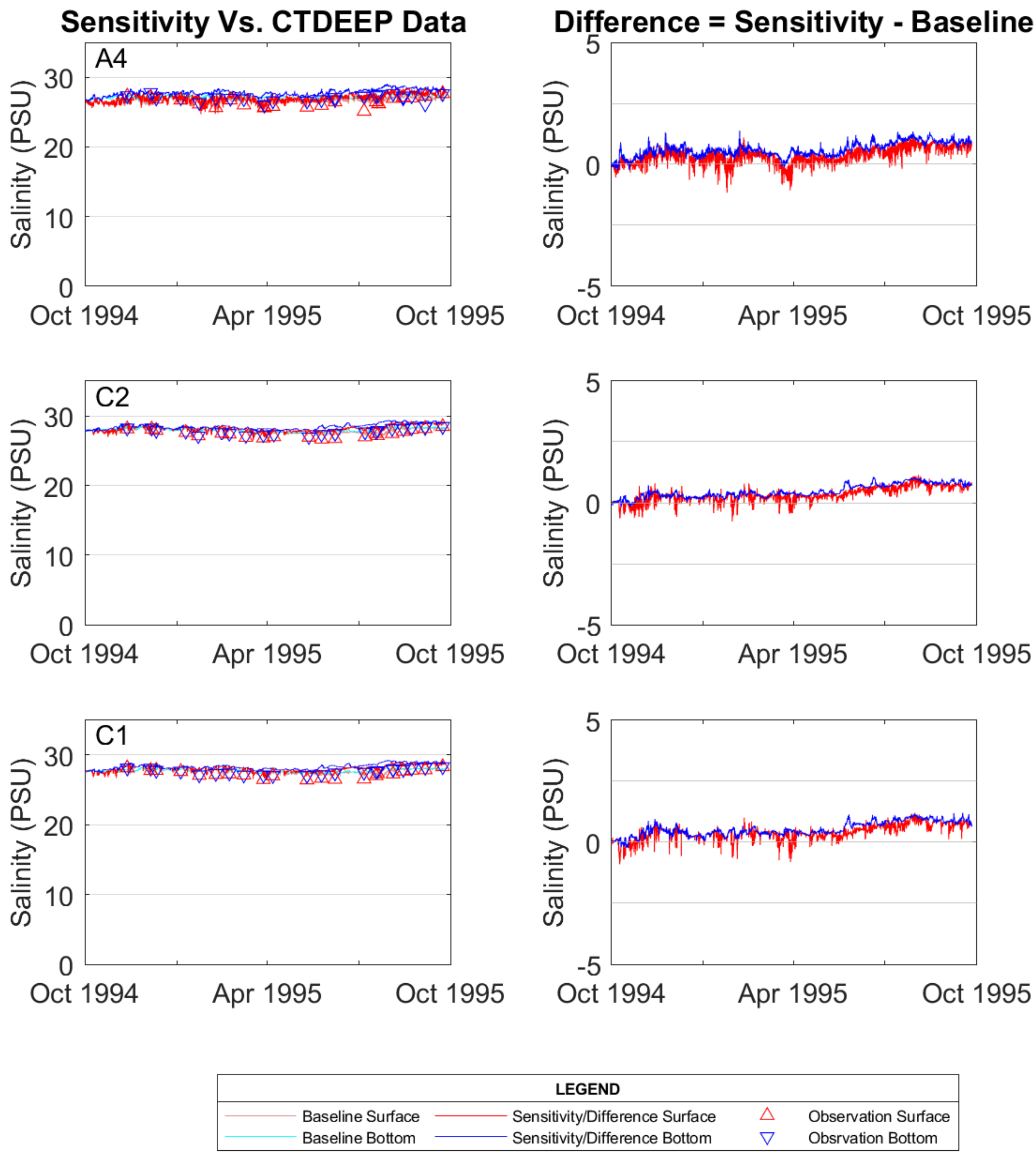


Baseline = Spatially Variable Bottom Friction
Sensitivity = Uniform Bottom Friction



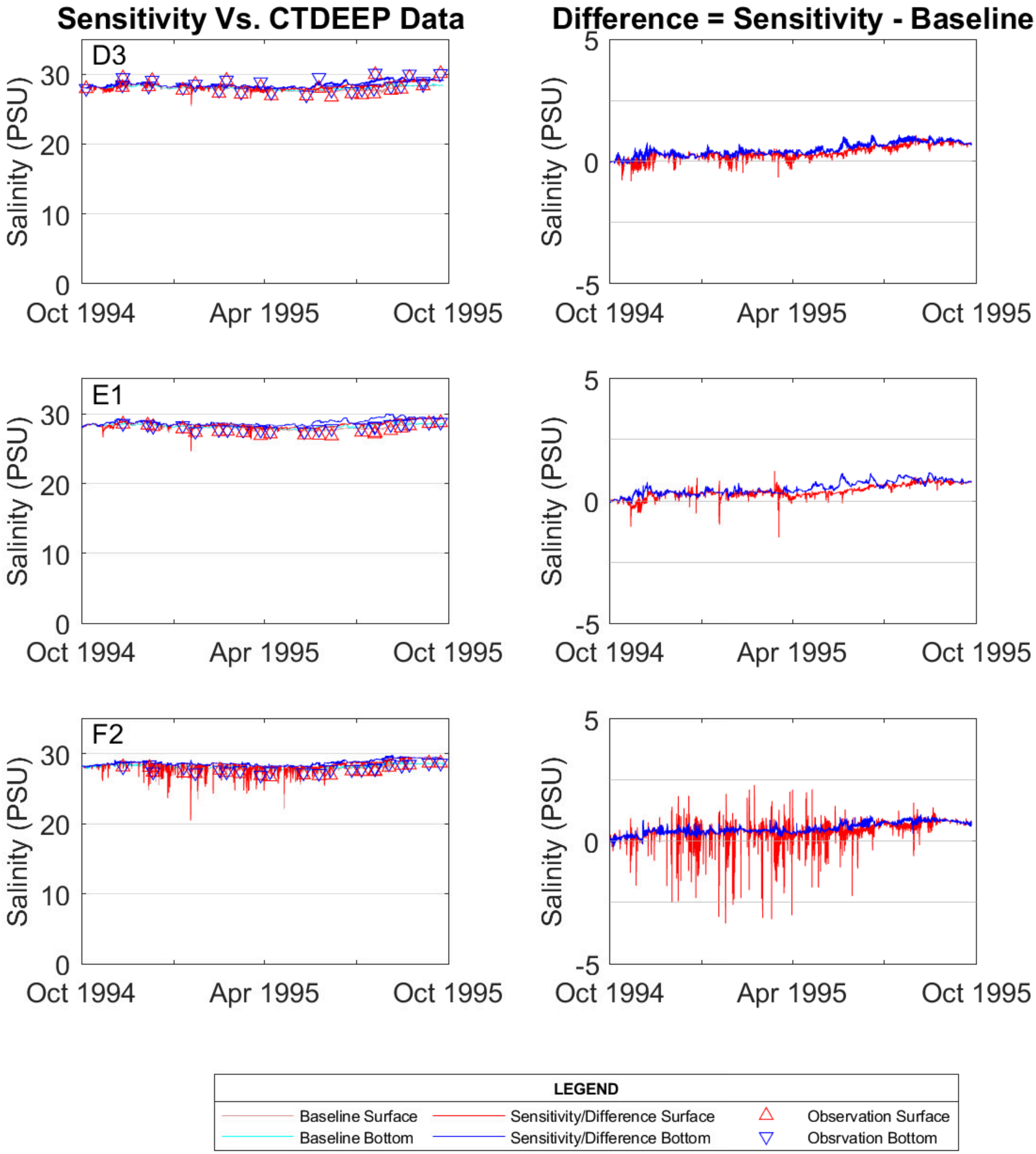
Baseline = Spatially Variable Bottom Friction

Sensitivity = Uniform Bottom Friction



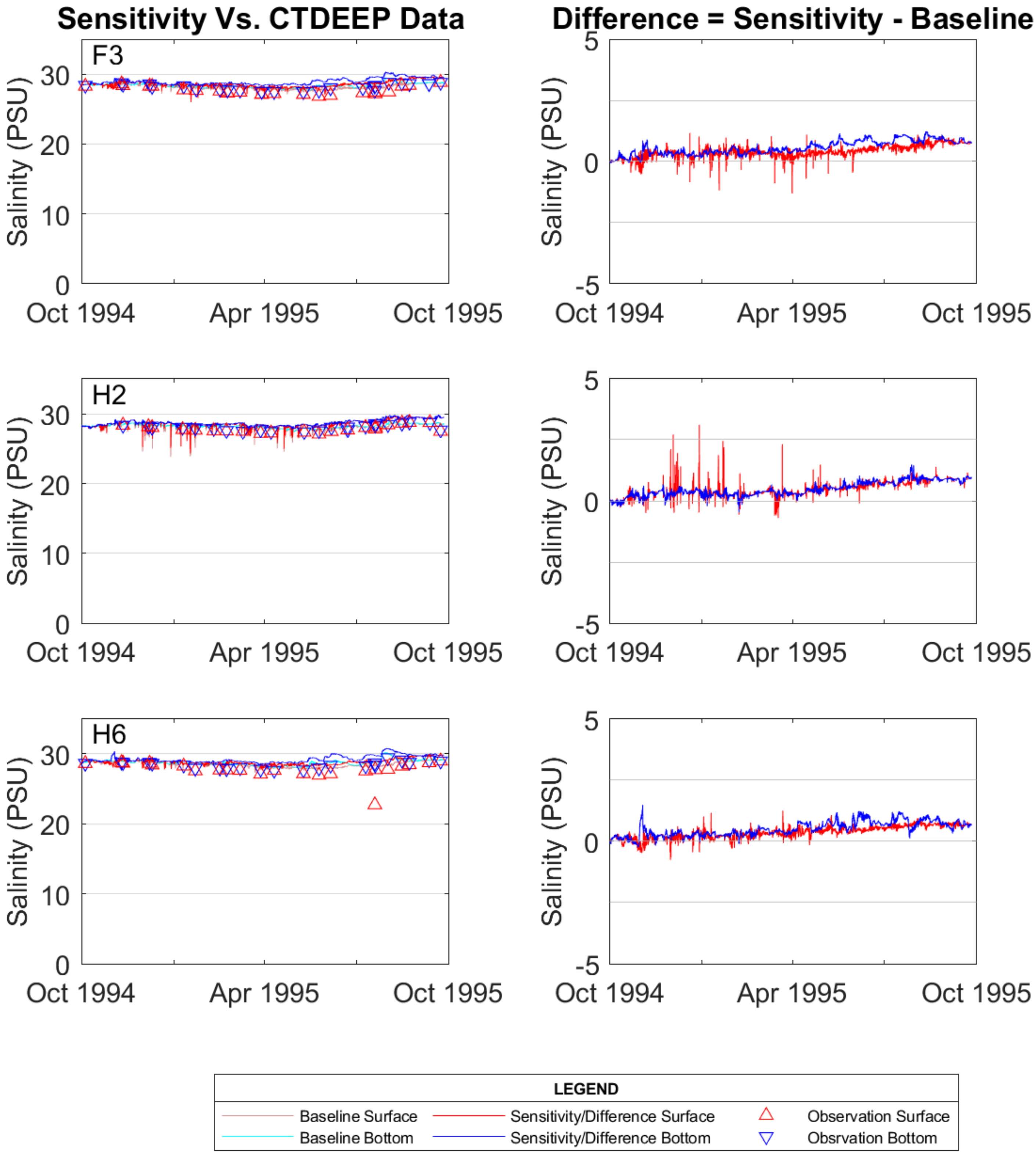
Baseline = Spatially Variable Bottom Friction

Sensitivity = Uniform Bottom Friction



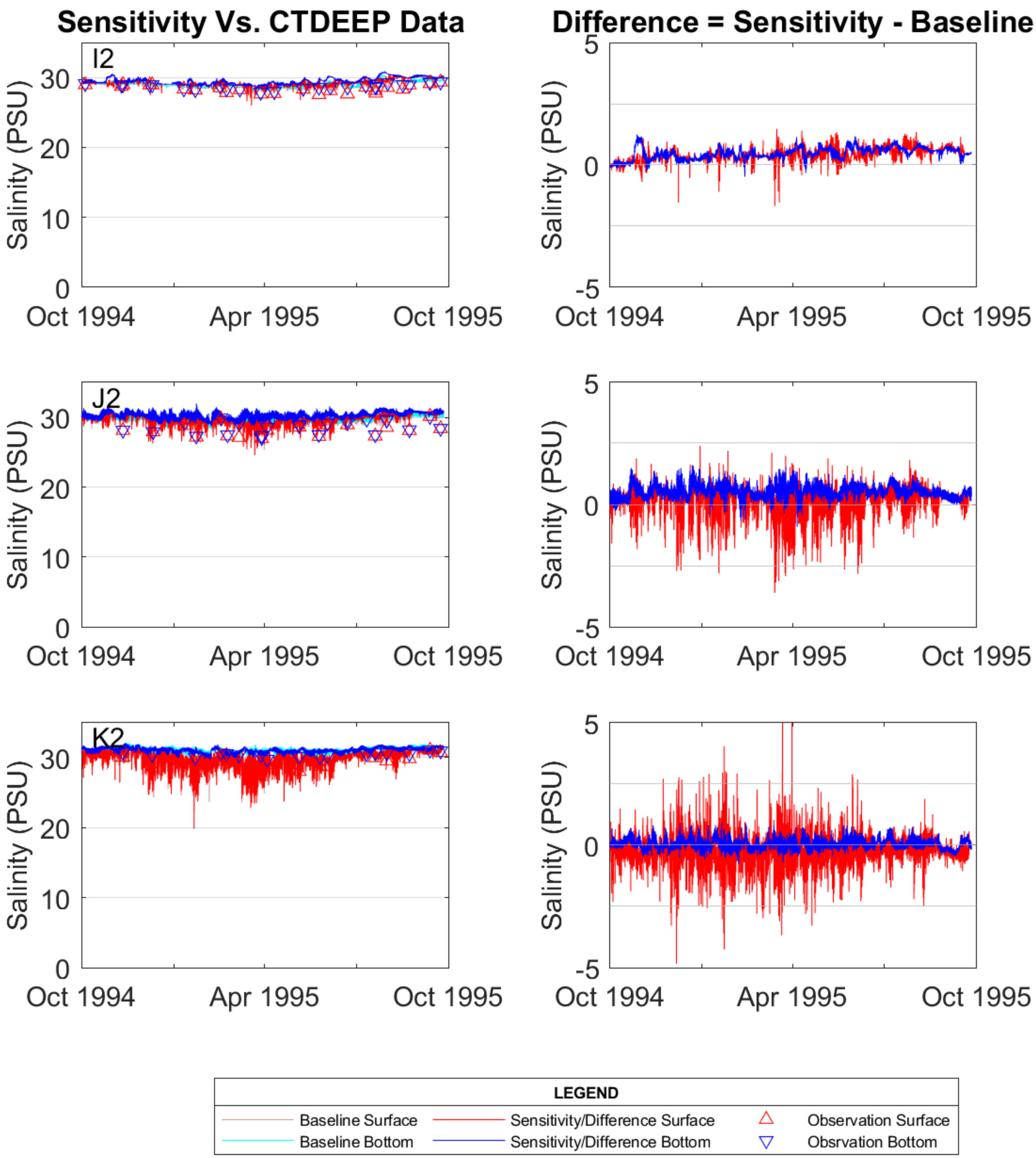
Baseline = Spatially Variable Bottom Friction

Sensitivity = Uniform Bottom Friction



Baseline = Spatially Variable Bottom Friction

Sensitivity = Uniform Bottom Friction



Baseline = Spatially Variable Bottom Friction

Sensitivity = Uniform Bottom Friction