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Understanding Drivers of Salinity and Temperature Dynamics in Barataria Estuary, Louisiana

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Key Points:

- Barataria salinity can be heavily influenced by the Mid-Barataria diversion and rainfall, reduced up to 14 and 10 ppt, respectively
- Neglecting the effect of nearshore density stratification underestimates salinity in Barataria Estuary by up to 9 ppt
- The well-mixed Barataria Estuary can be adequately modeled using a 2D local model, but offshore conditions need to be provided by a 3D model

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Barataria Estuary is an economically and ecologically important estuary in coastal Louisiana, USA. Due to rapid wetland loss, extreme Mississippi River flood and drought events (e.g., the flood of 2019 and the drought of 2022), devastating storm events (e.g., Hurricane Ida in 2021), eustatic sea-level rise (SLR), high subsidence rates, and human activities, temporal and spatial variability of salinity and temperature in the estuary is highly complex. This study comprehensively investigates environmental drivers that govern salinity and temperature dynamics, as well as the effects of a proposed large-scale, land-building diversion of Mississippi River water. A three-dimensional (3D), process-based hydrodynamic, salinity and temperature transport model system is formulated and implemented. Three different modeling domains are set up for nested computations. The model system is validated for the year 2018 against measurements of water level, salinity, and temperature. A series of numerical experiments are then carried out to quantitatively examine impacts of various environmental drivers, as well as nearshore density stratification and local baroclinic forcing. The drivers include wind, rainfall, freshwater point-source diversion, SLR, and Mississippi River discharge. Interestingly, the analysis shows that the proposed Mid-Barataria diversion and rainfall can cause a reduction of annual salinity up to 14 and 10 ppt, respectively. Neglecting the effect of nearshore density stratification could underestimate salinity by up to 9 ppt. The well-mixed estuary can be adequately modeled using depth-averaged models. However, to adequately capture proper salinity and temperature stratification, it is necessary to use 3D models for the coastal regional domain.

Plain Language Summary

Salinity and temperature are essential factors for coastal ecosystems. Barataria Estuary in coastal Louisiana is a semi-enclosed shallow estuary influenced by natural processes and human activities, which we call drivers. To investigate how various drivers affect salinity and temperature in the estuary, we developed a numerical model. Drivers considered in this study include wind, rainfall, river discharge, sea-level rise, and diversion projects that introduce freshwater from the Mississippi River. To be sure the model performed well, we compared the model output to observed measurements of water level, salinity, and temperature in Barataria Estuary. Next, we looked at the model results with and without each driver to see how it impacted the results. We found that the most significant drivers are the proposed Mid-Barataria diversion and rainfall. Both can cause huge salinity reductions in the middle and lower regions of the estuary. This research also showed the importance of using a three-dimensional model, rather than a horizontal two-dimensional model in which no changes are allowed in the water column, to capture salinity and temperature behavior in deep areas outside of barrier islands of Barataria Estuary.

1. Introduction

Salinity and temperature are two primary indicators for healthy estuarine and coastal ecosystems with significant and direct impacts on coastal wetlands wellbeing, water quality, fisheries, phytoplankton, and marine mammals (e.g., Chin et al., 2022; Garrison et al., 2020; Hornsby et al., 2017; Whitfield, 2021). They are essential inputs to ecological analyses such as those performed with food-web models (e.g., De Mutsert et al., 2021; Lewis et al., 2021) and Habitat Suitability Indices (HSIs), which represent the capacity of a given habitat to support a species of interest (Hijuelos et al., 2017; U.S. Fish and Wildlife Service, 1981; White et al., 2018). Temporal and spatial variability of coastal salinity and temperature are sensitive to environmental drivers, such as global warming and eustatic sea-level rise (SLR), and to anthropic activities, such as dredging of channels and coastal structures.

Figure 1. Location of Barataria Estuary, Louisiana, USA.

Wetlands and channels of the Mississippi River delta are important for fish and wildlife wellbeing in coastal Louisiana (e.g., de Mutsert et al., 2021; Fricano et al., 2020). Louisiana experienced 4,833 km^2 of coastal wetland loss from 1932 to 2016, roughly the size of the land area of Delaware (Couvillion et al., 2017). During the same period, Barataria Estuary (shown in Figure 1), located between the Mississippi River and Bayou Lafourche, experienced 1,120 km^2 of decline in wetland area (Couvillion et al., 2017). These changes in wetland area have altered tidal dynamics within the estuary and thus the estuarine salinity gradient (Day et al., 2021). Both subsidence and SLR are significantly affecting Barataria Estuary. Subsidence rate varies from 2 to 7 mm/yr across the estuary (Byrnes et al., 2019). The observed relative sea level trend at National Oceanic and Atmospheric Administration (NOAA) tidal station Grand Isle (see Figure 1) is 9.18 mm/yr. The hydrology of Barataria Estuary has been highly modified by human activities since the 1900s. The construction of the Mississippi River and Tributaries' (MR&T) levee system following the flood of 1927 and the closure of Bayou Lafourche at Donaldsonville in 1904 disconnected the Mississippi River from the estuary. Later, multiple salinity-control structures such as Davis Pond, and the siphon structures at Naomi and West Pointe à la Hache, attempted to reconnect the river with the estuary through a series of regulated point sources. In addition to these existing freshwater point sources, the State of Louisiana is in the process of building the Mid-Barataria Sediment Diversion (MBSD) to divert freshwater, sediment, and nutrients from the Mississippi River into the mid portion of the estuary. Remotely, salinity and temperature in the estuary are also influenced by "wrap around" inputs from the Mississippi River via discharge to nearshore waters and influx through the tidal passes. This impact can vary dramatically with river discharge, as observed during the flood of 2019 and the drought of 2022. In addition, cold fronts and tropical storms (e.g., the devastating Hurricane Ida in 2021) quickly change hydrodynamics, salinity, and temperature in the estuary due to the strong winds.

Studies have been carried out to simulate hydrodynamics and transport of salinity and temperature in Barataria Estuary. C. Li et al. (2011) investigated summertime tidal flushing in Barataria Estuary using a Finite Volume Community Ocean Model (FVCOM) (Chen et al., 2003). Payandeh et al. (2022) also developed an FVCOM model to investigate how tides in Barataria Estuary will be affected by future SLR and its associated marsh accretion. Das et al. (2012) used a two-dimensional (2D) coupled hydrology–hydrodynamic model (Das et al., 2011; Inoue et al., 2008) to study the impact of Davis Pond diversion on salinity in Barataria Estuary, while Ou et al. (2020) applied a three-dimensional (3D) Regional Ocean Model System (ROMS) (Shchepetkin & McWilliams, 2005) to Barataria to simulate salinity variations due to Mississippi River discharge and MBSD. In these previous studies, only very limited factors that influence salinity and temperature dynamics in Barataria Estuary were investigated due to model limitations or research objectives. For example, early 2D models are not suitable to study the impact of nearshore density stratification on estuarine salinity. Some models that cover only main water bodies and no marsh areas with no or very limited wetting and drying in simulations could induce big errors when surface water elevation is high, which makes them not suitable for studying the impacts of big diversions and SLR. In addition, temperature effects have been largely ignored.

To overcome the limitations of previous studies, a high-resolution, process-based, 3D model is used to characterize how different environmental drivers impact salinity and temperature in Barataria Estuary. In this study, the open-source numerical model suite Delft3D by Deltares (Lesser et al., 2004), which has been used widely for hydrodynamic and transport studies (e.g., Baustian et al., 2018; Brito et al., 2023; Hu et al., 2009, 2015, 2022; Meselhe et al., 2015; Ribeiro et al., 2022), was selected to perform numerical analysis. The Delft3D suite, consisting of multiple modules, can carry out simulations of flows, sediment transport, waves, water quality, and morphodynamics. Delft3D-FLOW is a multi-dimensional hydrodynamic (and transport) module which calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing on a rectilinear or a curvilinear, boundary-fitted grid. Features of Delft3D-FLOW for coastal applications include boundary-fitted grid generation for complex coastlines and estuary geometries, nesting tools for local boundary conditions, and "sub-grid" treatments for hydraulic and coastal structures. Please refer to Delft3D-FLOW manual (Deltares, 2023a) for details of model features.

After model development and validation, numerical experiments are carried out to explore following research questions:

- To what degree do riverine inflows, precipitation, wind, and density stratification influence estuarine salinity?
- Do these drivers influence salinity and temperature uniformly across the estuary?
- Is it necessary to utilize the more computationally expensive 3D to adequately resolve temperature and salinity dynamics; or is a 2D sufficient?

The paper is organized as follows. Study area and model development are presented in Section 2. After model validation in Barataria Estuary (Section 3.1), modeled distributions of salinity and temperature are provided and discussed in Sections 3.2 and 3.3, followed by a series of numerical experiments that are conducted to address research questions (Section 4). Section 5 discusses our results in comparison with previous work. Section 6 summarizes our findings.

2. Materials and Methods

2.1. Study Area

As shown in Figure 1, Barataria Estuary is a semi-enclosed estuary bounded on the east by the Mississippi River levees, on the west by Bayou Lafourche, and on the south by a chain of barrier islands that separate the estuary from Gulf of Mexico. Barataria Estuary is a well-mixed shallow estuary with an average depth of 2 m. It includes interspersed open water bodies, bayous, channels, and fragmented marsh areas. Key water bodies include Lac des Allemands, Lake Cataouatche, and Lake Salvador in the upper estuary, Little Lake in the middle estuary, Barataria Bay in the lower estuary, and Caminada Bay in the southwest corner. There are natural ridges at the west of the estuary (see green line in Figure 1) which can reduce water exchange between Caminada Bay and the rest of the estuary. Barataria Estuary is microtidal with diurnal tides. The dominating tidal constituents are K_1 and O_1 (Payandeh et al., 2022). Both amplitudes at NOAA tidal station Grand Isle are 0.37 m. As a low-pass filter, wetlands could significantly attenuate tidal signals from the Gulf (Nordio & Fagherazzi, 2022). Due to fragmented marshes, remnants of ridges, and other elevated features, tides dissipate quickly when propagating into the estuary. In this study, we focus on the estuary south of US Highway 90. This area is about 80 km long and covers approximately 4,000 km^2.

2.2. Hydrodynamic and Transport Model

2.2.1. Numerical Modeling Domains and Settings

To develop detailed 3D simulations for hydrodynamics, salinity, and temperature processes in Barataria Estuary, calculations have been performed using three-level nested domains shown in Figure 2.

The large-scale Gulf-Atlantic domain (level 1) encompasses the entire Gulf of Mexico and part of the Atlantic Ocean. The number of computational grid cells is 253 × 238 in x- and y-directions. This domain has a spatial resolution ranging from 6 km near the Louisiana coast to 40 km in the Atlantic Ocean. Vertically, seven sigma

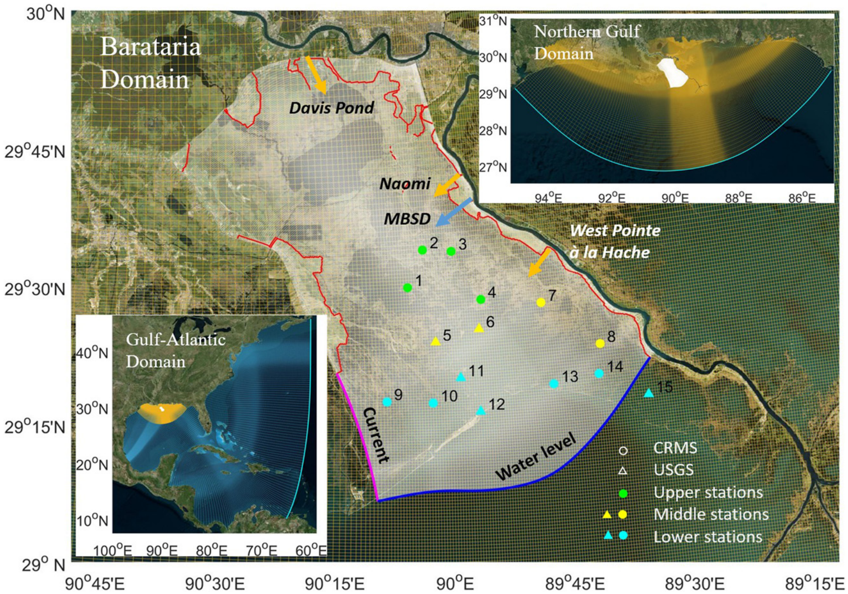

Figure 2. Three-level nested domains with grids and stations for model validation. Red lines denote levee structures; orange arrows denote discharge boundaries; blue arrow denotes the proposed Mid-Barataria Sediment Diversion; purple line and blue line denote current and water level boundaries, respectively.

layers are adopted. The thicknesses of these layers are 5%, 10%, 20%, 30%, 20%, 10%, and 5% of the total water depth, respectively. This distribution intentionally reduces the layer thickness near the surface and bottom. The time step is 6 min. Bathymetry and roughness (Manning's n) values are extracted from an Advanced Circulation (ADCIRC) (Luettich et al., 1991) model used in the Louisiana Coastal Master Plan (CPRA, 2017). From a tidal constituent database (Mukai et al., 2002), seven dominant constituents (O_1, K_1, Q_1, M_2, N_2, S_2, and K_2) are considered to determine tidal levels at the open-sea boundary across the Atlantic Ocean. The purpose of this large-domain model is to provide water level and 3D temperature at the boundaries of the level-2 regional domain. Testing revealed that regional calculation would experience numerical instabilities if driven by 2D uniform temperature at the boundaries.

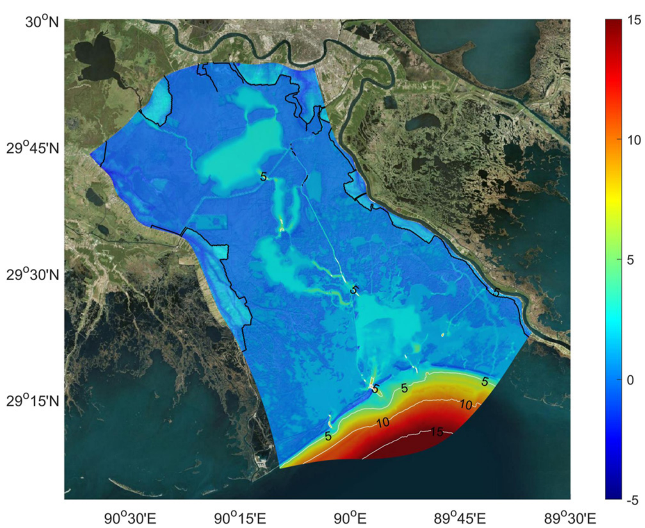

Figure 3. Barataria bathymetry (NAVD88, m, positive down) in the local domain. Black lines denote level structures; white lines denote contour lines every 5 m.

The regional Northern Gulf domain (level 2) focuses on the north-central region of Gulf of Mexico. The number of grid cells is 395 × 222. The domain has a spatial resolution ranging from 12.5 km offshore to 500 m near Barataria Estuary. The regional model calculates hydrodynamics, salinity, and temperature. The time step is 1 min. At the southern offshore open boundary, water level is interpolated from the Gulf-Atlantic domain. 3D temperature boundary data are also from the Gulf-Atlantic domain. In terms of salinity, a constant 2D uniform value of 36 ppt is used at the offshore boundary. The regional domain captures freshwater inputs from coastal rivers along Louisiana, Mississippi, and Alabama coasts.

The local domain (level 3) covers the main part of Barataria Estuary and some offshore areas. The number of grid cells is 395 × 222. Spatial resolution varies from 50 to 360 m. The time step is 0.5 min. Levee structures within the domain are represented by thin dams, a sub-grid feature in Delft3D, with limited heights along grid lines following the actual levee positions (see red lines in Figure 1). When surface elevation at either side is larger than levee height, two cells are connected and the flux between them is calculated with an empirical formula. The U.S. Geological Survey (USGS) 5 m-resolution Coastal National Elevation Dataset (CoNED) (Danielson et al., 2018) is used for interpolation of bathy-topography in Barataria Estuary (Figure 3). The local domain is clearly divided by barrier islands into two parts, that is,

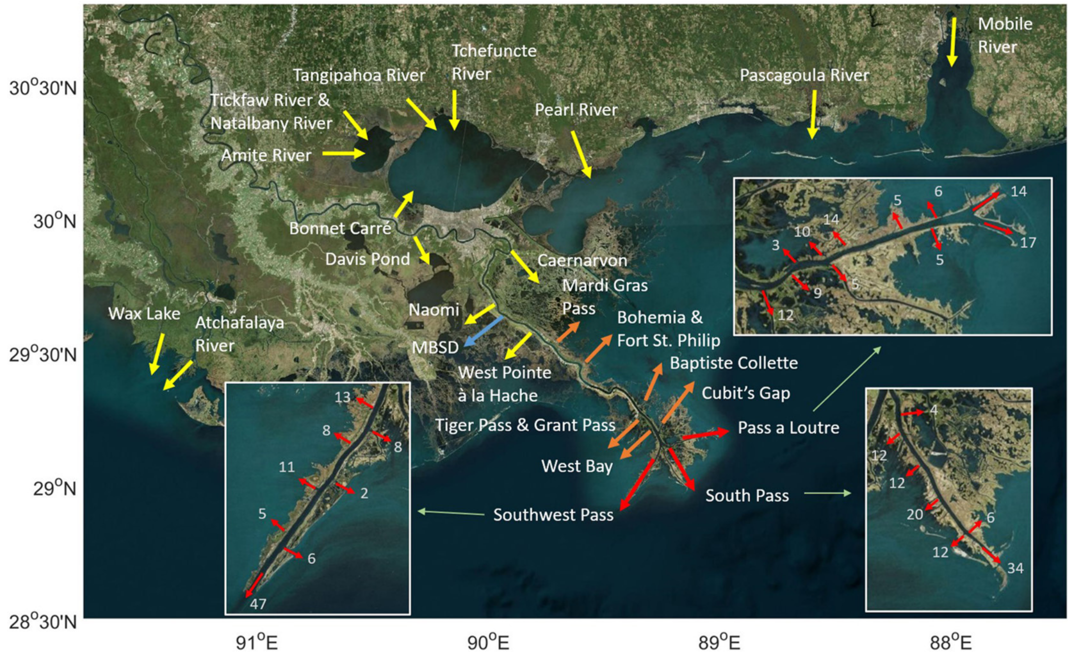

Figure 4. Locations of model freshwater inputs. Yellow arrows denote local river/pass/structure inputs; blue arrow denotes the proposed Mid-Barataria Sediment Diversion; orange arrows major passes of the Mississippi River; red arrows in the main figure denote three passes in Bird's Foot Delta; red arrows in sub-figures denote smaller distributaries and crevasses (white numbers are percentages).

Barataria Estuary area and the offshore area where water depth is larger than 5 m. Two different types of hydrodynamic boundary conditions are specified at the south boundary of the local domain, that is, water level at the southeast and current at the southwest (from Port Fourchon up to the levee structure). This setup has proven to offer more numerical stability than using a uniform boundary type. Water level, current, salinity, and temperature at the south boundary are provided by the regional model.

2.2.2. Freshwater Inputs

Figure 4 shows freshwater inputs considered in this study. River discharge is specified either using gauge measurements if available or estimates based on historical records. It should be noted that the Mississippi River main stem is not included in the model domain. Therefore, distributaries such as Bonnet Carré spillway, Davis Pond diversion, Caernarvon diversion, etc., are specified as point sources. In the lower Mississippi River (from Bohemia to Head of Passes) and Bird's Foot Delta, rating curves are obtained from historical field observations (Figures S1 and S2 in Supporting Information S1), and these curves are used to estimate flow through the eight major passes, as well as Mardi Gras Pass (denoted as orange and red arrows in Figure 4). Flow through Southwest Pass, South Pass, and Pass a Loutre (denoted as red arrows in Figure 4) is further distributed through smaller distributaries and crevasses (denoted as red arrows in three sub-figures of Figure 4). Table S1 in Supporting Information S1 lists detailed information about how freshwater inputs are specified in both regional and local domains, and data sources are also reported. Figures S1 and S2 in Supporting Information S1 show rating curves used at Mardi Gras Pass and eight major Mississippi River passes, respectively.

2.2.3. Additional Model Settings

Horizontal eddy viscosity and eddy diffusivity are chosen equal to the default values (1 and 10 m^2/s) in the Gulf-Atlantic domain, and to calibrated values in the Northern Gulf domain (2.5 and 25 m^2/s) and in the local domain (2.0 and 20 m^2/s). Vertically, the k-ε turbulence model is selected for all three domains. Atmospheric forcing including wind velocity at 10 m and surface air pressure for both the Gulf-Atlantic and the Northern Gulf domains is specified using the 6-hourly data from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Reanalysis (Kalnay et al., 1996). In the Barataria domain, atmospheric measurements at Grand Isle are used to specify atmospheric forcing. The *Ocean* heat flux model

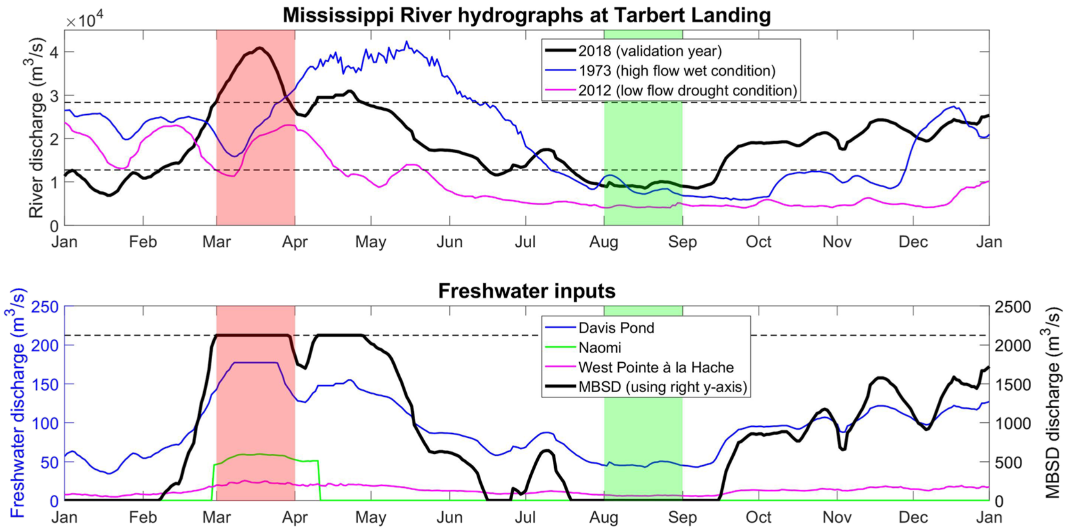

Figure 5. Mississippi River hydrographs at Tarbert Landing in 2018 (black), 1973 (blue), and 2012 (magenta) and freshwater inputs at Davis Pond (blue), Naomi (green), West Pointe à la Hache (magenta), and Mid-Barataria Sediment Diversion (black, using right y-axis). March and August are highlighted to represent the typical flood season and dry season of Mississippi River in 2018, respectively.

in Delft3D is selected for temperature calculation, and it needs inputs of relative humidity, air temperature, and cloud coverage. These input fields are assigned from the NCEP/NCAR Reanalysis as well. Zero values are set for initial conditions of water level and current. In terms of salinity and temperature, reasonable initial distributions can shorten the model warm-up period. We take the Gulf of Mexico Analysis by Hybrid Coordinate Ocean Model (HYCOM) (Wallcraft et al., 2009) as a first estimate, run the model for 1 month to warm up, then replace these initials with the calculated results from the end of the warm-up period.

3. Model Validation and Results

3.1. Model Validation

The whole year 2018 is selected for model validation. Figure 5 shows 2018 (validation year), 1973 (wet condition), and 2012 (drought condition) Mississippi River hydrographs, as well as 2018 freshwater inputs at Davis Pond, Naomi, West Pointe à la Hache, and MBSD. Daily water level, salinity, and temperature data collected at Coastwide Reference Monitoring System (CRMS) (CPRA, 2023a) and USGS stations in Barataria Estuary (Figure 2) are used for model-data comparisons. They are grouped into upper, middle, and lower estuary groups (shown with different colors in Figure 2). Note that all model results are from the Barataria domain except that results at Station #15 (USGS 07380260) are from the Northern Gulf domain.

Figure 6 shows the comparison of modeled water level with observations at 15 stations in Barataria Estuary and the scatter plot with correction coefficient (r) and root mean square error (RMSE) labeled. Refer to Text S2 in Supporting Information S1 for the expressions of statistics. Seasonal variation trend of water level is similar at all stations, indicating a homogeneous distribution of water level in the middle and lower estuary under no major diversion conditions. Overall, modeled water level agrees well with measurements ($r = 0.86$; RMSE = 0.08 m), which means the model captures hydrodynamic processes in Barataria Estuary. Figures 7 and 8 show modeled salinity and temperature against field data, respectively. Modeled results at the surface (thin black line) and at the bottom (thick green line) are presented. The scatter plots are for the surface results and observations. Time series plots show that bottom results coincides with surface ones almost at all stations for both salinity and temperature, which indicates that salinity and temperature vertically mix well in this shallow estuary. We do find that salinity stratification happens during some periods at Station #15 (USGS 07380260) near Empire Waterway in the lower estuary. The overall agreement of salinity is fairly good ($r = 0.83$; RMSE = 3.8 ppt). Note that several stations in the upper estuary (e.g., near Lake Salvador) where salinity is very low (<5 ppt) all year round are omitted in the comparison, and the overall agreement could be better if they were included. It is also important to note that the

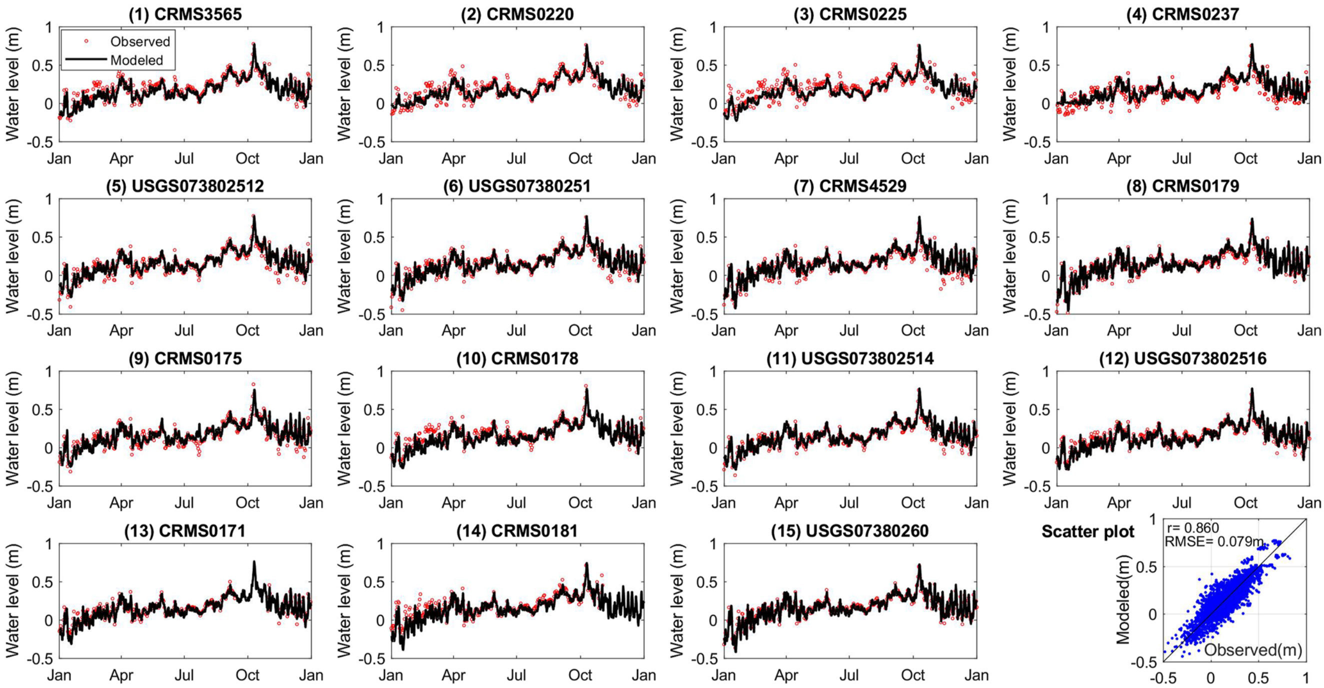

Figure 6. Comparison of modeled (black line) and observed (red circle) water level (m, NAVD88) at 15 stations in 2018 and their scatter plot (observed vs. modeled).

model effectively reproduces that salinity diminishes from the lower estuary to the upper estuary. The excellent agreement between modeled temperatures and measurements ($r = 0.97$; RMSE = 1.6°C) indicates an outstanding model performance in temperature calculations. Similar to water level, temperature also shows a seasonal variation at all stations. Temperature at a given location is dominated by solar radiation and convection/diffusion from nearby sources. Solar radiation is almost identical over Barataria Estuary due to its relatively small size, which

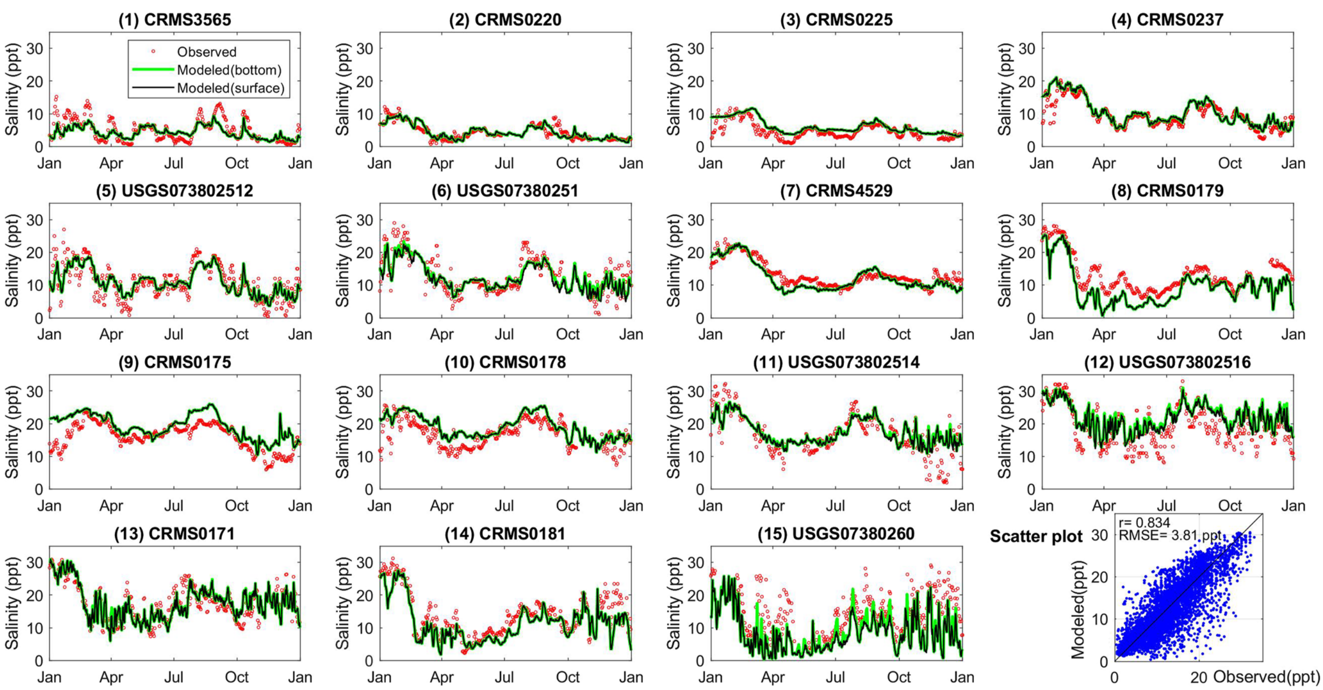

Figure 7. Comparison of modeled (thin black line for the surface; thick green line for the bottom) and measured (red circle) salinity (ppt) at 15 stations in 2018 and their scatter plot (observed vs. modeled at the surface).

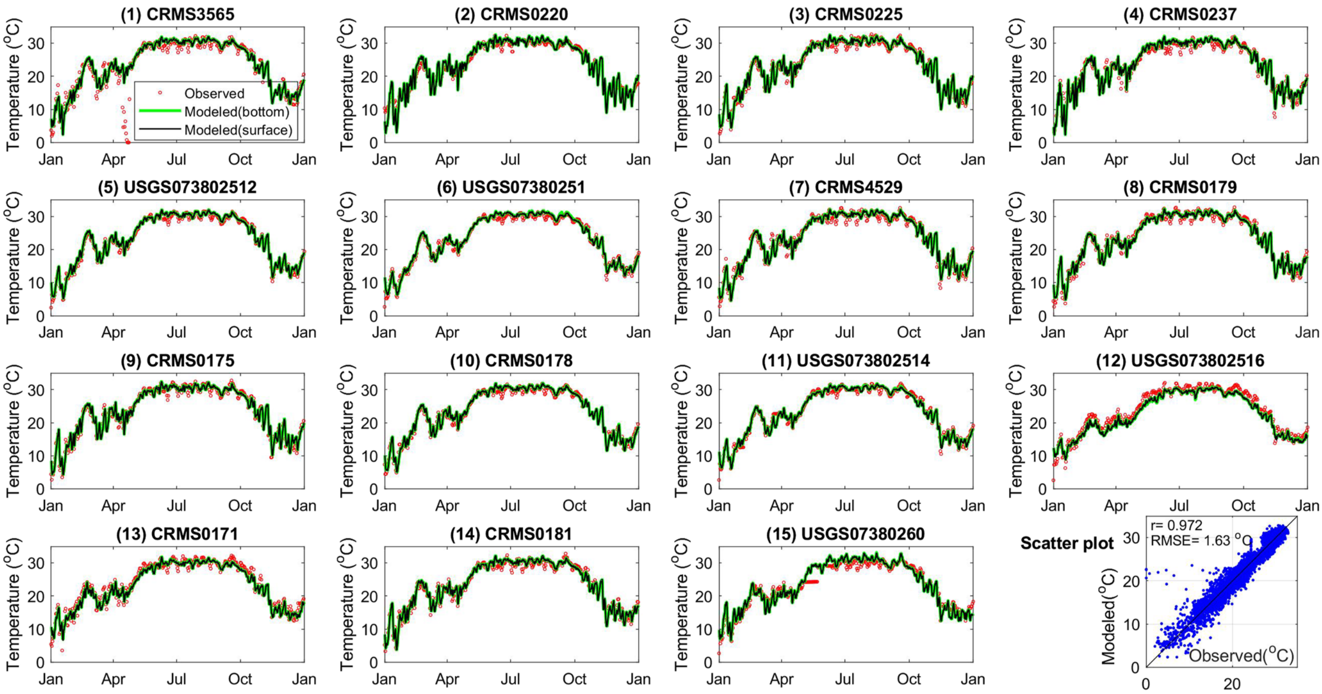

Figure 8. Comparison of modeled (thin black line for the surface; thick green line for the bottom) and measured (red circle) water temperature (°C) at 15 stations in 2018 and their scatter plot (observed vs. modeled at the surface).

implies that convection/diffusion has little influence on the spatial variation of temperature. This further suggests that under no diversion conditions, current freshwater sources would mix quickly and well with the water in the estuary and have little impact on water temperature changes.

Target and Taylor diagrams (Hofmann et al., 2008; Jolliff et al., 2009; Taylor, 2001) are adopted to illustrate a variety of skill metrics including normalized bias and normalized unbiased RMSE in target diagrams, and normalized standard deviation of modeled results, r and normalized unbiased RMSE in Taylor diagrams. Here skill metrics are normalized to the standard deviation of observation, as further illustrated in Text S2 in Supporting Information S1. Figure 9 shows target and Taylor diagrams illustrating model skill metrics at 15 stations simulating water level, salinity, and temperature in Barataria Estuary. In terms of water level (Figure 9a), the model performs better in bias (absolute values < 0.3) than RMSE (~0.5). Further, the r values at all stations are larger than 0.8, indicating a good performance for modeling water levels. As expected, in terms of salinity (see Figure 9b), the overall metric values are not as good as those for water level, reflecting the complexity and challenges of numerically capturing salinity dynamics. All stations except Station #15 are near or within the target circle with a radius of 1. At Station #15, the model underestimates the mean and the variability of observations, and the r is low (~0.65) as well. In terms of temperature (see Figure 9c), almost all symbols are very close to the perfect fit point "x", which means the model has excellent performance simulating temperature. The only exception is at Station #1. When checking the time series (see Figure 8), there are a few abnormally low observations in April, which deteriorates its metrics.

Overall, the model performance is reasonable, and the three-level model system well reproduces hydrodynamic and transport processes in Barataria Estuary. A variety of numerical experiments are discussed below to explore salinity and temperature dynamics within Barataria Estuary.

3.2. Salinity

Figure 10 shows the calculated, depth-averaged annual and monthly distributions of salinity and temperature in Barataria Estuary for the validation year 2018. As shown in Figure 10a, annual salinity gradually increases along northwest to southeast from zero at the upper estuary to 27 ppt offshore. Transversely, across the estuary, salinity also shows an increasing trend from the west bank of Mississippi River to Caminada Bay at the southwest

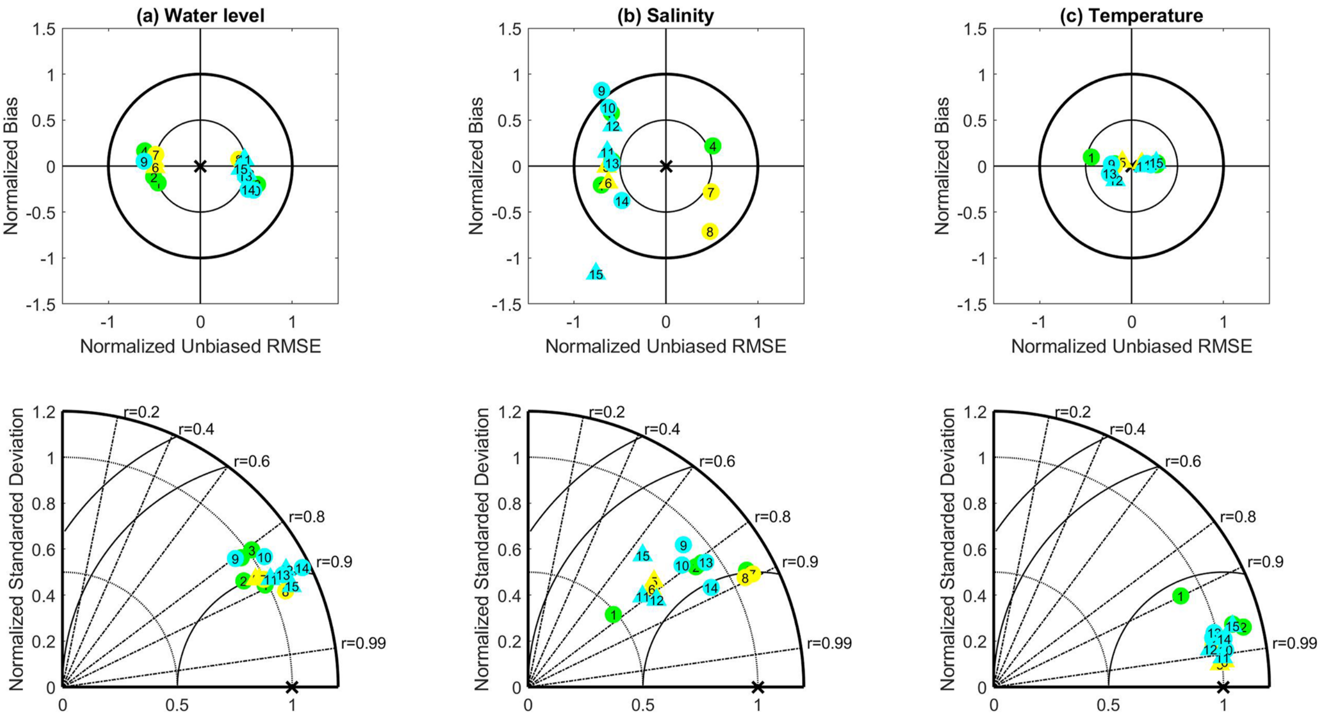

Figure 9. Normalized summary target (upper) and Taylor (lower) diagrams illustrating the model skill of simulating (a) water level, (b) salinity, and (c) temperature in Barataria Estuary. The "*x*" represents a model with perfect fits. The dotted, dashed-dot, and thin solid lines on the Taylor diagram denote lines of constant normalized standard deviation, *r*, and normalized unbiased root mean square error, respectively. Numbered color symbols denote metrics at upper (green), middle (yellow), or lower (cyan) numbered stations; circles denote Coastwide Reference Monitoring System stations; triangles denote U.S. Geological Survey stations.

corner. Main water bodies (e.g., Lake Salvador) at the upper estuary have near-zero salinity throughout the year due to the upstream riverine inputs (e.g., from David Pond) and rainfall. Salinity levels along the west bank of Mississippi River are consistently low by virtue of the series of freshwater point sources from Mississippi River (e.g., Naomi and West Pointe à la Hache). At the southeast corner, salinity is mainly controlled by the southern offshore boundary which is influenced by riverine discharges outside of the Barataria domain (e.g., from Tiger Pass, Grand Pass, and West Bay). In terms of high salinity areas, aside from the offshore region, Caminada Bay located in the southwest and semi-enclosed by natural ridges (see dashed lines in Figure 3) at the north is a region with relatively elevated salinity levels. Natural ridges bounding Caminada Bay restrict water exchange between the enclosed area and the rest of the estuary, especially when water level is low. Thus, ridge feature limits the entry of freshwater from the upper estuary and retains saline water from offshore, resulting in a relatively high salinity (∼21 ppt) within Caminada Bay.

Figures 10c and 10e show monthly salinity distributions in March (flood season) and August (dry season), respectively. The upper region of Barataria Estuary remains always fresh. Offshore, due to the influence of Mississippi River discharge, salinity in March is less than in August by ∼ 6 ppt. The seasonally low discharge of Mississippi River in the summer induces high salinity in August at the southeast corner and Caminada Bay. In the middle and lower regions of Barataria Estuary and east to Caminada Bay, salinity in August is about 3–6 ppt higher than in March, and the difference is decreasing from south to north.

3.3. Temperature

Compared to salinity, temperature distribution is spatially more uniform over Barataria Estuary due to its relatively small area when considering solar radiation. As shown in Figure 10b, annual temperature in Barataria Estuary is 23°C. Offshore temperature is about 1°C lower than in the estuary. Mississippi River temperature is normally lower than the Gulf water, which causes a slightly lower temperature offshore. Another lower-temperature region is near Davis Pond due to the diverted (cooler) riverine water. This river-sea temperature difference is more obvious in the flood season. For example, in March (see Figure 10d) the overall temperature in the estuary is 20°C,

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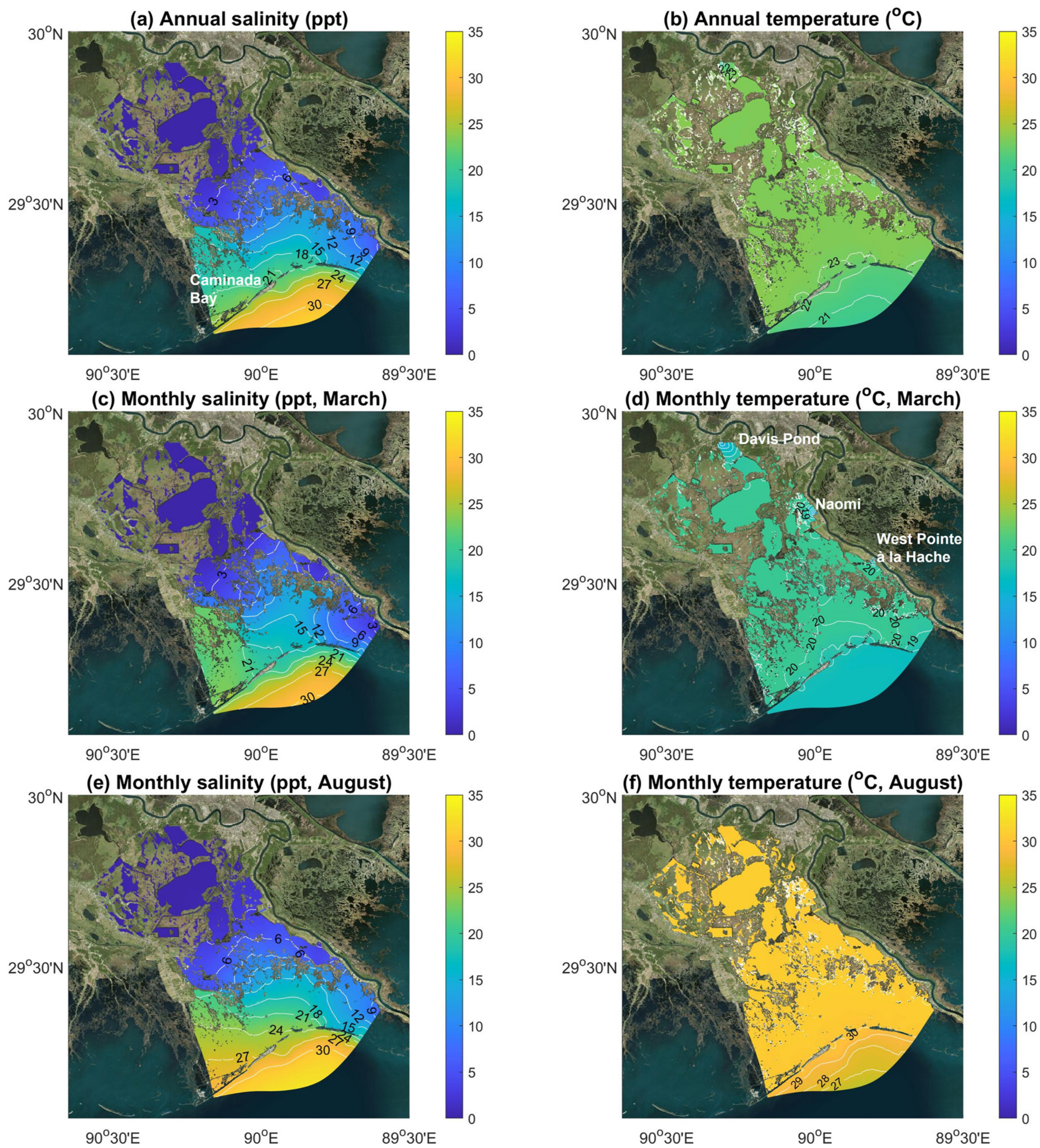

Figure 10. Distributions of depth-averaged salinity (left, ppt) and temperature (right, °C) in Barataria Estuary for the year 2018. (a) and (b) are annual averaged salinity and temperature, respectively; (c) and (d) are monthly averaged salinity and temperature in March (flood season), respectively; (e) and (f) are monthly averaged salinity and temperature in August (dry season), respectively. White lines for salinity denote contour lines every 3 ppt; white lines for temperature denote contour lines every 1°C.

while the offshore region (directly mixing with water released from the Mississippi River Deltaic Passes) temperature is only 17°C by virtue of the high Mississippi River discharge. Meanwhile, temperature near freshwater input locations (i.e., Davis Pond, Naomi, and West Pointe à la Hache, as labeled in Figure 10d) is about a few degrees lower than the rest of the estuary. On the other hand, during dry season in August (see Figure 10f), this kind of temperature difference vanishes due to the low Mississippi River discharge, and the monthly temperature is 31°C all over the estuary and the offshore area.

4. Analysis of Drivers

The validated model is used to conduct a series of numerical experiments to investigate impacts of individual environmental drivers, nearshore density stratification, and local baroclinic forcing.

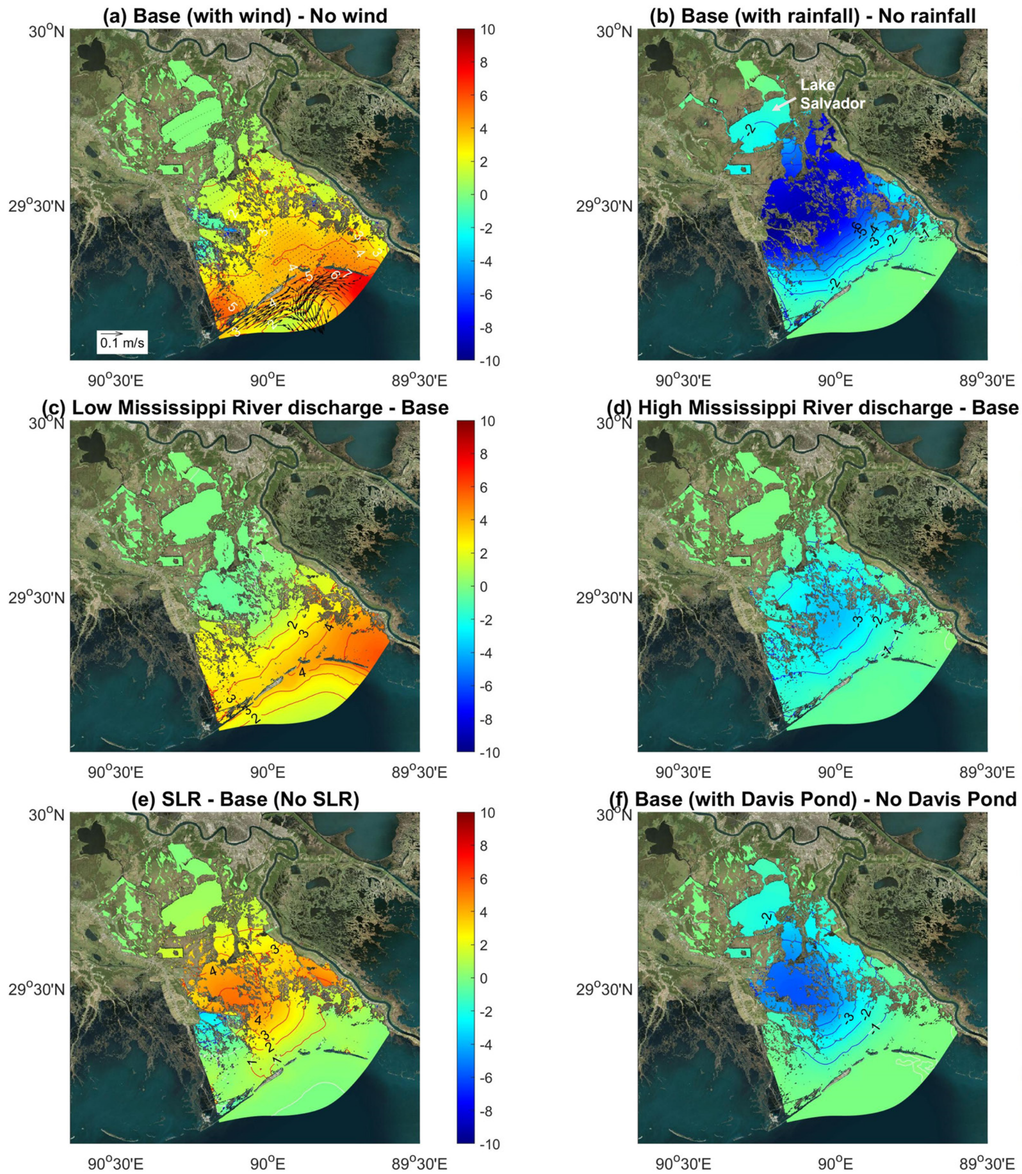

Figure 11. Distributions of depth-averaged annual salinity difference (ppt) in Barataria Estuary illustrating the impacts of (a) wind, (b) rainfall, (c) low Mississippi river discharge, (d) high Mississippi river discharge, (e) sea-level rise, and (f) Davis Pond discharge. Red lines denote contour lines for positive values every 1 ppt; blue lines denote contour lines for negative values every 1 ppt; black arrows in (a) denote annual wind-induced depth-averaged residual currents (m/s).

4.1. Environmental Drivers

Environmental drivers include winds, rainfall, river discharge/freshwater input, and SLR. They can impact Barataria Estuary "locally" through meteorological forcing and freshwater input to the domain or remotely as offshore conditions. To consider both local and remote effects, the regional and the local domains are both utilized in each experiment. Differences between annual maps obtained in simulations performed with and without one driver are used to assess driver impact. Figure 11 shows distributions of depth-averaged annual salinity difference in Barataria Estuary.

4.1.1. Meteorological Drivers

Two meteorological drivers, namely, wind and rainfall, are considered in this study. Figure 12 shows wind and rainfall forcing used in the Barataria 2018 simulations. The wind rose diagram (Figure 12a) indicates that prevailing winds originate from south and southeast with a speed of 2–4 m/s, while high-speed (>8 m/s) winds tend

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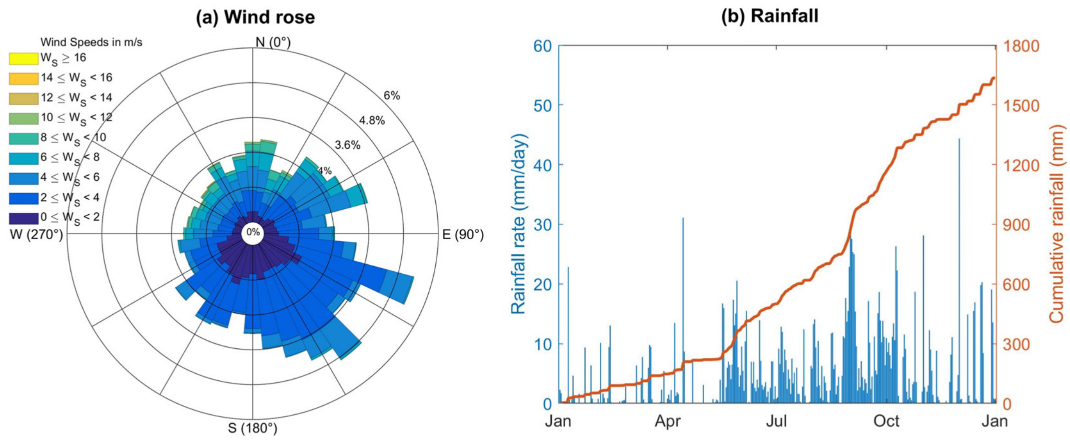

Figure 12. (a) Wind rose and (b) rainfall at Grand Isle (Station #12) in 2018. Wind rose is generated based on wind measurements from National Oceanic and Atmospheric Administration. Rainfall data is extracted from the National Center for Atmospheric Research/National Centers for Environmental Prediction reanalysis.

to originate from north and northwest but with lower frequency. As shown in Figure 11a, winds cause a net transport from the Gulf to the estuary due to their prevailing direction from south and southeast and increase salinity offshore (by ∼5 ppt) and in the middle/lower estuary (by ∼4 ppt). To better understand physical mechanics of salinity variation, wind-induced vertically averaged residual currents (see black arrows in Figure 11a) are calculated by obtaining vector differences of residual currents in simulations with and without wind conditions. Annual wind-induced residuals keep near zero in Barataria Estuary, while offshore residual currents are around 0.1 m/s in velocity and show a clear double semicircle circulation pattern, that is, an east counter-clockwise semicircle and a west clockwise semicircle. By the east circulation, saline water flows in across the eastern part of south boundary, moves west along barrier islands, then turns south and flows out across the middle part of south boundary. By the west circulation, nearshore water moves east along barrier islands, then turns south and flows out at the middle part of south boundary. Due to the inflow direction difference, the east circulation could carry more saline water into the Barataria domain than the west circulation, which causes offshore salinity to be higher at the east (∼6 ppt) and lower at the west (∼3 ppt). In the middle, wind-induced offshore salinity is the lowest (∼2 ppt) since both circulations push water out. Thus, wind-induced salinity difference is consistent with offshore residuals or net circulations. Tiny residuals within Barataria Estuary indicate that the increase in estuary salinity is caused by diffusion between high salinity offshore and low salinity in the estuary, not by convection of residuals. Some isolated areas (e.g., near nature ridges at the west of the estuary) show a decrease in salinity. The reason could be that freshwater fills into these areas by wind-induced (e.g., northernly strong wind) overbank (e.g., over low ridges) flow and resides there for a long time.

Rainfall has a much clearer spatial impact. Cumulative rainfall (see Figure 12b) over the estuary reached 1,636 mm in 2018, which cause a significant reduction of salinity (up to 10 ppt) in Barataria Estuary (see Figure 11b). Maximum salinity reduction happens in the middle of the estuary. In the upper estuary, rainfall impact is minor because the existing salinity without rainfall is already very low (due to runoff from the upper estuary as well due to the distance from the offshore region). At Lake Salvador, rainfall induces a 2 ppt of salinity decrease. Offshore, rainfall impact is minor as well due to the deep water depth (>5 m). Rainfall impact is of great importance in the middle and lower Barataria Estuary by virtue of the shallow water depth (∼3 m).

4.1.2. Mississippi River Discharge

The Mississippi River discharge in 1973 and 2012 (see Figure 5) is selected as representative of high and low flow conditions, respectively. The yearly discharges at U.S. Army Corps of Engineers (USACE) river station Tarbert Landing (a station with a long record approximately 493 km upriver from Head of Passes) in 2018 (base case), 1973 (high flow) and 2012 (low flow) are 18,915, 20,382, and 9,890 m^3/s, respectively. Freshwater inputs along the Mississippi River for high/low flow conditions are adopted either using available measurements (e.g., some inputs for 2012) or through rating curves as illustrated in Figures S1 and S2 in Supporting Information S1. The resulting salinity difference maps are shown in Figures 11c and 11d, respectively. At low flow conditions, salinity in the lower estuary and offshore increases up to 5 ppt compared to the base case, while the impact in the upper and middle estuary is minor. At the high flow conditions, salinity offshore changes little since the yearly discharges for 1973 and 2018 are similar. The high flow impact occurs in the middle and lower estuary and induces up to a 3 ppt salinity decrease. In addition, the difference between Figures 11c and 11d implies that different Mississippi River flows (e.g., 2012 low flow vs. 1973 high flow) could induce about a 5 ppt difference in the annual-averaged salinity in the middle/lower estuary and offshore areas. Please note that all these results are yearly averaged. When considering monthly results, the impact of different Mississippi River flows is likely more significant.

4.1.3. Sea-Level Rise

Based on the relative sea level trend at Grand Isle (9.18 mm/yr), the SLR from 2018 to 2050 is estimated as 0.294 m. If relative to 2000, SLR in 2050 is 0.459 m, which resides in the ranges for low and intermediate-low scenarios estimated by NOAA (Sweet et al., 2022). In this numerical experiment, the value of 0.294 m was added to the existing offshore water level boundaries in the regional domain. An intuitive hypothesis is that SLR will cause more severe saltwater intrusion and result in higher salinity in coastal and estuarine areas, while for a complex coastal area in terms of bathymetry and freshwater sources like Barataria Estuary, the conclusion may not be that simple. As shown in Figure 11e, the impact of SLR on salinity for the upper estuary and offshore is not as obvious or intuitive as hypothesized. In the middle and lower estuary, the SLR caused up to 5 ppt of salinity increase due to the enhanced saltwater intrusion, while interestingly, the SLR also induced about a 1–2 ppt salinity decrease at the area semi-enclosed by natural ridges in the southeast of the estuary. The reason for this unexpected result is that more freshwater from the upper estuary may overtop natural ridges into this area due to the elevated water level by SLR.

4.1.4. Davis Pond Freshwater Diversion

Davis Pond freshwater diversion project was implemented in 2009 to reduce saltwater intrusion in Barataria Estuary by introducing freshwater from the Mississippi River (CPRA, 2020). As shown in Figure 5, the average diverted discharge in 2018 is 94 m^3/s and the diversion is capped at 177 m^3/s. Davis Pond diversion induces up to a 5 ppt reduction of salinity in the middle estuary (see Figure 11f). Its spatial impact pattern is similar to rainfall (see Figure 11b), but the induced salinity reduction value is much smaller. In the upper estuary, the impact is not significant due to the already low-salinity condition. The influence of Davis Pond is most significant in the middle region of Barataria Estuary. The impact then gradually diminishes toward the lower estuary. The impact area of Davis Pond diversion is within Barataria Estuary and not beyond barrier islands.

4.1.5. Proposed Mid-Barataria Sediment Diversion

The primary purpose of the MBSD project is to reintroduce freshwater and sediment from the Mississippi River to Barataria Estuary to reestablish deltaic processes in order to build, sustain, and maintain land (CPRA, 2023b). The full flow capacity of this project is designed as 2,124 m^3/s (75,000 cfs). To investigate its impact, the MBSD is added with 2018 river hydrograph conditions, and freshwater inputs downstream of the diversion project are adjusted accordingly using rating curves.

The diversion discharge is shown in lower Figure 5 (see the thick black line). Refer to Text S1 in Supporting Information S1 for the detailed operation rules. The yearly diversion discharge is 857 m^3/s, which is about one order of magnitude larger than Davis Pond diversion (94 m^3/s). Figure 13 shows difference maps for yearly averaged water level, salinity, and temperature. In terms of water level (see Figure 13a), the diversion project induces a surge setup (>0.6 m) near the project location. This surge setup gradually diminishes as it propagates away from the project location, for example, to ∼0.2 m in Lake Salvador. The impact is significant along the west bank of Mississippi River near the project location. The diversion affects water level to a small extent in the lower estuary and offshore. In terms of salinity (see Figure 13b), due to the large freshwater input, the diversion project impacts greatly the lower estuary by inducing salinity reduction up to 14 ppt. The impact extends offshore as well. Due to the water temperature difference between river water and estuary water (see Figure 13c), the diversion project induced a temperature reduction (>7°C) near the project location. Similar to the surge setup pattern, this reduction gradually diminishes when moving away from the project location. The impact is minor in the upper estuary (e.g., Lake Salvador) and the west part of the estuary, as well as offshore. Overall, the Mid-Barataria diversion has great impacts in Barataria Estuary, especially on salinity. Please note that only one operation plan is tested in this study. Researchers have been seeking to optimize operation strategies to mitigate its impacts to the ecosystem while also taking advantage of its land-building benefit (Peyronnin et al., 2017).

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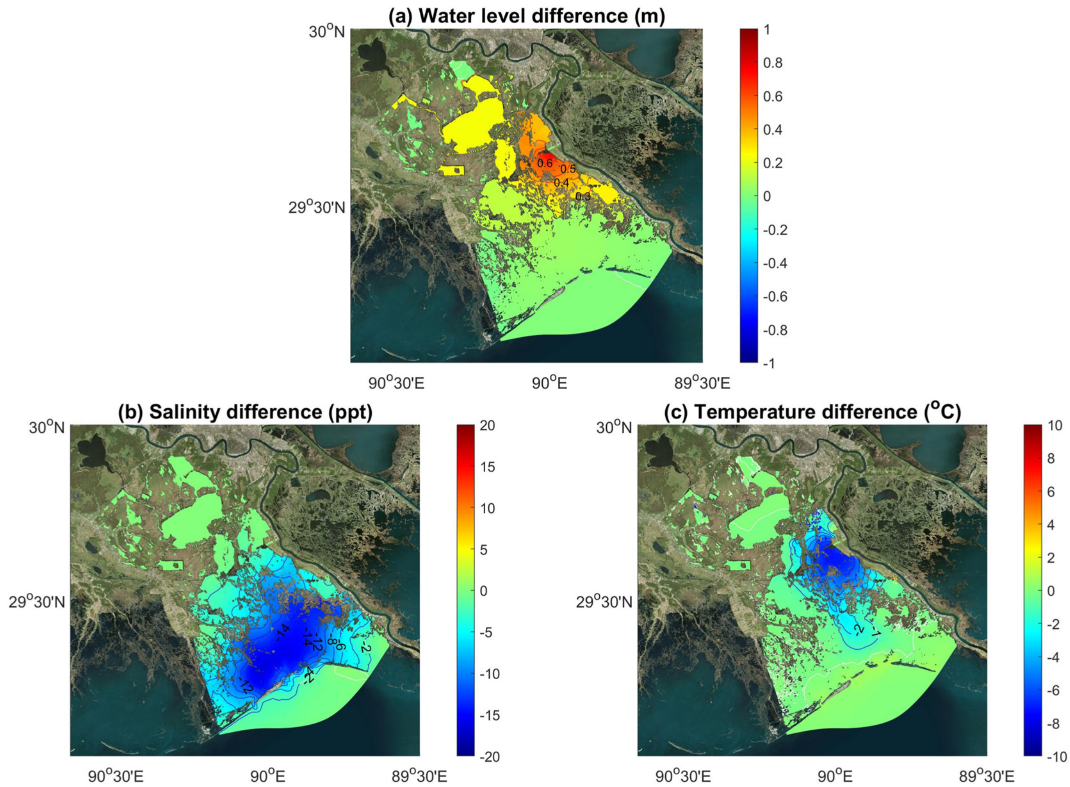

Figure 13. Difference (Mid-Barataria Sediment Diversion (MBSD)-Base) distributions of (a) water level (m), (b) salinity (ppt), and (c) temperature (°C) due to the proposed 2018 MBSD in Barataria Estuary. Red lines in (a) denote contour lines for positive values every 0.1 m; blue lines in (b) denote contour lines for negative values every 2 ppt; blue lines in (c) denote contour lines for negative values every 1°C.

4.2. Nearshore Stratification and Local Baroclinic Forcing

In coastal Louisiana, nearshore stratification is ubiquitous due to freshwater input of the Mississippi River. This phenomenon is of great importance to hypoxia formation in the northern Gulf of Mexico (Rabalais et al., 2002). Here the focus is its "remote" impact on local salinity in Barataria Estuary. A 3D phenomenon can be numerically eliminated by using a 2D model, which makes impacts of nearshore stratification and its resulting baroclinic forcing, and the choice of 3D or 2D in modeling (the third research question proposed in Section Introduction), all relevant. As such, two numerical experiments are designed. One is a 3D run in the Barataria domain with its south boundary provided by a 2D Northern Gulf run to demonstrate the impact of nearshore stratification. The other one is a 2D run in the Barataria domain to examine the impact of baroclinic forcing in the shallow estuary.

2018 annual nearshore salinity and temperature stratifications (bottom—surface) results are shown in Figure 14. Salinity stratification occurs when freshwater meets with saline water and floats on top of it. Shallow water areas do not experience stratification due to well mixing. It can be seen from the annual salinity stratification map (see Figure 14a) that high-stratification (>5 ppt of bottom-top difference, as denoted by the white contour line) area covers nearshore regions right off Bird's Foot Delta, Breton Sound, and Barataria Estuary. In terms of temperature, it is typical that ocean temperature at the surface is higher than that at the bottom due to solar radiation. Riverine freshwater is generally colder than ocean water, which can reduce temperature stratification nearshore where the surface is occupied with freshwater. That is why, opposite to salinity stratification, the area with high-stratification (<−5°C) of temperature (see Figure 14b) is missing near Bird's Foot Delta, Breton Sound, and Barataria Estuary.

Figure 15 shows results of how nearshore density stratification and local baroclinic forcing affect salinity transport in Barataria Estuary. Salinity transport is predominantly a 3D process (e.g., density stratification and its resulting baroclinic forcing), especially in coastal and estuarine areas where riverine freshwater mixes with ocean saline water. Often, 2D simulations may numerically exaggerate and distort salinity mixing processes. In the first

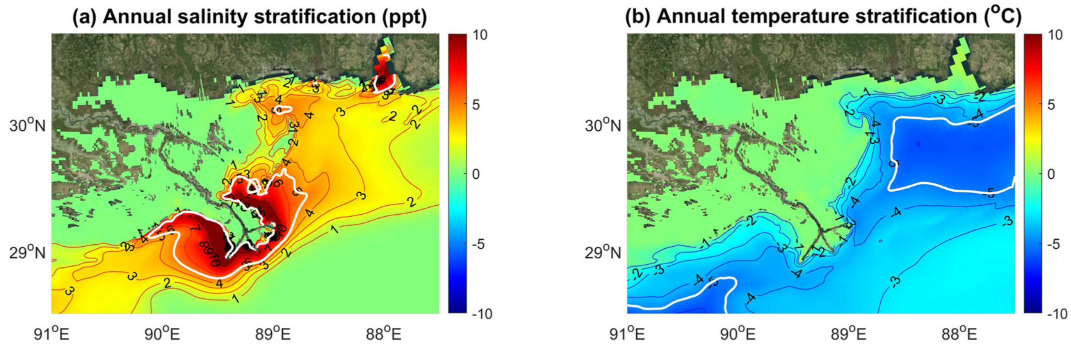

Figure 14. 2018 annual nearshore stratification (bottom—surface) distributions of (a) salinity (ppt) and (b) temperature (°C). Thick white lines denote contour lines with a value of zero; red lines denote contour lines for positive values every 1 ppt or °C; blue lines denote contour lines for negative values every 1 ppt or °C.

scenario (see Figure 15a), overmixing in the 2D regional run lowers salinity at local offshore boundaries, which causes a significant reduction of salinity up to 9 ppt in the lower estuary and offshore. In the second scenario with local baroclinic forcing neglected in the local 2D simulation (See Figure 15b), overmixing, however, increases salinity a little bit (1–2 ppt) near barrier islands, which indicates the impact of local baroclinic forcing is minor in a well-mixed shallow estuary. It is interesting that overmixing in 2D simulations is a double-edged sword that causes the high salinity (e.g., nearshore) to be lower and the low salinity (e.g., in Barataria Estuary) to be higher. In order to achieve reasonable salinity calculations in Barataria Estuary, offshore boundary conditions have to be provided by a larger-scale 3D model. Thus, the regional model calculations must be performed with a 3D setup. The local model preferably should be performed using a 3D setup, while sometimes 2D simulations may also be acceptable for some long-term applications to save computational time.

5. Discussion

The impacts of multiple environmental drivers, as well as nearshore density stratification and local baroclinic forcing, on salinity and temperature dynamics in Barataria Estuary are quantitatively investigated. Model simulations show that southerly wind causes an increase of salinity in the estuary and offshore (see Figure 11a), which can be verified using the observation during 2018–2019 by G. Li et al. (2021). To physically understand this impact, the wind-induced circulation pattern is analyzed, showing double semicircle circulations offshore. The east circulation matches the typical current pattern calculated by C. Li et al. (2011) in this area. The impact of Davis Pond diversion is found to be significant in the middle estuary (see Figure 11f), which is similar to the distribution by Inoue et al. (2008) using a coupled hydrology-hydrodynamic model with local freshwater runoff included. The MBSD induces a huge reduction of salinity up to 14 ppt (see Figure 13b), which is in accordance

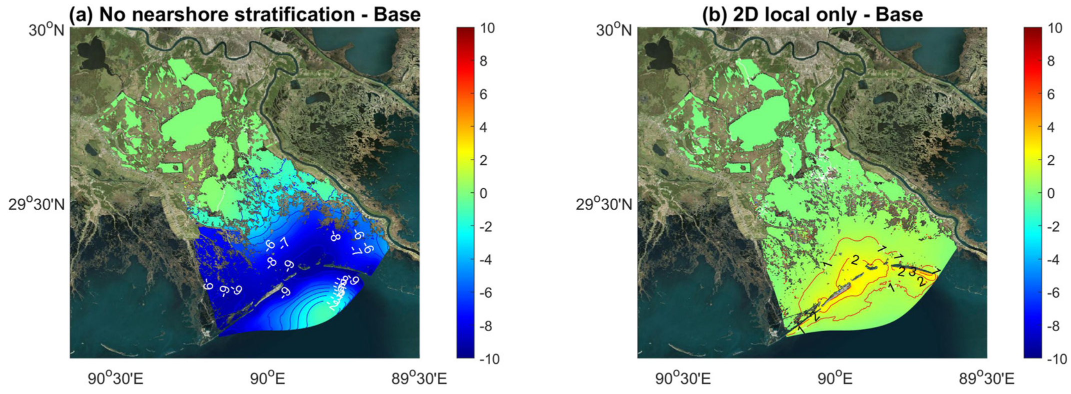

Figure 15. Distributions of depth-averaged annual salinity difference (ppt) in Barataria Estuary illustrating impacts of (a) nearshore density stratification and (b) local baroclinic forcing. Red lines denote contour lines for positive values every 1 ppt; blue lines denote contour lines for negative values every 1 ppt.

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with the value (13 ppt) in Ou et al. (2020). The same previous study also reveals a decrease of salinity by 5.6–7.5 ppt when doubling the multi-year Mississippi River discharge, which is consistent with the reduction value (~5 ppt) in this study when comparing the high river flow scenario (Figure 11d) with the low river flow scenario (Figure 11c) since the low discharge is almost half (0.52 exactly) of the high discharge. In addition to these similar results, our work also provides some findings that are seldom discussed in previous studies, such as salinity difference distribution by rainfall and the impact of nearshore density stratification on local salinity in the estuary.

6. Summary and Conclusions

A 3D process-based hydrodynamic and transport model system with three-level nested domains (i.e., the large-scale Gulf-Atlantic, the regional Northern Gulf, and the local Barataria) are used to investigate salinity and temperature dynamics in Barataria Estuary, Louisiana, USA. The Mississippi River flow is captured through a series of point sources where the discharge at each outlet is represented by a measurement-based rating curve. The model system is validated with daily water level, salinity, and temperature measurements at 15 stations in Barataria Estuary for the year 2018. The direct model-data comparisons as well as Target and Taylor diagrams demonstrate a satisfactory model performance in reproducing the hydrodynamics and transports of salinity and temperature in the estuary.

Through a series of numerical experiments, the impacts of various environmental drivers as well as nearshore density stratification and local baroclinic forcing on salinity and temperature dynamics are investigated. Environmental drivers include wind, rainfall, Mississippi River discharge, SLR, and freshwater point-source diversion. The analysis shows that rainfall has a significant influence on salinity dynamics, resulting in a salinity difference reaching up to 10 ppt in the middle and lower regions of the estuary. Prevailing southernly wind can induce about a 4 ppt salinity increase in the lower region of the estuary and offshore. Wind-induced residual current analysis reveals near-zero residuals in the estuary and ~0.1 m/s residual currents offshore with a clear double semicircle circulation pattern.

The difference in Mississippi River discharge (e.g., 2012 low flow vs. 1973 high flow) can induce about a 5 ppt difference in the annual-average salinity in the middle and lower regions of the estuary. The examined SLR of 0.294 m can cause up to 5 ppt salinity increase in the middle region of the estuary while resulting in a 1–2 ppt salinity decrease in the southwest corner of the estuary.

The freshwater diversion (Davis Pond) has the most impact (a 5 ppt salinity reduction) in the middle region of the estuary. However, its impact is confined within Barataria Estuary and does not go beyond barrier islands. The larger (nearly an order of magnitude larger than Davis Pond) Mid-Barataria diversion has substantial impacts on water level, salinity, and temperature in Barataria Estuary. The operation strategy with a maximum diversion of 2,124 m^3/s could induce a surge setup up to 0.6 m and a temperature reduction up to 7°C near the project location. Due to a large amount of the diverted discharge, the middle and lower estuary will be substantially freshened by up to 14 ppt in salinity reduction. However, efforts could be made to mitigate any adverse habitat impacts by optimizing diversion operation plans.

The analysis also included the importance of nearshore density stratification. Due to the continuous freshwater input of the Mississippi River, salinity stratification is ubiquitous in coastal Louisiana. 2D simulations may numerically exaggerate and distort the vertical mixing process of freshwater and saline water. Neglecting the effect of nearshore density stratification could underestimate salinity in the lower estuary up to 9 ppt. If local baroclinic forcing is ignored by a local 2D simulation, the impact on local salinity is small, that is, a 1–2 ppt increase of salinity in the lower estuary. These results also indicate the importance of using 3D simulations in the regional domain, while although using 3D is preferred in the local domain as well, using 2D is acceptable especially if long-term (annual average) quantities are the target.

Overall, the impacts of multiple environmental drivers on salinity and temperature dynamics in Barataria Estuary were quantitatively investigated in this study. Improving our understanding of salinity and temperature dynamics in estuaries such as Barataria Estuary is critical for the proper implementation of numerical models used to evaluate restoration and protection measures. Further, adequately capturing salinity and temperature dynamics is critical as they are primary drivers for ecological models and HSIs.

The analysis also highlights some suggestions for future model improvements such as adding more vertical layers if details of offshore salinity values are needed, considering wave effects on hydrodynamics and transport especially during cold front and storm events, inclusion of vegetation effects on bottom friction and mixing, and introducing bed level change and bottom friction adjustment for future scenarios. Moreover, due to the limitation of structured grids, the Mississippi River and its bifurcations and passes are not easy to resolve, and that's why they are excluded in the regional domain and multiple point sources are added instead. The unstructured version of Delft3D, called the Delft-Flexible Mesh (Kernkamp et al., 2011), could be a good choice for this purpose.

Data Availability Statement

The open-source Delft3D 4 Suite is freely available by Deltares (2023b). The raw bathy-topography data are extracted from CoNED (USGS, 2023a). The atmospheric forcing is from the 6-hourly NCEP/NCAR Reanalysis I (NOAA PSL, 2023a) and NCEP/DOE Reanalysis II (NOAA PSL, 2023b). The initial salinity estimate is from HYCOM Gulf of Mexico Analysis (HYCOM Consortium, 2023). The measurement data used in this study is from Water Data for the Nation (USGS, 2023b), Tides & Currents (NOAA NOS, 2023), River Gage Data for Rivers, Streams and Tributaries (USACE, 2023), and CRMS (CPRA, 2023a).

Acknowledgments

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