

# Hydrodynamic Tipping Points in the Mississippi Sound in Response to Bonnet Carré Spillway Openings

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# Executive Summary

## Background and Objectives

This project examines the current operational strategy of the Bonnet Carré Spillway (BCS), a Mississippi River flood-control structure located about 21 miles northwest of New Orleans, Louisiana, and managed by the U.S. Army Corps of Engineers. The BCS is part of the larger Mississippi River and Tributaries Project, a network of levees and control structures designed to minimize flooding from the American plains to southern Louisiana. The spillway is opened when river discharge at New Orleans is forecasted to exceed 1,250,000 cubic feet per second, diverting significant volumes of Mississippi River water into Lake Pontchartrain which subsequently flows into Mississippi Sound.

The Mississippi Sound normally maintains salinities of 5–18 parts per thousand, fluctuating with seasonal wet and dry periods. While natural salinity deviations can occur due to local factors, these are usually brief. However, under the influence of extended BCS openings, salinity conditions can reach near-zero values for periods that may persist for multiple weeks or even months across much of the estuary. Past BCS openings have been linked to elevated mortality in marine species, including oysters.

Over the first eight decades of its existence, the BCS was opened 9 times, in line with its original design expectations. In contrast, over the past 15 years the BCS has been opened six times, which is more frequent than during the previous six decades. After the two BCS openings in 2019, it became clear that spillway operations can have severe impacts on ecosystems and fisheries, as harvestable oyster reefs in the Mississippi Sound experienced up to 100% mortality based on MDMR field surveys during the summer of that year. Mississippi's on-bottom oyster fishery was closed for five years after this event. With increasing rainfall trends at both local and national scales, there is an urgent need to explore alternative flood-control strategies and management approaches that minimize ecological harm and protect Mississippi's marine resources.

This is the report on the hydrodynamics and physical water quality component of the project “Development of an operational alternative to the Bonnet Carré Spillway accounting for ecological tipping points in the Mississippi Sound”. The objective of this component is to identify where and when environmental stressors (e.g., low salinity) lead to the hydrodynamic tipping points whereby (or salinity thresholds when) oyster exposure to low salinities is significantly increased due to BCS releases, and at what diversion duration, pace and volume these occur.

## Approach

The eastern oyster is known to have strong resilience and remarkable tolerance to wide ranges of temperature and salinity, partially attributed to their ability to close their valves, especially during extreme low salinity events (Le Peyre et al, 2013). However, they are not able to tolerate exposure to low salinities for more than 1-2 weeks and a critical threshold of 2 for oyster mortality was suggested by Southworth et al. (2017) because extended valve closure may result in mortality due to a variety of reasons such as starvation or hypoxia (Lee et al., 2026). In this study, a hydrodynamic tipping point for oysters was initially determined to be 14 consecutive days of exposure to extreme low salinities below 2.

We used a regional application of the Coupled Ocean Atmosphere Wave Sediment Transport modeling system (msbCOAWST) within an integrated modeling framework to simulate scenarios based on “historic spillway opening pace implementations” that have been employed in the past under identical typical environmental conditions to reduce uncertainty about what the environmental

conditions are during BCS release events. To make the scenarios comparable and focused on the effects of the BCS openings, the tidal and atmospheric forcings of the same year (2018) were used in each scenario, climatological natural riverine forcing was used, and the BCS was opened at the same time in each modeling scenario. These historical openings reflect seven scenarios, detailed below.

1. Scenario 1: Recreate the 2011 opening, which spanned 43 days with a total freshwater discharge volume of 329.6% of Lake Pontchartrain.
2. Scenario 2: Recreate the 2018 opening, which spanned 21 days with a total freshwater discharge volume of 86.6% of Lake Pontchartrain.
3. Scenario 3: Recreate the 2019 first opening, which spanned 44 days with a total freshwater discharge volume of 219.5% of Lake Pontchartrain.
4. Scenario 4: Recreate the 2019 second opening, which spanned 79 days with a total freshwater discharge volume of 346.9% of Lake Pontchartrain.
5. Scenario 5: Recreate the combined 2019 openings, which spanned a total of 123 days across two openings with a total freshwater discharge volume of 566.4% of Lake Pontchartrain.
6. Scenario 6: Recreate the 2020 opening, which spanned 29 days with a total freshwater discharge volume of 59.9% of Lake Pontchartrain.
7. Scenario 7: Recreate the river inflow only from natural rivers under typical climatological conditions, without BCS openings.

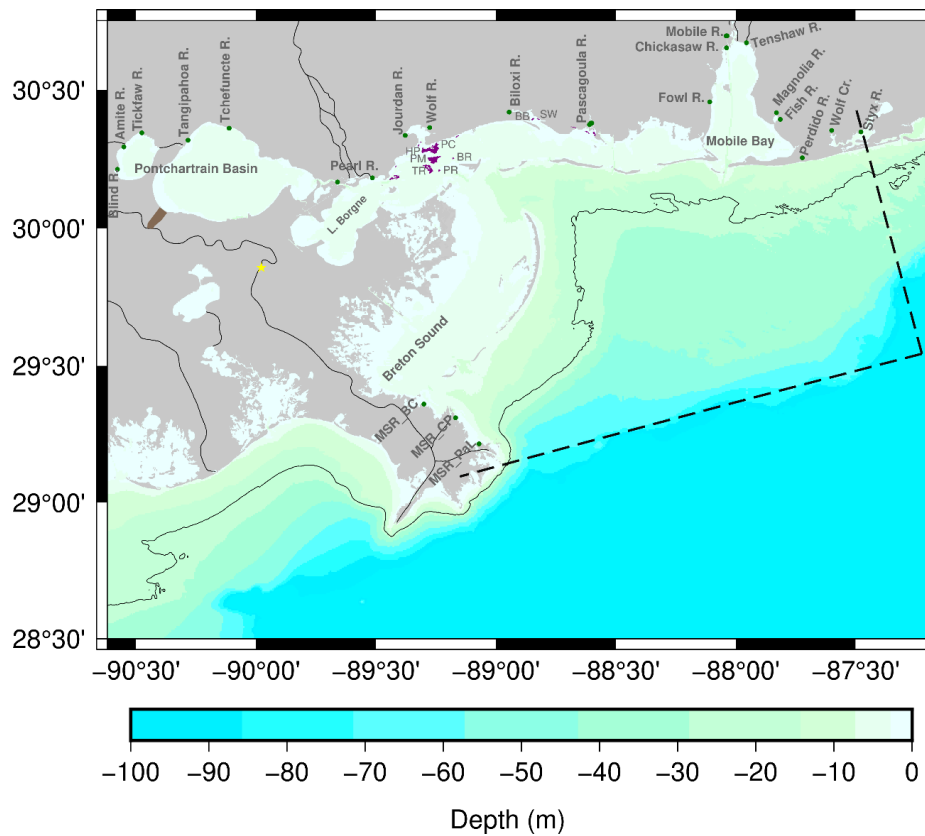


Figure E1. Study area showing the modeling domain bounded by the dash lines and the coastline, Bonnet Carré Spillway and local rivers (green circles) and oyster reef locations in Mississippi Sound (purple). Data from the USGS gauge station at Belle Chasse (yellow diamond) is the basis for inputs of MS River water along the Birdsfoot Delta.

The resulting salinity and temperature output from running these scenarios with the hydrodynamic model in the study area (Figure E.1) was used to determine hydrodynamic tipping points for oysters within the Mississippi Sound and Bight.

## Key Findings and Recommendations

In this report, the hydrodynamic/water quality tipping point focuses on salinity as a hydrodynamic/physical water quality parameter and uses the more acute and critical threshold of 2 psu. **The tipping point is defined as 14 consecutive days below 2 psu because it has been found that oysters are not able to tolerate exposure to low salinities for more than several weeks (Southworth et al., 2017; Le Peyre et al., 2013).**

The ecological assessment which utilized monthly timescales identified 2018 and 2020 as years that did not reach the ecologically defined tipping point (de Mutsert, Riddall, and Milroy, 2026). **The high resolution of the msbCOAWST model allows a detailed look into daily/hourly timescales and shows that only 2020 does not exceed the defined hydrodynamic tipping point on a daily/hourly timescale. The critical threshold of 2 psu for 14 consecutive days is exceeded for 2011, 2018, 2019A, 2019B, and 2019Full BCS opening scenarios.**

- Longest streaks were assessed with a focus on the 5 psu and 2 psu thresholds under which settled oysters experience significant stress. While all scenarios drop below 5 during the spring freshet, **only those scenarios with BCS open remain below 5 and/or drop below 2 for “streaks” of consecutive days that extend beyond the tipping point in Mississippi Sound.**
- Area of impact: In addition to the 320K square kilometers which remain under a salinity of 2 for a minimum of 2 consecutive weeks due to the natural riverine input into the system, BCS scenarios increase the area by 57.8% (2020) to 73.7% (2019 Full). The area of impact can mainly be attributed to volume, since spillway operations of similar duration (43 days in 2011 and 44 days in 2019A) result in different area increases (73.7% and 69.4%, respectively) depending on the volume released (329.6% in 2011 vs 219.5% in 2019A). **Limiting BCS opening volume will limit the increased area of impact.**
- Pace vs Volume vs Duration Discussion :
  - Pace: Arrival of low salinity waters following the BCS opening is proportional to the opening pace of each scenario. Scenarios where opening pace (first 20 days) is between 4% and 5.8% of Lake Pontchartrain volume (LPV) per day reach reefs in Western Mississippi Sound 5-7 days later than the 2011 scenario which has an opening pace of 9.6%. **Limiting opening pace to less than 5% of LPV per day gives fisheries managers additional time to make resource management decisions.**
  - Duration: The duration of the spillway openings in days is highly correlated with the cumulative percent of time salinities are below 2 at each reef location. **System recovery is delayed for longer spillway openings.**
  - Tidal influence: Tidal variations provide increased salinities during flood tide providing relief to oyster reefs experiencing salinities between 2 and 5 psu. These tidal reliefs only occur during shorter more controlled BCS operation scenarios (2020 and 2018). **Limiting the duration and volume of spillway operations allows for intermittent reliefs driven by tides and provides a chance for oyster recovery and resilience.**

- Volume: The total volume released for the 2020 scenario which did not reach the tipping point threshold was 60% of Lake Pontchartrain volume while the total diverted volume for 2018 which did reach the tipping point for a limited number of reefs (2 out of 8) was 86.6%. **Limiting diverted volume to less than 80% of LPV could limit the negative impacts on oyster reef health in Western Mississippi Sound.**
- Background Natural Riverine Input when BCS is open: Pace impacts the system's ability to flush additional freshwater input. 2020 is the only scenario where the opening pace is less than 3% of LPV per day and the only scenario where streaks below 2 are limited to 2 days at one reef. The climatological spring freshet volume flowing into the Western Mississippi Sound is ~1% of LPV. **Limiting the combined BCS pace and freshet volume to less than 4% of LPV per day during the spring season could prevent introducing more water than the Mississippi Sound can flush, avoiding long streaks of days with salinity below 2 psu.**
- The number of days the pace is greater than 3% of LPV per day is highly correlated ( $R^2=0.99$ ) with the percentage of days annually the salinity at each reef is below 2 psu. This allows an estimation of the number of days the spillway can be open at a pace greater than 3% before the hydrodynamic tipping point is reached at each Reef. This value ranges between 11 and 20 days. **Limiting the number of days the spillway pace is >3% LPV to less than 11 days could prevent reaching the hydrodynamic tipping point at Reefs in Western Mississippi Sound.**

Further Recommendations:

- Neptune Pass Influence: One of the largest crevasses of Mississippi River is now Neptune Pass which is diverting a significant amount of Mississippi River waters towards Breton and Chandeleur Sounds. Neptune Pass became deeper and wider during the 2019 Bonnet Carré Spillway opening and can divert a large amount throughout the year and especially when the BCS is open. **The impact of the Neptune Pass plume may reach all the way into the inner shelf area south of Mississippi Sound and this could limit the relief provided to the oyster reefs by tidal influences.** Therefore, it is recommended to **limit the pace, volume and duration of BCS operations as much as possible** and operate the Bonnet Carré spillway as conservatively as possible by **considering operating other diversion structures upstream** (e.g. Morganza Spillway) if and when necessary. The decision makers could also accomplish this by **considering modifying the Mississippi-Atchafalaya split at the old river control structure and changing the standard 70-30 split to a 60-40 split** so that the pressure on the Mississippi River levee system is reduced and the BCS could be operated as conservatively as possible if and when needed. The 2020 opening is a good example of a conservative opening limiting the opening duration at 29 days, the total diverted volume at 60% of Lake Pontchartrain Volume, and the pace of opening at less than 3% of LPV.
- Combined River Influence: While the primary decision to operate the Bonnet Carré Spillway is made based on the Mississippi River stage (and discharge), the ecological impact on shellfisheries and fisheries is a combined influence of diverted Mississippi River waters and the

local riverine input. This study used climatological riverine input for local rivers so that an average representative local river influence is considered. However, considering interannual variability, there will be years when the local river influence will be higher than this average. Therefore, the negative combined (BCS+local) riverine influence can be larger if and when the natural local riverine input is larger. **We recommend the consideration of adding the local riverine input into the decision-making framework for the BCS operations and reducing the opening pace, volume and duration accordingly or considering utilizing other flood control measures as described above.** The slow opening pace is crucial because, if the natural resource managers discuss relocating oysters during a BCS opening, it will extend the time available for taking action. Natural resource managers could also monitor salinity conditions at upstream locations to better predict the timing of low salinity freshwater arrival at the reefs and plan accordingly.

- Forecast modeling: The advancement of modeling capabilities now allows us to make short-term (e.g., hourly-to-daily, 0-48 hours), mid-term (e.g. daily-to-weekly, 3-7 days), and long-term (e.g. weekly-to-monthly) hydrodynamic and hydrologic predictions. **We recommend the dynamic operation of Bonnet Carré Spillway considering the use of forecast model predictions for the ocean (monitoring water quality forecasts) and for the rivers (monitoring precipitation and river discharge forecasts) to ensure minimizing the stressful conditions for the estuarine systems, fisheries and shellfisheries.** It has been disseminated by USACE in public meetings that BCS operations are triggered by the Mississippi River stage/discharge and gate opening/closure decisions are also made solely based on the Mississippi River stage/discharge to prevent flooding. We recommend the simultaneous use of ocean/water quality model forecasts so that the operators may be more informed about the potential for hazardous estuarine/ecological conditions when making decisions and could therefore act to minimize potentially dire consequences for the fisheries and shellfisheries under their purview.

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## Terms of Reference

### **B**

Biloxi Bay Reef (**BB**)  
Bonnet Carré Spillway (**BCS**)  
Buoy Reef (**BR**)

### **C**

Central Mississippi Sound (**CMSS**)  
Community Sediment Transport Modeling  
System (**CSTMS**)  
Consortium for Coastal River-Dominated  
Ecosystems (**CONCORDE**)  
Coupled Ocean-Atmosphere-Wave-Sediment  
Transport Modeling System (**COAWST**)  
Cubic Feet per Second (**cfs**)

### **D**

Digital Elevation Model (**DEM**)  
Division of Marine Science (**DMS**)

### **F**

Florida (**FL**)

### **G**

Gulf of Mexico Research Initiative (**GoMRI**)

### **H**

Habitat Suitability Index Model (**HSI**)  
Henderson Point Reef (**HP**)  
High Resolution Rapid Refresh (**HRRR**)

### **L**

Louisiana (**LA**)  
Lake Pontchartrain Volume (**LPV**)

### **M**

Mississippi (**MS**)  
Mississippi Department of Marine Resources  
(**MDMR**)  
Mississippi Sound and Bight Regional  
Application of the COAWST Model  
(**msbCOAWST**)

### **N**

National Oceanic and Atmospheric  
Administration (**NOAA**)  
Navy Coastal Ocean Model Gulf of Mexico  
(**NCOM-GOM**)

### **P**

Pass Christian Reef (**PC**)  
Pass Marianne Reef (**PM**)  
Pelican Reef (**PR**)

### **R**

Regional Ocean Modeling System (**ROMS**)  
Rivers Only Hydrodynamic Model Experiment  
(**RO**)

### **S**

Shearwater Reef (**SW**)  
Simulating Waves Nearshore (**SWAN**)

### **T**

Telegraph Reef (**TR**)  
Thematic Real-time Environmental Distributed  
Data Services (**THREDDS**)

### **U**

United States Army Corps of Engineers (**USACE**)  
United States Geological Survey (**USGS**)  
The University of Southern Mississippi (**USM**)

### **W**

Western Mississippi Sound (**WMSS**)

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## Introduction

### Background

Eastern oysters, *Crassostrea virginica*, have long been a preferred target for management and restoration efforts in coastal waters, particularly for the wide-ranging economic and ecological benefits they provide. For example, commercial oyster landings within northern Gulf waters have generated an average of \$85M revenue per year over the last decade, representing more than 50% of all U.S. oyster value from 2011-2020 (NOAA Office of Science and Technology, 2023). Beyond their economic significance, oysters also provide a host of valuable ecosystem services, such as their capacity to: enhance shoreline protection and mitigate coastal erosion in low-energy environments (La Peyre et al., 2017; Morris et al., 2021; Piazza et al., 2005), accelerate carbon sequestration (Fodrie et al., 2017; Veenstra et al., 2021), improve water quality via nutrient removal (Ayvazian et al., 2021; Humphries et al., 2016; Kellogg et al., 2013; Parker & Bricker, 2020), enhance water clarity via clearance of suspended particulate matter (Coen et al., 2007; Kreeger et al., 2018; Turner, 2021), and provide critical habitat to other economically- and ecologically-important species (Coen et al., 2007; Gilby et al., 2018; Mann, 2001).

Eastern oysters play a defining role in the economic and ecological function of Mississippi coastal waters and is a critical focus of MS state restoration efforts. The need for dramatically more effective restoration strategies has become especially acute in recent years, as the Mississippi oyster fishery suffered a precipitous three-fold decrease in year-to-year commercial landings from 2017 to 2018, and then dwindling to zero by 2019, where it remains to-date (NOAA Office of Science and Technology, 2023). While the decimation of the Mississippi oyster fishery has largely been attributed to the ecological impacts from Hurricane Katrina in 2005 (Buck, 2005; Mackenzie Jr., 2006; Sheikh, 2005; Supan & Voisin, 2006) and the Deepwater Horizon oil spill in 2010 (Baker et al., 2017; Blancher II et al., 2017; Grabowski et al., 2017; Vignier et al., 2018), prolonged (or ill-timed) exposure to excessive river effluent has also served as a dominant threat to oyster recovery and restoration in northern Gulf waters (Gledhill et al., 2020; La Peyre et al., 2013; Posadas, 2020; Soniat et al., 2013). In fact, freshwater flooding impacts to the shrimp and oyster fisheries within MS state waters have led to two federal disaster declarations in 2011 and again in 2019, with another declaration in 2020 pending decision (NOAA Office of Sustainable Fisheries, 2023).

### Bonnet Carré Spillway History and Environmental Effects

The Bonnet Carré Spillway (BCS) was constructed in 1931 in response to the catastrophic Mississippi River flood of 1927 and remains the largest freshwater diversion influencing the Mississippi Sound and Bight (United States Army Corps of Engineers, 2021). Located approximately 52 km upstream of New Orleans, the BCS consists of 350 floodgates that can divert up to  $7,079 \text{ m}^3 \text{ s}^{-1}$  (250,000 cfs) of Mississippi River water into Lake Pontchartrain, which then flows into Lake Borgne and ultimately into the northern Gulf via the Mississippi Sound and Chandeleur Sound. The U.S. Army Corps of Engineers is mandated to open the spillway when Mississippi River discharge at New Orleans exceeds  $35,396 \text{ m}^3 \text{ s}^{-1}$  (1.25 million cfs) (United States Army Corps of Engineers, 2021). Since its construction, the BCS has been opened 15 times, averaging one opening every six years, but the frequency has increased markedly in recent decades. Five openings occurred between 2016 and 2020 alone, including the first-ever three consecutive annual openings from 2018–2020 as well as the first instance of dual openings within a single calendar year in 2019 (Parra et al., 2020).

Although designed as a flood-control structure to protect New Orleans, the BCS has far-reaching ecological effects when operated. High-volume releases of freshwater alter circulation, stratification, and water quality in Lake Pontchartrain and the Mississippi Sound, often reducing salinities to near zero for extended periods (Parra et al., 2020; Wiggert et al., 2022). These changes are accompanied by the delivery of nutrient-rich water that can intensify eutrophication, promote harmful algal blooms (Soto Ramos et al., 2023), and exacerbate hypoxia (Wiggert et al., 2022). The 2019 openings, which lasted a combined 123 days and discharged an estimated 38.1 km<sup>3</sup> of water, caused massive oyster mortality (approaching 100% at most harvest reefs), harmful algal blooms, beach closures, and hypoxia that forced mobile fauna to flee and subjected benthic species such as oysters to lethal physiological stress (Gledhill et al., 2020; Hendon et al., 2019).

As described above, BCS operations affect more than just salinity and temperature; they also alter nutrient loads, sediment delivery, turbidity, and pathogen dynamics, all of which can further impact oyster populations through mechanisms such as food dilution, burial, and reduced clearance and respiration rates (Davis & Hidu, 1969; Lenihan, 1999; Loosanoff, 1962; Loosanoff & Tommers, 1948; Park & Clough, 2018; Poirier et al., 2021). However, the modeling work presented here focuses exclusively on the effects of BCS-driven temperature and salinity changes. As such, our results should be viewed as representing the minimum expected hydrodynamic impact of spillway operations, with future modeling efforts needed to fully incorporate the impacts of nutrient loadings, hypoxia, and sediment-related stressors for a more complete understanding of BCS effects.

### Primary Objective and Goals

This project will provide the Mississippi Sound Coalition with the scientific information needed to determine how much freshwater diverted through the BCS is too much for eastern oyster (*Crassostrea virginica*) at several historically and currently important oyster reefs in the Mississippi Sound. The core objective is to develop model-based guidance on the critical salinity threshold and BCS operation and duration that lead to environmental conditions where oyster mortality is significantly increased to such an extent that recovery is severely impaired. The ultimate goal of this project is to provide the best available scientific information needed to accurately address public concerns regarding the potential effects of BCS flood diversion on the shellfisheries within the jurisdictional waters of Mississippi. The report presented herein provides model-based guidance on the impacts that various historical BCS opening scenarios have had on hydrodynamics and salinity distributions in Mississippi's jurisdictional waters.

### Study Area

Located in the northern Gulf, the Mississippi Sound (Figure 1) is a shallow (~3 m), predominantly well-mixed estuarine basin with microtidal range (~0.6 m) (Eleuterius, 1978), extending from Grand Island, Louisiana to Dauphin Island, Alabama, spanning the entire Gulf coast of the state of Mississippi (U.S. Fish and Wildlife Service (USFWS), 1982). Water exchange with the Gulf is restricted by five major barrier islands (Cat, Ship, Horn, Petit Bois, and Dauphin Islands), with natural freshwater fluxes largely dominated by the Pascagoula River in the eastern Sound and the Pearl River in the western Sound (Eleuterius, 1978), although the Mobile and Tensaw rivers can contribute fresh water to the eastern Sound as well (Cambazoglu et al., 2017). When the Mississippi River reaches flood stage upstream of New Orleans, the Bonnet Carré Spillway is used to divert flood waters into Lake Pontchartrain, resulting

in episodic (but quite significant) freshwater fluxes which ultimately flow into the western MS Sound (Cambazoglu et al., 2017; Greer et al., 2018).

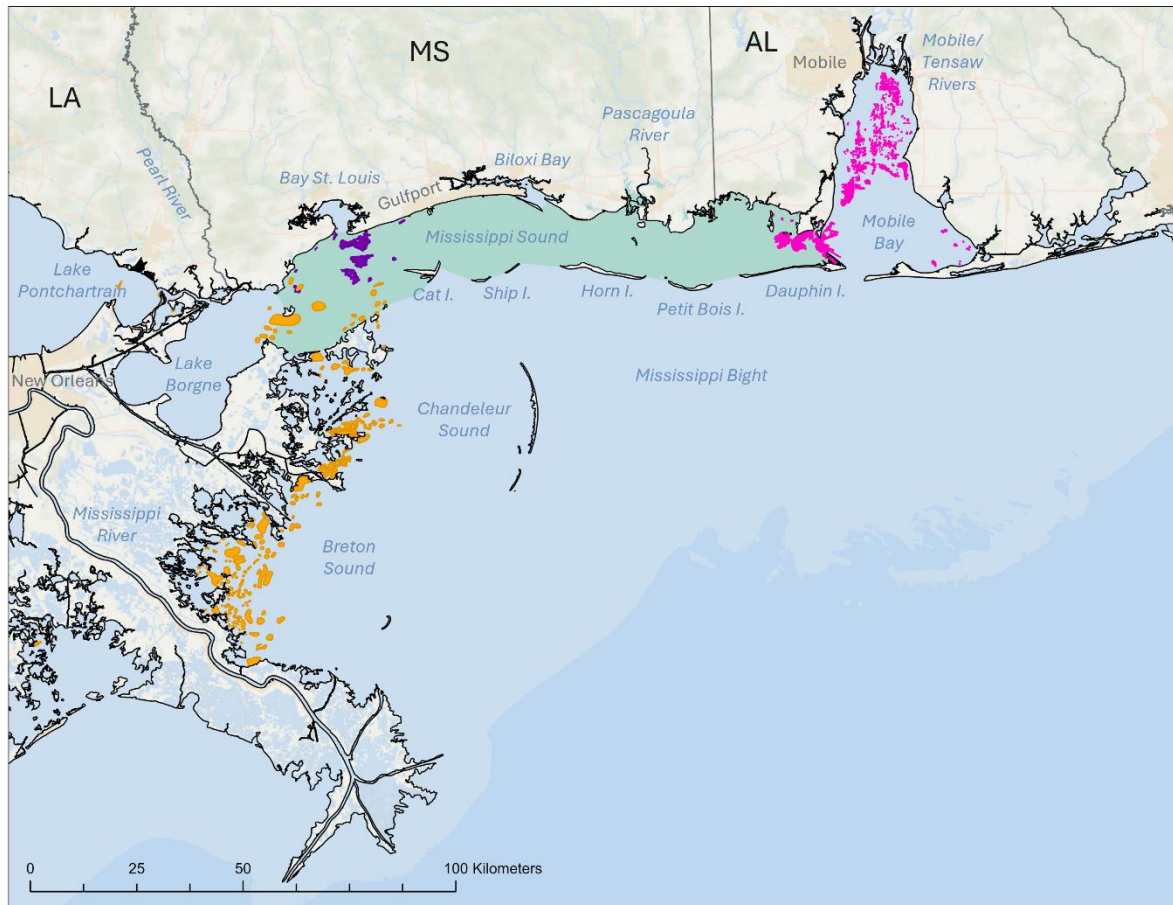


Figure 1. Map of the general study area (adapted from NOAA Office of Science and Technology, 2011). Current locations of known reef and/or on-bottom lease areas for the eastern oyster (*Crassostrea virginica*) are indicated in orange (Louisiana, LA), purple (Mississippi, MS), or fuchsia (Alabama, AL).

As an obligate estuarine organism, the eastern oyster is found throughout the entire Mississippi Sound, and in the neighboring coastal waters of Breton and Chandeleur Sounds of Louisiana and within Mobile Bay, Alabama (Figure 1). While it has been noted that oyster physiology and ecology are governed almost entirely by temperature, salinity, and food availability (La Peyre et al., 2021), the greatest density of oysters within the Mississippi Sound are relegated to those areas which are also host to substrate of suitable firmness to support the weight of accreting oyster reefs. In Mississippi waters, the most productive oyster reefs have historically been restricted to the western Mississippi Sound, south of Bay St. Louis and nestled between Cat Island, MS and Grand Island, LA.

## Project Description

This project addresses the current operational strategy of the Bonnet Carré Spillway (BCS) which is a flood control structure for the Mississippi River located 21 miles northwest of New Orleans, LA and operated by the United States Army Corps of Engineers (Figure 1). The structure is one of the many parts of the Mississippi River and Tributaries Project, a system of levees and structures that work together to

reduce terrestrial flooding from the American plains to South Louisiana. The BCS opens and closes when river flows at New Orleans are predicted to exceed 1,250,000 cubic feet per second. The operation of the BCS causes large amounts of Mississippi River continental drainage water to be introduced into the Mississippi Sound Estuary (MSE).

This estuary naturally functions by the balance of smaller coastal drainages with the offshore marine waters and typically experiences salinity variations of 5-18 parts per thousand from seasonal wet and dry periods. Salinities can naturally fall outside this range due to local influences, but these excursions are short and episodic. By contrast the BCS, when opened for extended periods, has caused salinities to be reduced to zero parts per thousand for more than 39 days over the majority of the MSE. In addition, nutrient pollution in the Mississippi River can cause algae blooms and areas of depleted oxygen in the MSE. Studies on the impacts of past openings have shown to cause elevated mortality rates for multiple marine organisms including oysters and bottlenose dolphins.

There have been more BCS openings in the last 14 years ( $n=7$ ) than the previous 60 years causing catastrophic ecological impacts and reducing Mississippi's on-bottom oyster harvest to zero over the last five years. With recent increases in annual rainfall both locally and nationally, there is a great need to investigate and construct alternative strategies for flood control structures and marine management to reduce ecological impacts and preserve the state of Mississippi's marine resources.

## Project Objectives

We use an integrated modeling framework to simulate scenarios with varying river flow, and BCS release regimes under a prevailing wind field. These scenarios are based on "hindcasts" of BCS releases that have occurred in the past with representative (climatological) natural river flow conditions - to reduce uncertainty about what the environmental conditions are during BCS release events. Because the ecological impacts on oyster reefs for any given BCS release event will vary, the different historic BCS opening paces are simulated under the same environmental conditions.

Output from the hydrodynamic model experiments is analyzed for hydrodynamic tipping points based upon physical environmental stressors (e.g., salinity). Output from the hydrodynamic model is also provided for application in the habitat suitability and ecosystem models, which determine suitability and mortality tipping points for oysters.

## Methods: Model Framework

In this project, we applied an application (structured grid, 400 m horizontal resolution, 24 vertical layers) of the Coupled Ocean Atmosphere Wave Sediment Transport (COAWST, Warner et al., 2010) modeling system which was originally developed during the Gulf of Mexico Research Initiative (GoMRI)-funded Consortium for Coastal River-Dominated Ecosystems (CONCORDE, Greer et al., 2018). The Regional Ocean Modeling System (ROMS, Shchepetkin & McWilliams, 2005) is the core circulation model that serves as the central framework within COAWST for Mississippi Sound and Bight (msbCOAWST). Our msbCOAWST application has been implemented to leverage additional fully interactive modeling capabilities, such as the Community Sediment Transport Modeling System (CSTMS; O'Brien, 2019), the Weather Research and Forecasting (WRF) Model, surface wave models such as SWAN (Simulating Waves Nearshore) or WAVEWATCH III (Warner et al., 2010), or biogeochemical modules (e.g., Wiggert et al.,

2017; Ajibade, 2026). Biogeochemical, sediment, and wave modeling are not activated for the model implementation employed for the work presented here. msbCOAWST has been used to study the impact of river diversions on Mississippi Sound and Bight such as studying the impact of past Bonnet Carré Spillway openings (Parra et al., 2020; Armstrong et al., 2021; Dyson, 2026), and studying the potential impact of proposed sediment diversion projects (Wiggert et al., 2022). Finally, the model has also been used as an active daily forecast system (Cambazoglu et al., 2024), with the model output data sets made publicly available via the DMS THREDDS server and USM's Coastal CUBEnet (Stanic et al., 2024)

The model's domain covers from the MS Sound / Bight down to the continental shelf break in the south, encompasses the entire Pontchartrain Basin in the west, and extends beyond Mobile Bay to Perdido Bay, FL in the east (Figure E1). The 3 arc second digital elevation model (DEM) developed as part of the Northern Gulf Coastal Hazards Collaboratory (Twilley et al., 2014; Wiggert et al., 2017) is the source data for generating the model's bathymetry, which was subject to mild smoothing when processed to achieve the 400 m resolution needed for our msbCOAWST application. The Bonnet Carré Spillway component of our model was implemented earlier during the Mid-Breton Sediment Diversion Assessment project and further details can be found in Wiggert et al. (2022) and Armstrong et al. (2021).

## Methods: Model Application Scenarios

To isolate and understand the impact of Bonnet Carré Spillway operations on the hydrodynamic/water quality tipping points for oysters, we developed numerical experiment cases that encompassed various spillway operation scenarios (Figure 2, Table 1). We adhered to the historic spillway operations such that the scenarios ran were identical to those of the historic operations of BCS in the chosen years. Focusing on the most recent openings of BCS which provided a wide range of spillway operations, we ran numerical experiments in which all forcing (i.e., atmospheric, natural/local riverine, tidal) is the same but only the riverine forcing coming through BCS is different. Keeping atmospheric, local riverine and tidal forcing the same for all experiments was designed to ensure we can isolate and intercompare the impact of different spillway operations. Figure 2 shows a comparison of the BCS operations in the chosen years with duration shown on the x-axis and the total diverted riverine water volume (w.r.t. the volume of Lake Pontchartrain, LPV) shown in the y-axis. Table 1 summarizes the details of these openings and categorizes them by duration and intensity of the opening.

To establish a baseline for all BCS scenarios, a Rivers Only (RO) experiment is conducted. The BCS scenarios consist of the realistic amount of riverine water diverted through the Bonnet Carré Spillway into Lake Pontchartrain (Table1, Figure 2). A comparative methodology will be used throughout the results and discussion to understand the influence of BCS openings on hydrographic properties, primarily salinity. In order to facilitate this, model runs are created to be identical in all ways except for the diverted riverine inflow from BCS. This ensures that differences between the model outputs with BCS openings and the model output for the RO experiment are solely due to the impact of the respective BCS operation. The focus on these numerical experiments within the last 15 years is because BCS has been operated more frequently during that time frame, relative to the previous 80 years, and these openings are representative of a variety of opening scenarios, some of which significantly and negatively impacted the oyster fisheries in the Mississippi Sound.

Table 1. BCS Operations used for numerical model experiments

Opening scenario	Abbreviation	Opening Duration	Duration Category	Opening Volume	Volume/Intensity Category	Notes
2011	BCS11	43 days	Moderate	329.6%	Extreme	Fastest opening
2018	BCS18	21 days	Short	86.6%	Below Average	Second shortest opening
2019-A	BCS19A	44 days	Moderate	219.5%	Above Average	
2019-B	BCS19B	79 days	Long	346.9%	Extreme	Longest opening
2019-full	BCS19Full	123 days	Long	566.4%	Extreme	Only two back-to-back openings
2020	BCS20	29 days	Short	59.9%	Lowest	Most conservative opening
Rivers Only	RO	NA	NA	NA	NA	

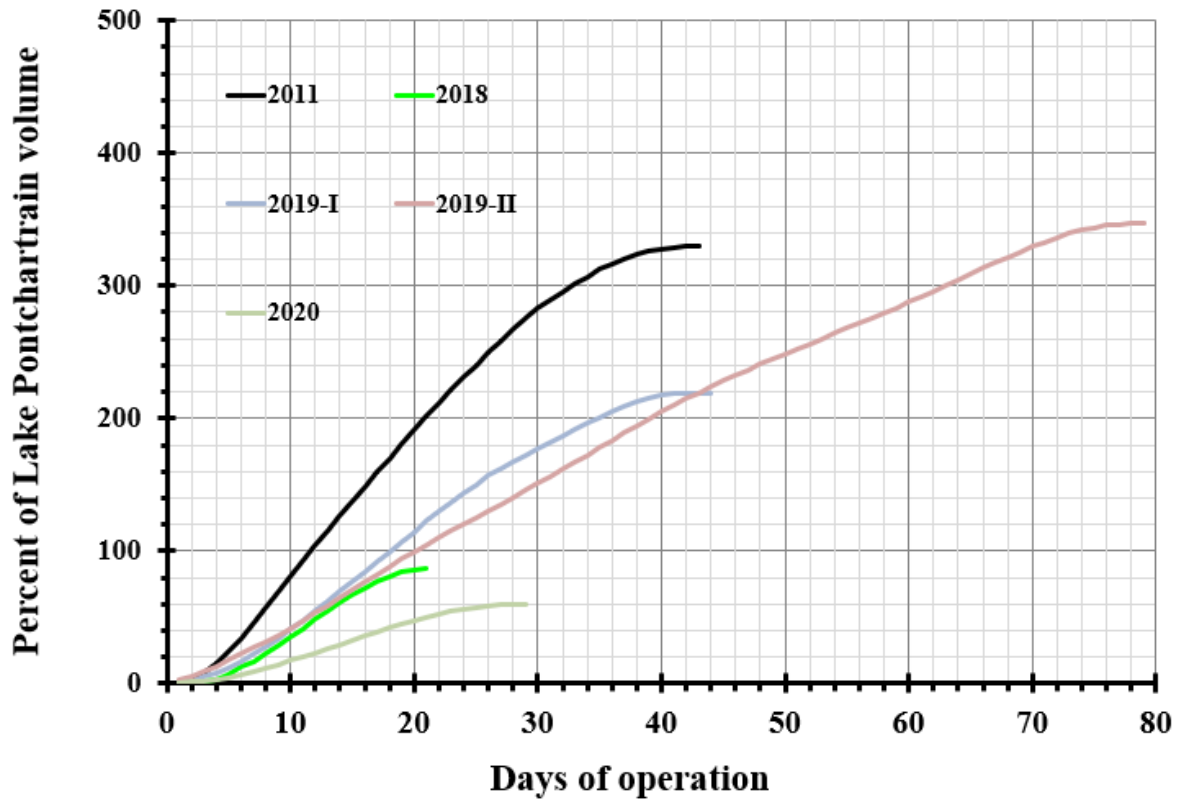


Figure 2. The duration (days of operation) and the diverted river volume (as percent of Lake Pontchartrain Volume, LPV) of historic BCS operations used for the numerical model experiments.

## Methods: Model Forcing Fields

All the numerical experiments summarized in Table 1 required the application of forcing fields for the atmospheric forcing, riverine forcing, and open boundary forcing. Table 2 provides a summary of the source information for the data sets accessed to develop the forcing fields. We developed a climatological riverine forcing for the 11-year (2010-2020) period of interest to establish typical freshwater inflow conditions during the simulations of BCS scenarios. We also developed climatological open boundary forcing for temperature, salinity and current velocities to establish typical outer boundary conditions. We considered 2018 as the representative year for the atmospheric forcing and also for the water levels (tides) at the open boundaries as forcing for all BCS simulations. A similar representative climatological forcing approach was followed by Wiggert et al. (2023) to study the impacts of the then-proposed (now-cancelled) Mid-Breton Sediment Diversion in the study area.

Table 2. Source information for the model forcing parameters applied in performing the simulations.

Model Forcing	Provider	Spatial Resolution	Temporal Resolution	Reference and Web Link (if available)
River Forcing	USGS Stream Gage Data	point data	daily averages	U.S. Geological Survey (2021) <a href="http://waterdata.usgs.gov/nwis">http://waterdata.usgs.gov/nwis</a>
River Temperature	Group for High Resolution Sea Surface Temperature (GHR SST)	6 km 0.05°	daily averages	Govekar et. al. (2022)
Atmospheric Forcing	NOAA High Resolution Rapid Refresh (HRRR)	3 km	hourly	Benjamin et. al. (2016) <a href="https://rapidrefresh.noaa.gov/hrrr/">https://rapidrefresh.noaa.gov/hrrr/</a>
Open Boundary Conditions	Navy Coastal Ocean Model - Gulf of Mexico (NCOM - GOM) regional model	1 km	3 hourly	Jacobs et al. (2016) Jacobs (2017)

## Forcing Data

### Atmospheric Forcing

The circulation in the shallow estuarine system is primarily driven by the wind and hydrodynamic processes such as estuarine-shelf exchange are impacted by atmospheric processes such as diurnal sea-land breeze. Therefore, the atmospheric forcing is critical in capturing the high-resolution atmospheric dynamics that drive the hydrodynamic variability. In this study, a high-resolution atmospheric forcing product was created using the NOAA High Resolution Rapid Refresh (HRRR) model solution for 2018. The

fidelity of estuarine exchange and circulation processes relies on using fully resolved winds, therefore unfiltered winds for calendar year 2018 (Figure A1) were used instead of average climatological conditions (Figure A2).

HRRR has 3-km spatial resolution and hourly temporal resolution. HRRR assimilates 3 km radar data every 15 minutes of a 1 hour period and provides an extended 48 hour forecast every 6 hours (NOAA Global Systems Laboratory, 2024). For each day, the first 24 hours of HRRR forecast was used to create the hourly atmospheric forcing for 2018. The parameters applied as atmospheric forcing are: zonal and meridional wind, surface air pressure and temperature, precipitation, short-wave radiation, cloud cover and humidity.

Figure A1 shows the monthly average winds for 2018 realistic winds created by averaging the higher resolution (3-km spatial, 1-hrly temporal) HRRR winds for the study area. Figure A2 shows the monthly average winds for climatological winds created by averaging the coarse resolution (32-km spatial, 3-hrly temporal) NARR winds for the study area. It may clearly be seen that the resolution of climatological forcing is unable to resolve the complex coastline. Besides, our earlier studies showed that higher resolution atmospheric products can capture the Sea-Land Breeze (SLB) atmospheric circulation, which is a crucial process driving estuarine circulation and estuarine-shelf exchange (Greer et al., 2018; Bouchard, 2021; Saran et al., 2022). SLB cannot be captured accurately at hourly timescales by coarse resolution winds, thus impacting the ocean model's fidelity in capturing important circulation processes, e.g., upwelling or inertial response.

It may be seen in the wind roses at Pass Marianne reef from January to June (Figure A3) that the wind magnitudes are larger (frequently stronger than 8 m/s) in the actual 2018 atmospheric forcing while they are weaker (usually smaller than 4 m/s) in the climatological atmospheric forcing which may indicate that the realistic winds introduce enhanced mixing. Wind directionality has more variability in the actual 2018 wind. Climatological winds have a very weak-to-none westerly (eastward) component from March to May while the realistic winds show more frequent eastward component which are upwelling favorable, therefore tending toward increased salinities. Also, realistic winds have more frequent and stronger northeasterly (southwestward) winds which would drive currents to enhance inflow of shelf water into the Mississippi Sound.

### Open Boundary Forcing

The lateral boundary conditions for the model were created using the regional high-resolution Navy Coastal Ocean Model (NCOM). The parameters used for open boundary forcing are: water temperature, salinity, zonal and meridional current velocities and water levels. The climatological boundary conditions for temperature, salinity and velocities were developed using regional applications of NCOM: 1-km resolution application to the Gulf of Mexico (NCOM-GOM produced by Naval Research Laboratory (NRL)) and a 3-km resolution regional application to the American Seas (NCOM-AMSEAS produced by Fleet Numerical Meteorology and Oceanography Center (FNMOC)), over the 11-year period from 2010 to 2020 (Wiggert et al., 2023). The water levels are interpolated from the NCOM-AMSEAS solution for 2018 onto the open boundary grid nodes of msbCOAWST. The open boundary forcing is anticipated to capture and introduce the influence of offshore processes such as the Loop Current and Loop Current eddies and may also introduce plumes of Mississippi River water that retroreflect and reenter the domain via the open boundary.

## Riverine Forcing

The riverine forcing for the natural rivers flowing into the domain was created using discharge measurements collected by USGS gauges available through the National Water Information System. A climatological river forcing was developed using the period covering the Bonnet Carré operations studied (2010-2020) to represent a typical amount of annual input of riverine waters. The daily climatological riverine input was calculated after filtering out the discharge values greater than the mean value plus three standard deviation margin for each day of the year. The filtering method allowed for the elimination of extreme values as the representative typical conditions were created. The rivers in the study area are tidally influenced and for that reason, an average salinity value was used for each river based on its location and available in-situ data. As salinity data is not available at each river mouth, existing specific conductance data at USGS stations (East Pearl River station, id:301141089320300, Pearl River at Pearl river LA station, id:02492600) and Louisiana Department of Environmental Quality stations (East Pearl River West of Pearlington, id:0032; West Pearl River Southeast of Slidell, Louisiana, id:0105, Little Lake Northeast of New Orleans, Louisiana, id: 1037) has been used to calculate the practical salinity unit using (PSS-78) polynomial formula Table (Webster, 2013). The tTable shows the salinity values used for the river source points. These values were determined based on available measurements from USGS stations or reported observations (USEPA, 2005). The river temperature climatology was created using GHRSSST data for 2010-2020 time period.

The Pearl River is the largest river near Western Mississippi Sound having a significant influence on the nearby oyster reefs however some of the water carried by the Pearl gets stored in the wetland area in between the two branches and the water flowing out of the two main branches is less than the measured flow at the upstream USGS station at Bogalusa, LA. Therefore, we studied the discharges predicted by the National Water Model at the mouths of the East Pearl and West Pearl River to modify the climatological river forcing created using the measurements at Bogalusa. A percentage of the total flow from Bogalusa was determined using a power function to parameterize the data. The available USGS Bogalusa station data, from Oct. 1995 to Apr. 2025, was compared with NWM years 2022 through Apr. 2025 to calculate this power function. As the power function split resulted in greater than 100% of the flow at Bogalusa station coming out of the river mouths during flow rates lower than 141 cubic meters per second, we decided to switch to a constant split during these periods. At lower flow rates, the West Pearl retains 60% of the flow measured at Bogalusa, with the East Pearl retaining the other 40%. When the Pearl River above the East/West split experiences high flow, less than 100% of the water flows out of the final East and West Pearl River mouths determined based on the power function created using the NWM results.

Figure A4 shows the climatological river forcing (2011-2020 average) used in this project (black lines) for Pearl, Biloxi and Pascagoula Rivers along with the five-year average of years with a BCS opening (blue lines) and the five-year average of the years without a BCS opening (red lines). It may be seen that the 10-year climatological averages are consistently between the averages of BCS years and non-BCS years. It may also be seen that Pearl and Pascagoula Rivers have a higher peak discharge average during spring for BCS opening years.

Figure A5 shows the daily accumulative river discharges averaged over all years compared to the averages of only BCS years and only non-BCS years. It may be seen that the total volume of water coming from Pearl River is higher in BCS years. This is not the case for the Biloxi and Pascagoula Rivers as they have higher flow in non-BCS Years. This difference reflects that the watersheds for the Biloxi and

Pascagoula Rivers have distinct influences, whereas the neighboring watersheds for the Mississippi and Pearl Rivers result in the similarities in seasonal variability that they exhibit.

*Table 3. Salinity values for river forcing in the study area.*

msbCOAWST River, river_id index	Salinity Value
Styx River	5
Wolf Creek	5
Perdido River	5
Fish River	2.9
Magnolia river	2.9
Tensaw	2.9
Chickasaw Creek	2.9
Fowl river	2.9
Singing river	2.9
W Pascagoula	2.9
Biloxi River	5
Wolf River	5
Jourdan River	5
Pearl River	2.9
Mississippi River	0
Mobile River	2.9
Amite River	0
Tickfaw	0
Tangipahoa River	2
Blind River	0
West Pearl River	2.9
Tchefuncte	2

### Bonnet Carré Spillway Discharge

The Bonnet Carré discharge was calculated based on the spillway operation information shared by the USACE (USACE, 2025) and was introduced to msbCOAWST as riverine forcing (Armstrong et al., 2021). The salinity of the Mississippi River waters diverted to flow through the BCS is assumed zero and the temperature of the diverted waters is extracted from GHRSSST. To intercompare the impact of different operational procedures (Table 1), the experiments are built in such a way that it is assumed that the operations for all scenarios started on the same day of the calendar year. Early March was the most common opening time period for the most recent BCS operations since 2010. Therefore, we have chosen the 2018 opening as the representative opening and all modeling simulation scenarios had the spillway opened on March 8<sup>th</sup>.

### Methods: Analysis Tools

Salinity is one of the main stressors for oysters during Bonnet Carré Spillway operations because of the excess amount of Mississippi River waters with low salinities entering the estuarine system via Lake Pontchartrain. The diverted riverine waters flow out of the Lake via the Rigolets Channel and enter Lake Borgne and Western Mississippi Sound. Therefore, we track modeled salinities under different scenarios to investigate the influence of different BCS operations with the goal of identifying when the tipping

point thresholds are exceeded, leading to oyster mortality. For this purpose, a set of model products were created as follows:

- 1- **Time series plots of modeled bottom salinity at reef locations:** These plots allow us to see the variation of salinity at reef locations and the results may be intercompared in between simulations and may also be compared with the results of the Rivers Only (RO) scenario to identify how the various BCS operational strategies impact the region's oyster reefs.
- 2- **Field plots of areas that were exposed to salinities below 2 at the bottom for at least 14 consecutive days:** These plots allow us to identify the areas in which settled oysters (spat, seed or sack) at the bottom get exposed to low salinities below two for at least two weeks which may lead to their mortality.

msbCOAWST produces hourly model output which is also used in this report to understand higher frequency hourly variations of salinity, while model results were daily averaged and provided to the HSI model and monthly averaged and provided to the Ecological model.

### Model Skill Assessment

Model results of bottom salinity and temperature at the Pass Marianne reef (one of the largest historic reefs in western Mississippi Sound) for the Rivers-only scenario are compared to the measurements collected at the MDMR/USGS Merrill Shell Bank Light station in Mississippi Sound (USGS station ID: 301429089145600), which is adjacent to Pass Marianne. Figure A6 shows that the model is capable of successfully capturing both the seasonal variation and the seasonal magnitude of bottom salinity. Both the model and available data show salinity decreases in January and February; episodic events and multiple peaks during April and May; and an increase in salinity in summer months peaking in August. The salinity drop in October and subsequent increase in November and December also correspond well between the model and measurements.

The figure also shows the importance and need for using actual/realistic atmospheric forcing using 2018 conditions. Salinities remain low in Spring for an extended period from early-March to mid-June when climatological atmospheric forcing is used (blue line). However, when 2018 atmospheric forcing is used, the model is able to reproduce the salinity increases in Spring (red line), where such bursts of high salinities may provide relief to the reefs in the Sound during Spillway operations.

Figure A7 shows the daily averaged bottom temperature measured at the MDMR/USGS station (black dots) nearby the Pass Marianne reef and the modeled bottom temperature using climatological atmospheric forcing (blue line) and the 2018 atmospheric forcing (red line). While model captures the seasonal temperature variation accurately with both configurations, the model solution is again closer to the measurements using the realistic winds especially in winter months (Jan-Feb), spring months (March-April) and fall months (September thru November) emphasizing the importance of using actual/realistic winds to capture more accurate results.

### Bonnet Carré Impact on Salinity at Reefs

In this report, we will first focus on salinity as a hydrodynamic/physical water quality parameter. The bottom salinities at 8 reef locations listed in Table 4 and shown on Figure 3 are investigated. We will focus our analysis primarily on the following eight reefs in Mississippi Sound: Telegraph Reef (TR), Pelican Reef (PR), Buoy Reef (BR), Pass Marianne (PM), Pass Christian (PC), and Henderson Point (HP) in

Western Mississippi Sound (WMSS); and Biloxi Bay Reef (BB) and Shearwater Reef (SW) in Central Mississippi Sound (CMSS). The water depth is shallow at all reef locations, ranging over 3-4 m in WMSS and consistently ~1.6 m for reefs in CMSS.

Table 4: Reef locations of interest with coordinates used for the hydrodynamic tipping point analysis in this report were also used for ecological tipping points in de Mutsert et al., (2026).

Location name	Location ID	Longitude	Latitude
Henderson Point Reef	HP	-89.2727	30.28370
Pass Christian Reef	PC	-89.2738	30.27916
Pass Marianne Reef	PM	-89.2577	30.24820
Telegraph Reef	TR	-89.280624	30.217103
Pelican Reef	PR	-89.236	30.20950
Buoy Reef	BR	-89.1795	30.25250
Biloxi Bay Reef	BB	-88.846116	30.394796
Shearwater Reef	SW	-88.823367	30.394664

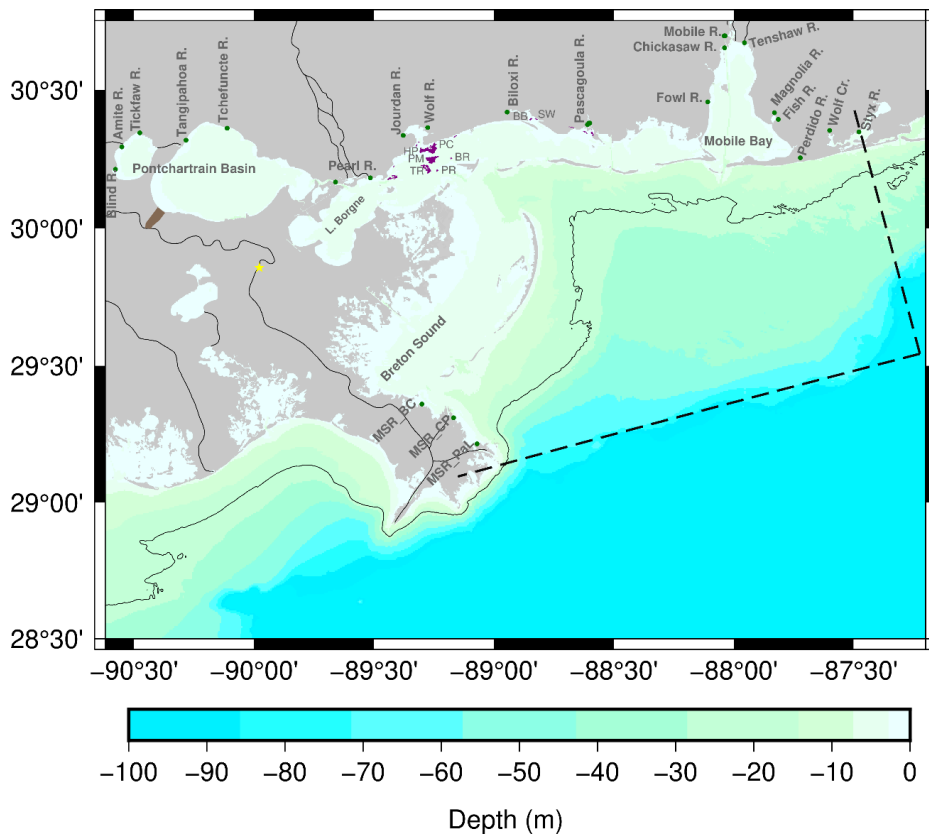


Figure 3. Study area showing the modeling domain bounded by the dash lines and the coastline, Bonnet Carré Spillway and local rivers (green circles) and oyster reef locations in Mississippi Sound (purple). Data from the USGS gauge station at Belle Chasse (yellow star) is the basis for inputs of MS River water along the Birdsfoot Delta.

### Daily-averaged salinity variations at reef locations

We initially used the daily-averaged modeled salinities to analyze the impact of BCS operations on the water quality in the study area and at oyster reef locations. Figure 4 shows the salinity variations from

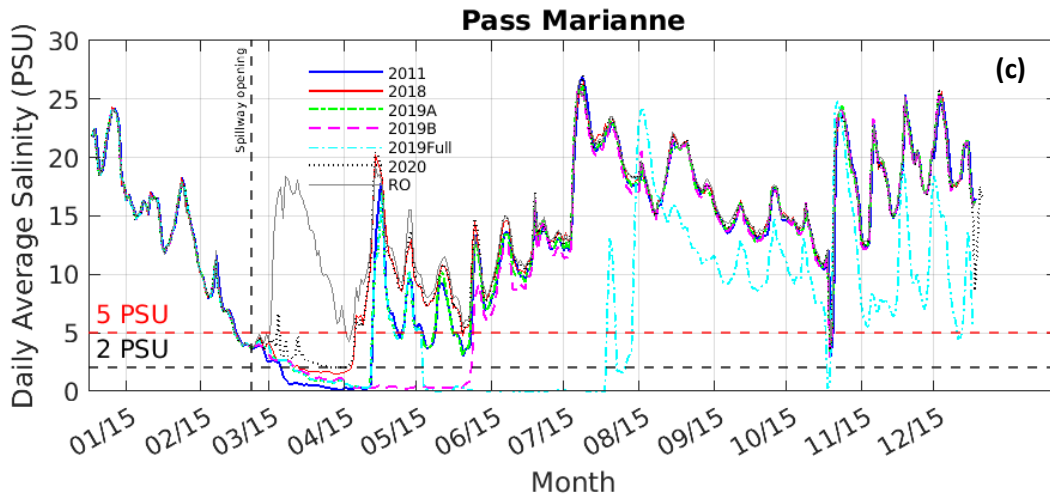
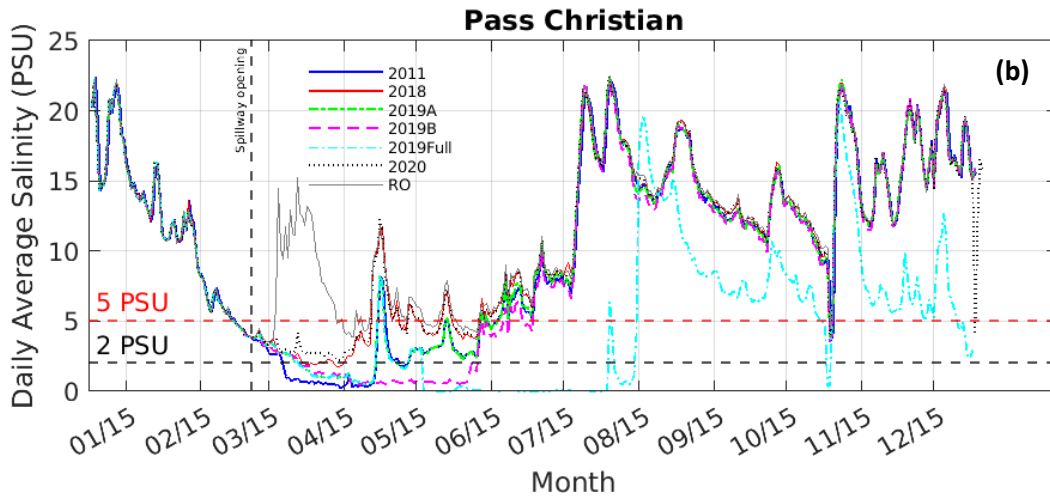
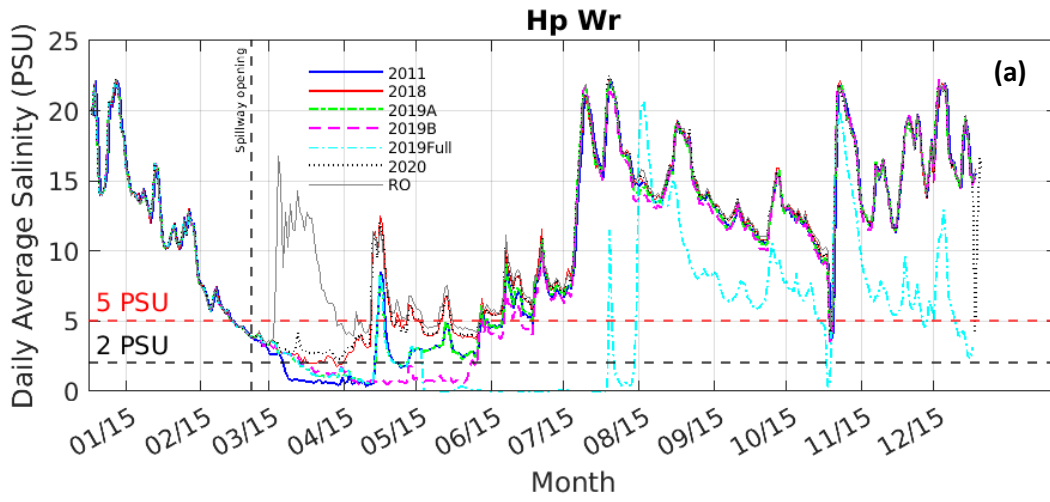
each model scenario at HP, PC, PM, TR, PR, BR, BB and SW reef locations. We particularly focus on 2 psu and 5 psu thresholds which are known critical thresholds under which settled oysters are under stress and excessive exposure to such low salinities may lead to an increase in oyster mortality.

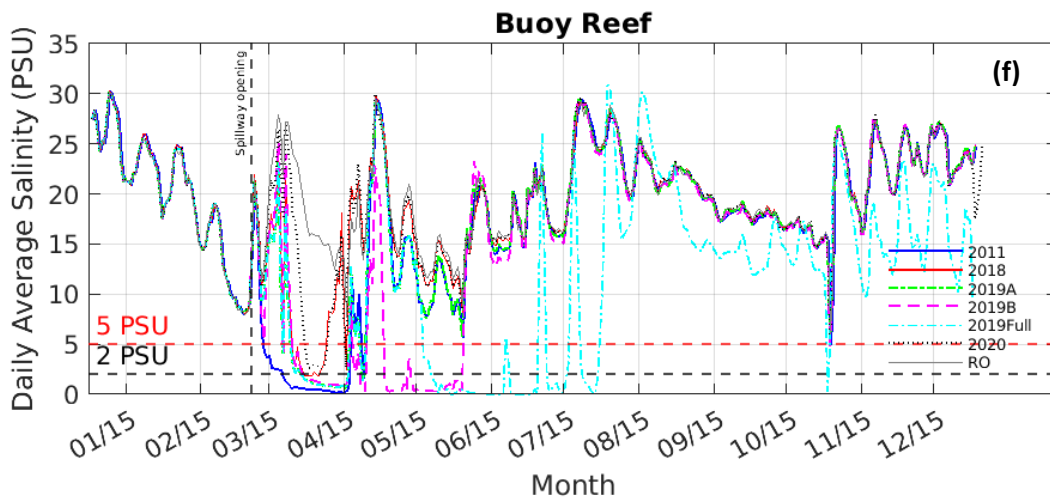
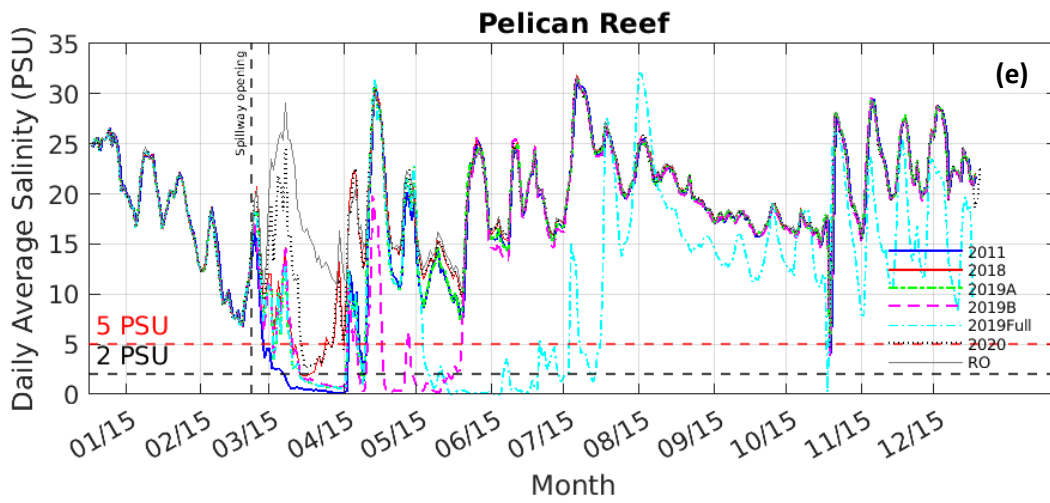
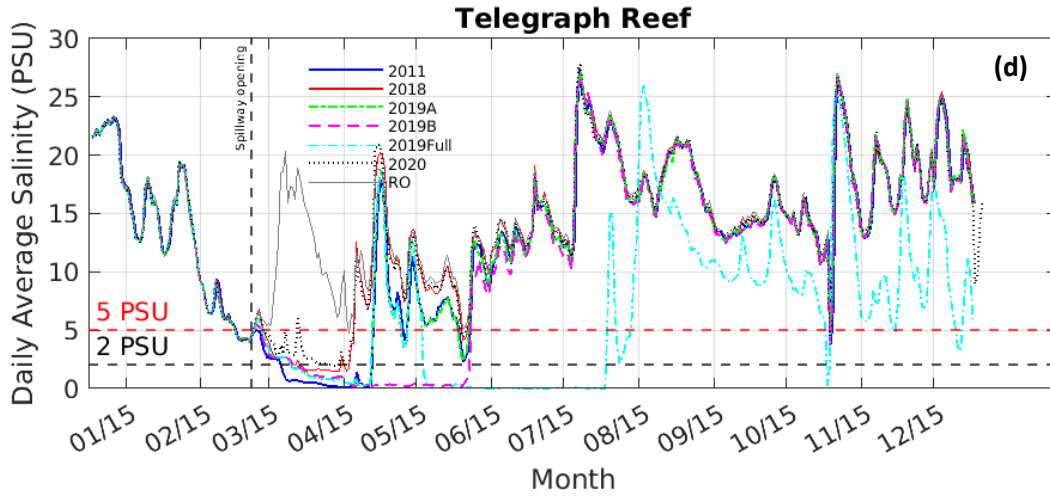
Salinity of 5 psu is considered a critical ecological threshold representing salinity tolerances for all oyster age-classes and specifically critical for spat. Salinity of 2 psu is considered a more acute and critical threshold for adult oyster health and survival and leading to rapid mortality especially during high summer temperatures (Le Peyre et al., 2025).

It can be seen in Figure 3 that the salinity at all reef locations remains over 2 before the spillway opens on 03/08. The salinity starts decreasing in January in all scenarios and continuously decreases below 5 at four Western Mississippi Sound reef sites due to the spring freshet of the Pearl River, during the January-March time period, which typically precedes the Bonnet Carré spillway openings. It can be seen in the RO scenario that the salinity does not drop below 2 and rises back up to 15-28 range in March when there is no Spillway operation. On the other hand, the spillway operations keep the salinity below 5 and even drop it below 2 depending on the intensity (volume and pace) and duration of the operation. The quickest fall below 2 at all reef locations happens in the 2011 scenario (in mid-March) because that is the fastest opening of all scenarios (the highest opening pace as can be seen in Figure 1) and the arrival of low-salinity waters are associated with opening pace (See Table 5a) of each operation. This is followed by 2019A (and 2019Full), 2019B and 2018. Average opening pace as a percentage of Lake Pontchartrain volume calculated over the first 20 days is shown in Table 5 demonstrating that the timing of salinity going below 2 during a BCS opening scenario is directly proportional to the opening pace. The salinity does not fall below 2 in the 2020 operation scenario. While it took 10 days after opening for the 2011 BCS waters to arrive at the WMSS reef sites, the arrival takes at least an additional week, and the salinity drops below 2 in late March in other scenarios with smaller opening paces (with less than 6% LP volume per day). In 2011 scenario 104.2% of LP volume was released in the first 12 days (until 03/20), averaging 8.7% per day, while it took 19 days (until 03/27) to reach 106.8%, averaging 5.6% per day, in 2019A scenario. This is crucial because if the natural resource managers discuss relocating oysters during a BCS opening, the slow opening pace will provide longer time to take action. In fact, a total of 81% of LP volume is diverted within the first 10 days in 2011 opening scenario while 80% is exceeded on day 18 in 2018 opening scenario, on day 16 in 2019A (and 2019Full) opening scenario, and on day 17 in 2019B opening scenario (See Figure 1). 80% was never exceeded in the 2020 opening scenario, and the total diverted volume for the 2018 opening was 86.9% with limited impact on reefs. Therefore, limiting the intensity of BCS openings by keeping the diverted volume below 80% of LP volume might be crucial for preserving oyster reef health in Western Mississippi Sound and to limit negative impacts on this critical shellfishery.

Salinity remains under 2 until late April in the 2011 and 2019A (and 2019 Full) scenarios, until early June in 2019B scenario and from early May until August in 2019 Full scenario at WMSS reef sites (HP, PC, PM, TR) while the BCS impact is weaker at PR and BR because they are closer to the barrier island inlets and are more exposed to the influence of the higher salinity shelf waters. It is important to remind here that the 2011 and 2019A opening scenarios are almost for the same duration (43 days vs. 44 days respectively) while the 2019B opening is for 79 days. The fact that salinities went back above 2 in late April (~45 days after the opening) for both 2011 and 2019A scenarios and in early June (~90 days after opening) for the 2019B scenario is indicative of the importance of the duration of spillway operation regarding the extended exposure to low salinities especially at those reefs away from the barrier island

inlets. At the CMSS sites (BB and SW), salinity falls below 2 only for the 2019 Full operation scenario after mid-May and falls below 5 only for a limited time for the 2011 and 2019B opening scenarios.





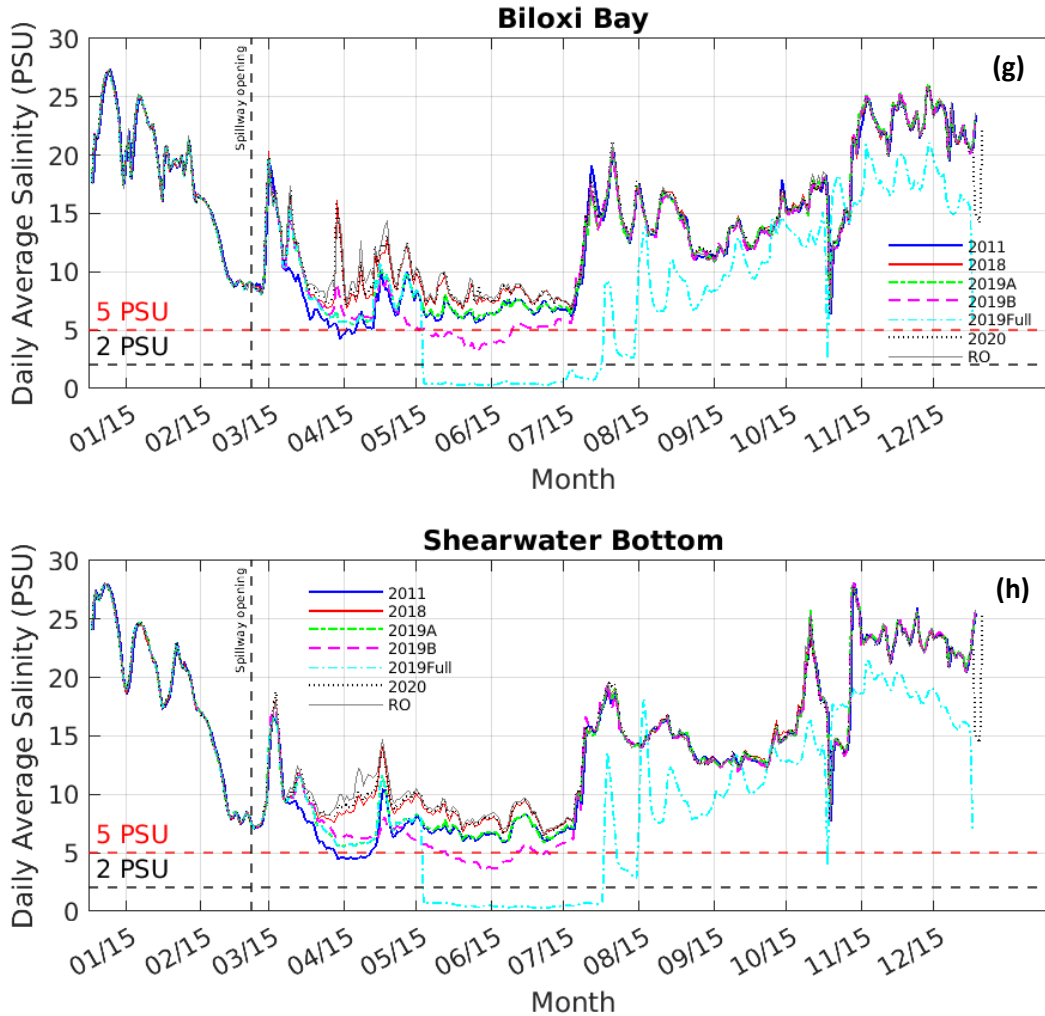


Figure 4. Daily salinity variation at oyster reef locations in Western and Central Mississippi Sound during the rivers only (RO) scenario and the historic BCS operation scenarios (2011, 2018, 2019A, 2019B, 2019Full, 2020) (a) Henderson Point (b) Pass Christian (c) Pass Marianne (d) Telegraph Reef (e) Pelican Reef (f) Buoy Reef (g) Biloxi Bay (h) Shearwater Bottom.

#### Consecutive days of salinity below 2 at reef locations

Because the exposure of oysters to low salinities for an extended period of time is a primary cause for mortality, we identified the longest streaks of consecutive days of salinity below 2 at each site for each historic operation scenario.

##### a) 2011 Scenario

The 2011 opening scenario diverted 326.6% of Pontchartrain volume and is the fastest opening scenario (on average 9.6% of LP volume diverted per day). The diverted river water volume reached 80% within 10 days and exceeded 200% within 20 days and reached 300% within 32 days, which is almost twice as fast as any other opening scenario (Figure 1). The total diverted volume reached 326.6% within 43 days, which on that day of the opening was 50% higher than the diverted volume during both 2019A and 2019B scenarios. On day 21 of each opening (which is the shortest 2018 opening duration), 2011 scenario diverted 4 times more water than the

2020 opening, 2.3 times more water than the 2018 opening, 1.9 times more water than the 2019B opening, and 1.65 times more water than the 2019A opening.

It led to significant consecutive days of salinity below 2 at the reef locations as follows:

- Henderson Point (HP): 38 days
- Pass Christian (PC): 39 days
- Pass Marianne (PM): 38 days
- Telegraph Reef (TR): 38 days
- Buoy Reef (BR): 28 days
- Pelican Reef (PR): 27 days
- Biloxi Bay (BB): 0 days
- Shearwater Reef (SW): 0 days

Pelican and Buoy reefs are those closest to the barrier islands, and the impact of the opening is reduced at those locations. The Biloxi Bay (BB) and Shearwater (SW) sites within CMSS experienced no streaks.

#### b) 2018 Scenario

The 2018 opening scenario diverted 86.6% of Pontchartrain volume and is the second weakest opening scenario behind the most conservative 2020 scenario (56%). It led to consecutive days of salinity below 2 at the reef locations as follows:

- Henderson Point (HP): 4 days
- Pass Christian (PC): 6 days
- Pass Marianne (PM): 22 days
- Telegraph Reef (TR): 17 days
- Buoy Reef (BR): 4 days
- Pelican Reef (PR): 4 days
- Biloxi Bay (BB): 0 days
- Shearwater Reef (SW): 0 days

This indicates the salinity remains below two for less than a week at Henderson Point, Pass Christian, Pelican and Buoy reefs while it remains below two for 3-8 days above two consecutive weeks at Telegraph and Pass Marianne reefs. The Biloxi Bay (BB) and Shearwater (SW) sites within CMSS experienced no streaks. It is important to note here that the 2018 opening exceeded 80% on day 18 of the opening and had 4 additional days before the end of the operation.

#### c) 2019A Scenario

The 2019 first opening scenario diverted 219.5% of Pontchartrain volume and led to significant consecutive days of salinity below 2 at the reef locations as follows:

- Henderson Point (HP): 32 days
- Pass Christian (PC): 32 days
- Pass Marianne (PM): 33 days
- Telegraph Reef (TR): 33 days
- Buoy Reef (BR): 20 days
- Pelican Reef (PR): 20 days

- Biloxi Bay (BB): 0 days
- Shearwater Reef (SW): 0 days

Pelican and Buoy reefs are those closest to the barrier islands, and the impact of the opening is reduced at those locations while the reefs at the WMSS were exposed to below 2 salinity for more than 4 weeks at a stretch. The Biloxi Bay (BB) and Shearwater (SW) sites within CMSS experienced no streaks.

#### d) 2019B Scenario

The 2019 second opening scenario is the longest operation scenario with a 79-day opening diverting 346.9% of Pontchartrain volume and led to significant consecutive days of salinity below 2 at the reef locations as follows:

- Henderson Point (HP): 70 days
- Pass Christian (PC): 71 days
- Pass Marianne (PM): 71 days
- Telegraph Reef (TR): 71 days
- Buoy Reef (BR): 22 days
- Pelican Reef (PR): 20 days
- Biloxi Bay (BB): 0 days
- Shearwater Reef (SW): 0 days

Pelican and Buoy reefs are those closest to the barrier islands, and the impact of the opening is reduced at those locations. Biloxi Bay (BB) and Shearwater (SW) sites at CMSS have no streaks.

#### e) 2019Full Scenario

This scenario replicates the actual 2019 BCS opening scenario. The 2019 full opening scenario diverted a total of 566.4% of Pontchartrain volume among two back-to-back openings (2019A followed by 2019B) and led to significant consecutive days of salinity below 2 at the reef locations as follows:

- Henderson Point (HP): 77 days
- Pass Christian (PC): 77 days
- Pass Marianne (PM): 76 days
- Telegraph Reef (TR): 76 days
- Buoy Reef (BR): 30 days
- Pelican Reef (PR): 25 days
- Biloxi Bay (BB): 74 days
- Shearwater Reef (SW): 75 days

Pelican and Buoy reefs are those closest to the barrier islands and the impact of the opening is still reduced at those locations, indicative of the influence of shelf waters providing relief for oysters. Even the BB and SW in CMSS is significantly impacted by the 2019Full scenario indicating that the excessive volume of riverine water covered most of the Mississippi Sound.

#### f) 2020 Scenario

The 2020 opening scenario is the weakest and most conservative opening scenario (59.9% in 29 days) and led to minimal to zero consecutive days of salinity below 2 at the reef locations as follows:

- Henderson Point (HP): 0 days
- Pass Christian (PC): 0 days
- Pass Marianne (PM): 0 days
- Telegraph reef (TR): 2 days
- Buoy reef (BR): 0 days
- Pelican reef (PR): 0 days
- Biloxi Bay (BB): 0 days
- Shearwater Reef (SW): 0 days

This means no reef location was exposed to salinities below 2 for 14 consecutive days and this opening scenario would be the most reasonable opening with the least impact on marine life and specifically on oysters in Mississippi Sound.

Longest Streak of consecutive days of salinity below 2 analysis

Table 5 shows a summary of these longest streaks at each reef location along with the total diverted river water volume as a percentage of the total volume of Lake Pontchartrain as well as the average opening pace as a percentage of Lake Pontchartrain volume per day. The longest streak at each reef is also the only streak longer than 14 days for each opening.

Table 5a. Longest streaks for consecutive days of salinity below 2.

Opening Scenario (total volume as % LP)	Ave. opening pace (% LP/day) *	Total opening duration	HP	PC	PM	TR	BR	PR	BB	SW
2019Full (566.4%)	5.8%	123	77	77	76	76	30	25	74	75
2019B (346.9%)	5.0%	79	70	71	71	71	22	20	0	0
2011 (329.6%)	9.6%	43	38	39	38	38	28	27	0	0
2019A (219.5%)	5.8%	44	32	32	33	33	20	20	0	0
2018 (86.6%)	3.9%	21	4	6	22	17	4	4	0	0
2020 (59.9%)	2.4%	29	0	0	0	2	0	0	0	0

\* Average opening pace as a percentage of Lake Pontchartrain volume calculated over the first 20 days.

Table 5b. First day when salinity goes below 2 at reef sites.

Opening Scenario (total volume as % LP)	Ave. opening pace (% LP/day) *	Total opening duration	Day number after opening when salinity drops below 2							
			HP	PC	PM	TR	BR	PR	BB	SW
2019Full (566.4%)	5.8%	123	20	20	17	17	20	20	71	71
2019B (346.9%)	5.0%	79	21	20	18	17	22	20	NA	NA
2011 (329.6%)	9.6%	43	13	13	12	12	13	13	NA	NA
2019A (219.5%)	5.8%	44	20	20	17	17	20	20	NA	NA
2018 (86.6%)	3.9%	21	23	22	20	20	22	21	NA	NA
2020 (59.9%)	2.4%	29	NA	NA	NA	101	NA	NA	NA	NA

The model results show that the longest streak for consecutive days with salinity below 2 psu was experienced during the 2019 full scenario at Pass Christian, Henderson Point, Pass Marine and Telegraph reefs with 76-77 days. This scenario diverted the largest combined volume of Mississippi River water (566.4% over a total of 122 days combined between two openings, Table 1, Figure 1) into Lake Pontchartrain and Mississippi Sound because of the double opening. The scenario only with the second opening of 2019 (2019B) diverted 346.9% over 79 days (Table 1) and led to a significant longest streak with 70-71 days at Pass Christian, Henderson Point, Pass Marine and Telegraph reefs. The 2011 scenario diverted 329.6% over 43 days and led to a much shorter streak of 39 days below 2 psu. While the volume of water diverted during 2011 opening and 2019B are similar (347% and 330%), 2019B opening duration is much longer (79 days vs 43 days) and that may be the reason for the longer streak of 2 psu below 2 at the reef locations. This is indicative of a mechanism that once a tipping point is reached because of the amount/volume of flow, the duration of opening becomes critical, dictating how long oysters experience stressful conditions that may lead to their mortality. In fact, 2019 first opening scenario (2019A) also has a 44-day opening and longest streak in 2019A (32 days) is similar to 2011 (39 days) even if the volume of 2011 (330%) is considerably larger than 2019A (220%). Once again this strengthens the importance of duration over volume for larger volume (>200%) and longer duration (>40 days) openings.

The longest streak of 2020 opening is less than that of 2018 opening even if the 2020 opening was longer (29 days) than the 2018 opening (21 days). The volume of 2020 opening (60%) is less than the volume of 2018 opening (87%). This indicates the importance of volume over duration for shorter openings (<30 days) with smaller volumes (<100%), such that there is a saturation volume threshold where a shift occurs between volume and duration as the dominant control for the impact of salinity below 2.

The impact of BCS openings is similar on Henderson Point, Pass Christian, Pass Marianne and Telegraph reefs with 1 day difference in longest streak results. The impacts on Pelican reef and Buoy reef are similar and reduced primarily because they are located farther south and closer to the Cat and Ship barrier islands. This may be considered a consequence of the proximity of these reefs to their nearby tidal inlets. In other words, higher salinity inner shelf waters enter the estuarine system regularly due to tidal fluctuations and therefore reefs closer to the inlets are exposed to these tidal influences.

If 14 days of exposure to salinities below 2 is considered the mortality tipping point for eastern oysters, model results indicate that the 2020 opening scenario is a reasonable opening scenario. None of the reefs experienced 14 consecutive days of salinity below 2 and the maximum was 11 days at St. Joe reef which is the western-most reef closest to Pearl River and Lake Pontchartrain. A salinity threshold of 5 has also been used in the literature, especially as a measure for successful oyster growth (Lee et al., 2026). If 14 days of exposure to salinities below 5 is considered limiting oyster growth, model for 2020 results indicate 10 consecutive days of salinity below 5 at Pelican and Buoy reefs (those closest to the barrier islands) while 57, 31 and 23 days at Pass Christian, Pass Marianne and Telegraph reef respectively. This indicates even a conservative opening scenario such as the 2020 opening may adversely impact the oyster growth in Mississippi Sound.

### [Area under the influence of 14 consecutive days of salinity below 2](#)

A particular portion of the study area covering approximately 320K square kilometers remains under a salinity of 2 for a minimum of 2 consecutive weeks even without a Bonnet Carré opening, simply due to

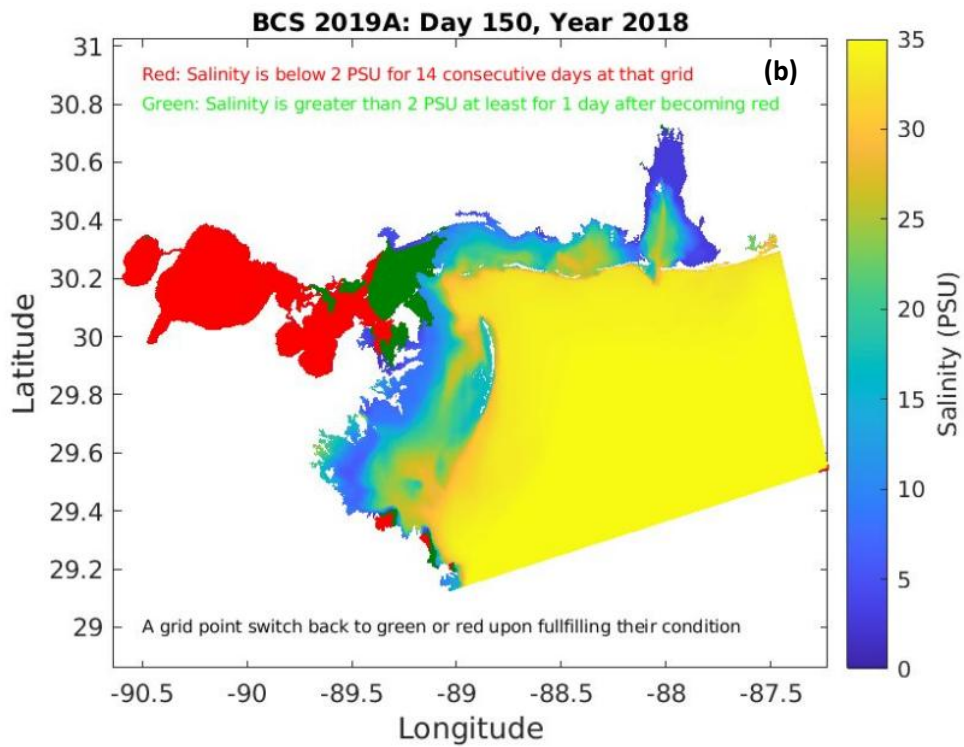
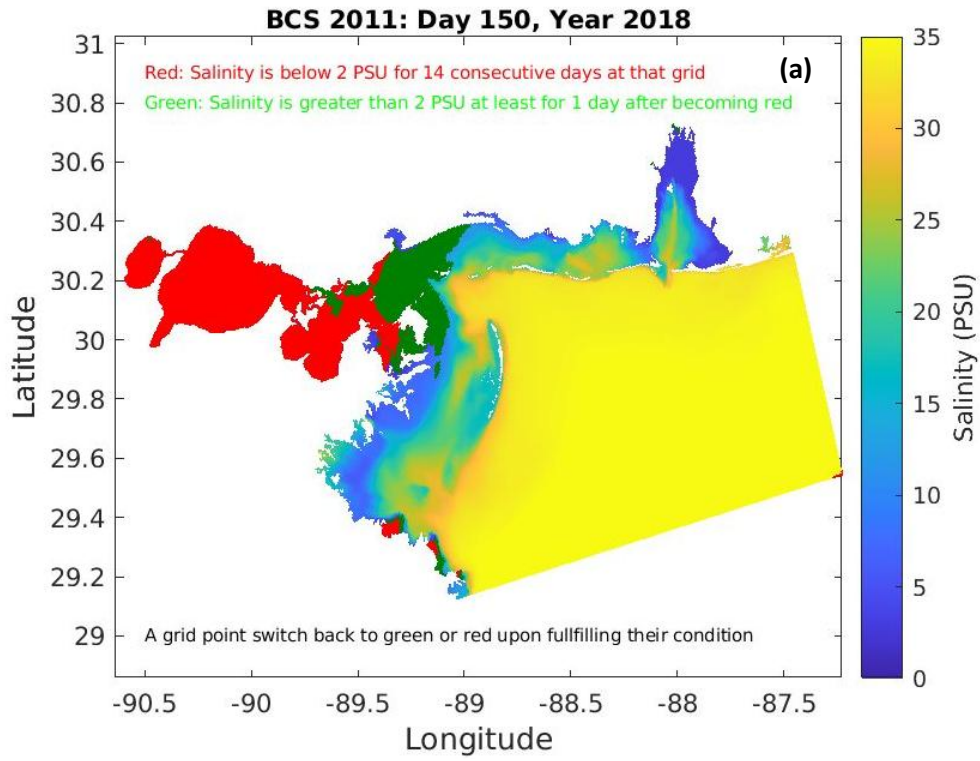
the natural riverine input to the system. When the spillway is operated, this area increases in size. Consequently, for the 2020 scenario, 57.8% of the total area is due to the Spillway opening followed by 62.7% in 2018, 68.8% in 2019A, 69.4% in 2019B, 71.6% in 2011 and 73.7% in 2019 full. Figure 4 shows the area impacted by salinity below 2 for at least 14 consecutive days for each BCS scenario. The red/green zone indicated the area that goes below 2 psu and stayed below two for at least 14 consecutive days based on daily average salinity. The red portion is the area that still stayed under the influence on June 1 while the green portion is the area that bounced back and went back above 2 psu but it is still marked because of reaching the tipping point earlier. When the conditions on June 1 (Day 150) are observed, parts of the area which crossed the tipping point recovered (green zone) while some portion remained under 2 (red zone) for each scenario.

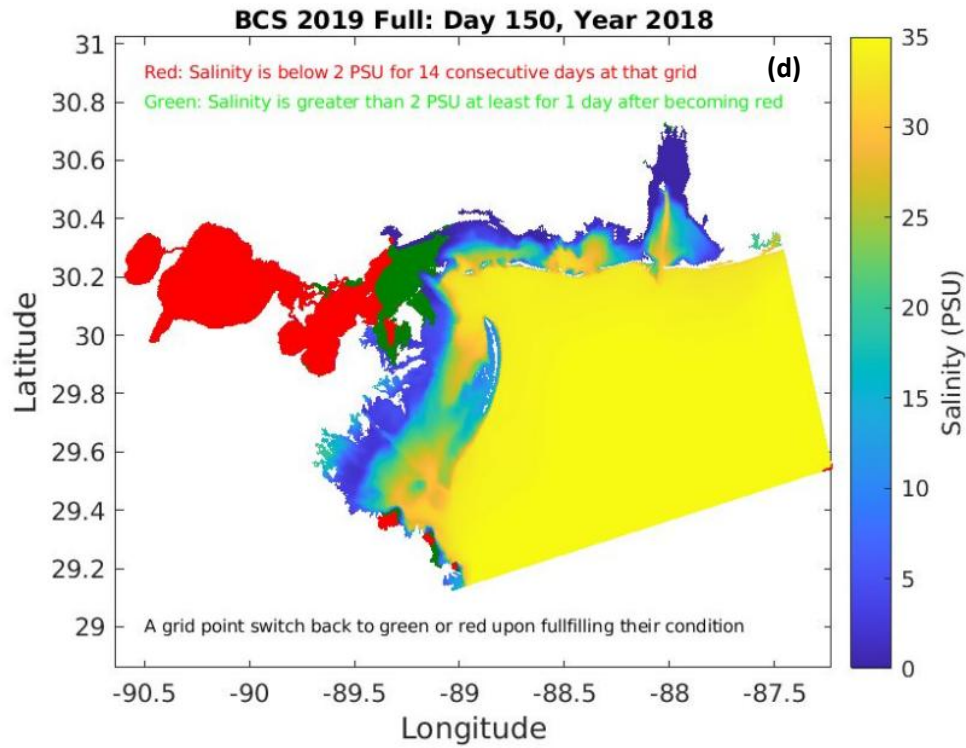
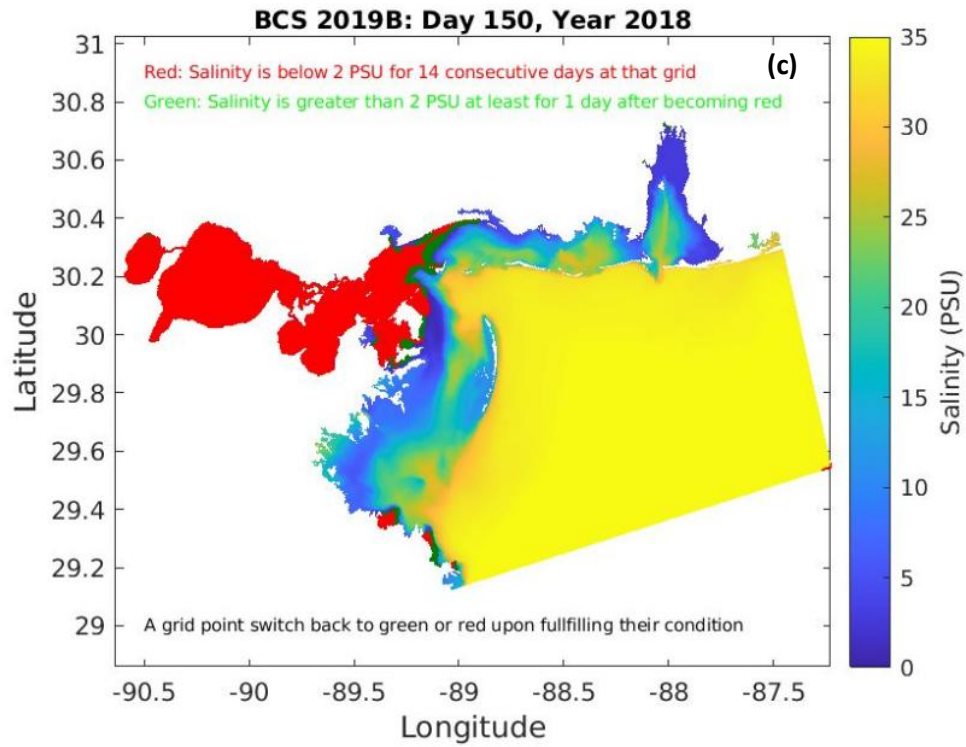
2011 scenario results indicate the impact of the Spillway reached north shore of Cat Island, near Biloxi Bay and also impacted Biloxi Marsh. While WMSS recovered on June 1, Lake Borgne, Lake Pontchartrain and western side of Grand Island and part of Biloxi Marsh remains beyond the tipping point nearly 3 months after the spillway opening date. The area impacted by the 2019A scenario is slightly smaller than that of the 2011 scenario while the BCS impact still reached the Cat Island and north of it. This difference may be attributed to the difference in volume released (329.6% in 2011 vs. 219.5% in 2019A) because the durations are nearly identical

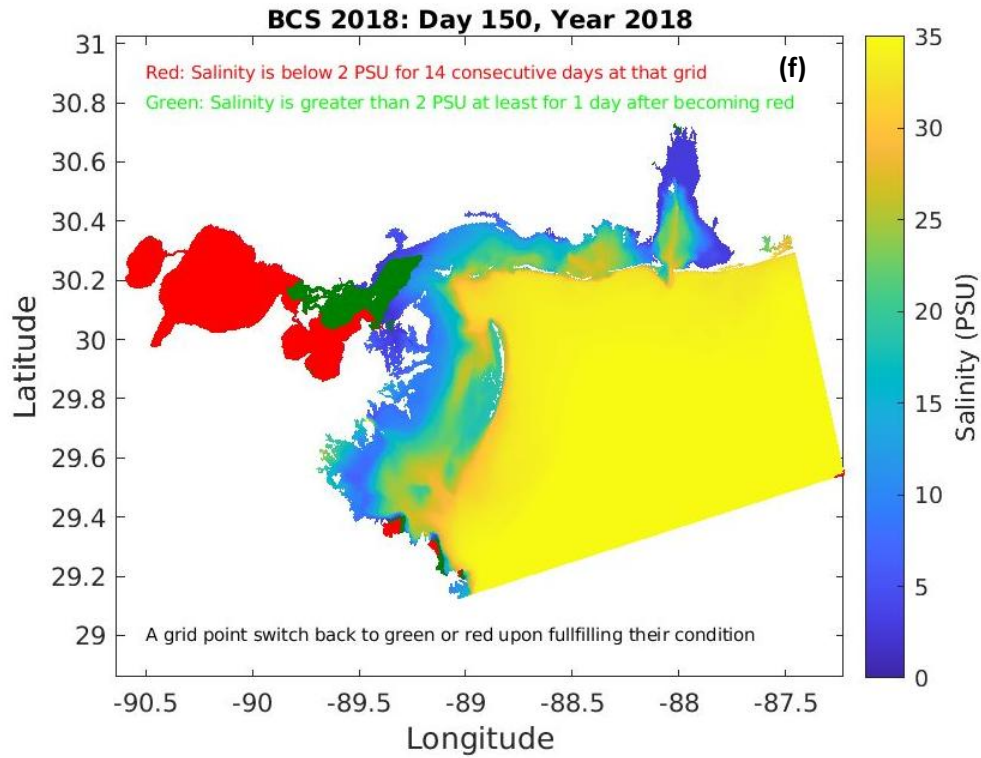
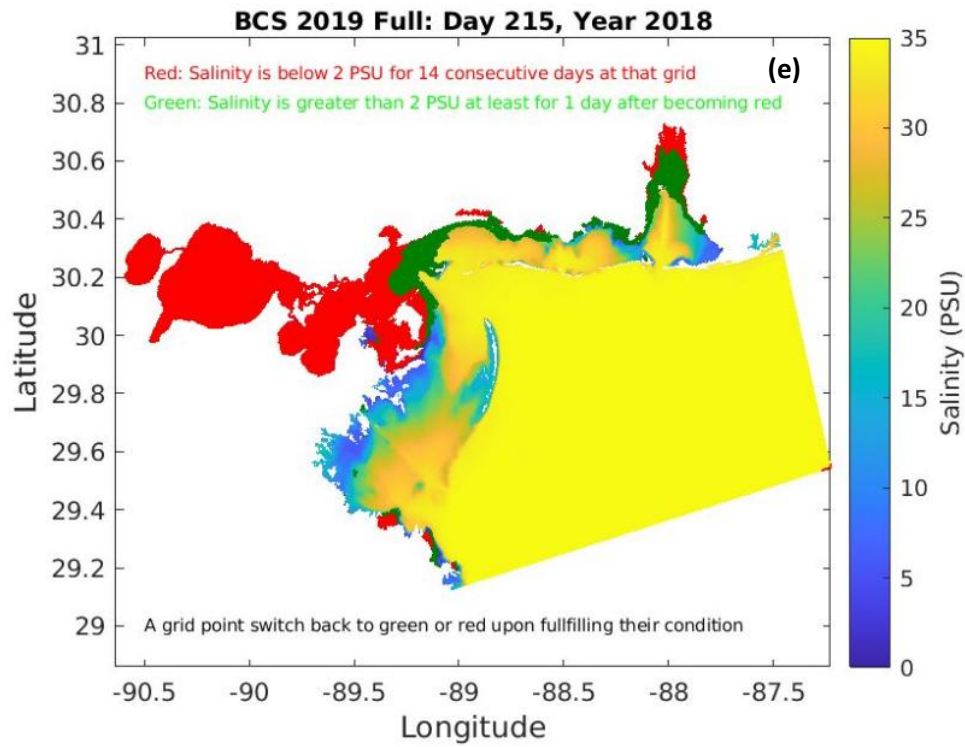
While the overall area impacted by the 2019B scenario is also similar to 2019A and 2011 scenarios, most of that area could not recover and remained beyond the tipping point, which is indicative of the impact of long duration. Since we looked at day-83 after the opening (June 1 and Day 150 of the calendar year) for 2011, 2019A and 2019B scenarios (Figure 5a, 5b and 5c), we look at 83th day after the second opening for 2019Full (Day 215 of the calendar year, Figure 5e) as well and it can be seen that the area of impact on day 215 for the 2019Full scenario is much larger in 2019Full covering Biloxi Bay, Pascagoula Bay and Grand Bay, also the recovery in WMSS is limited even in early August. The area impacted by 2018 and 2020 Bonnet Carré Spillway operation scenarios is much smaller with 2020 scenario not even impacting WMSS oyster reef sites and 2018 with limited impact, also in both cases the recovery is quicker and all the way into both Lake Pontchartrain and Lake Borgne. It can be seen in the RO scenario that only parts of Lake Pontchartrain have salinities below 2 for two consecutive weeks when Bonnet Carré Spillway is not operated while in all BCS scenarios all of Lake Pontchartrain is impacted.

#### Spillway Region of Influence Analysis:

It may be seen that for those spillway openings with large volumes diverted into Lake Pontchartrain (219.5% in 2019A, 329.6% in 2011, 346.9% in 2019B and 566.4% in 2019full) with longer durations (larger than 43 days), 68.8% to 73.7% of the area with salinity below 2 for 14 consecutive days is additional area influenced by the spillway opening. This percentage is down to 62.7 and 57.8 % in the smaller volume (less than 87%) and shorter duration (less than 29 days) openings. Further, it is observed that the system recovery is delayed if the spillway opening is longer.







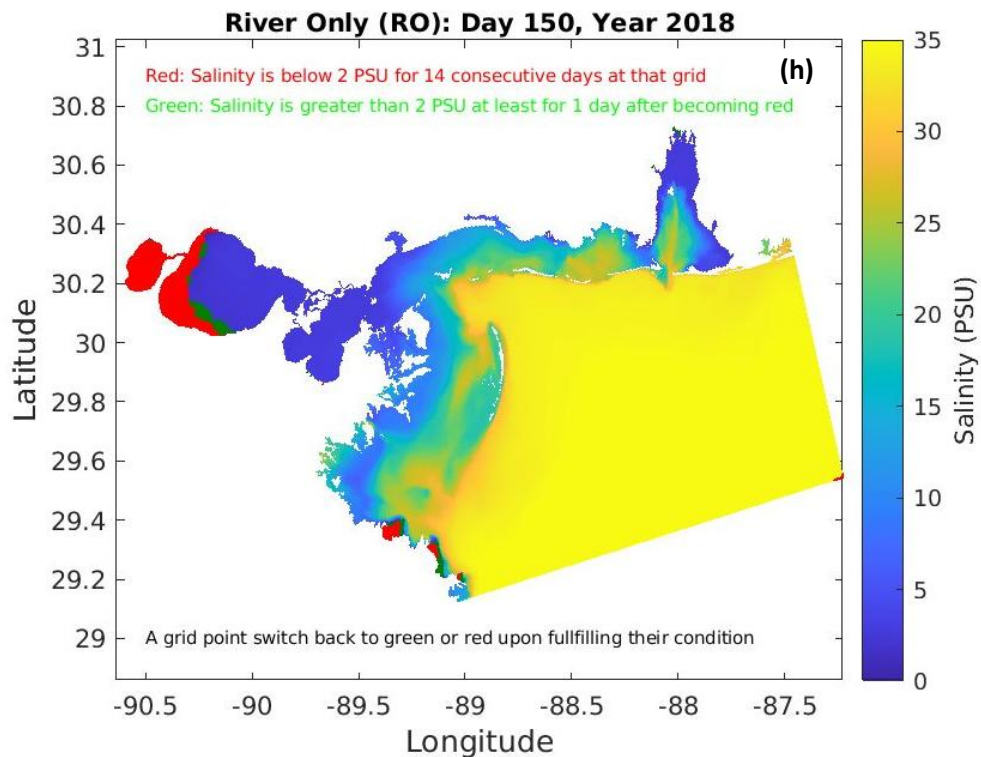
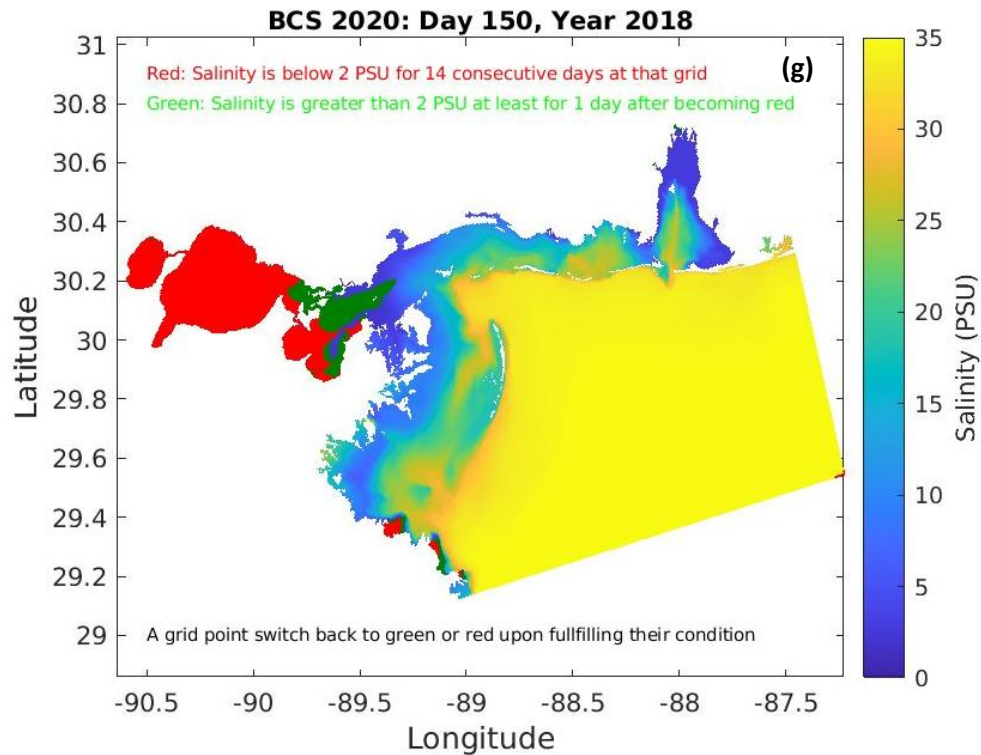


Figure 5. The salinity within the study area and the area (red) which has remained under the influence of salinities below 2 for more than two weeks and the recovered area (green) during: (a) 2011 BCS opening scenario at day 150, (b) 2019A BCS opening scenario at day 150, (c) 2019B BCS opening scenario at day 150, (d) 2019Full BCS opening scenario at day 150, (e) 2019B BCS opening scenario at day 215, (f) 2018 BCS opening scenario at day 150, (g) 2020 BCS opening scenario at day 150, (h) River Only (No BCS) scenario at day 150.

## Hourly Salinity Variation and Analysis

While the results and analysis so far focused on the daily-averaged salinities, the physical model allows us to analyze hourly variability to detect whether oysters on a given reef experience intermittent relief from below threshold salinity conditions, which could act to facilitate their survival. We first analyzed the daily standard deviations around the daily means used for habitat suitability analysis. Figure 6 shows 2020 scenario results indicating that salinities at Pass Christian, Pass Marianne, Henderson Point and Telegraph reefs in Western Mississippi Sound never go below 2 psu because of the conservative opening, hence the decision to divert limited riverine waters using BCS. Salinities fell below 5 at the beginning of March at all reef locations and remained between 2 and 5 for an extended period in March and April. 5 psu is considered as the lower threshold for habitat suitability index models (de Mutsert, Riddall, and Milroy, 2026) and therefore any relief during this period could serve to reduce oyster stress. It is observed that such intermittent periods of relief were experienced, especially at Pass Marianne and briefly at Pass Christian and Henderson Point, between days 70 and 90.

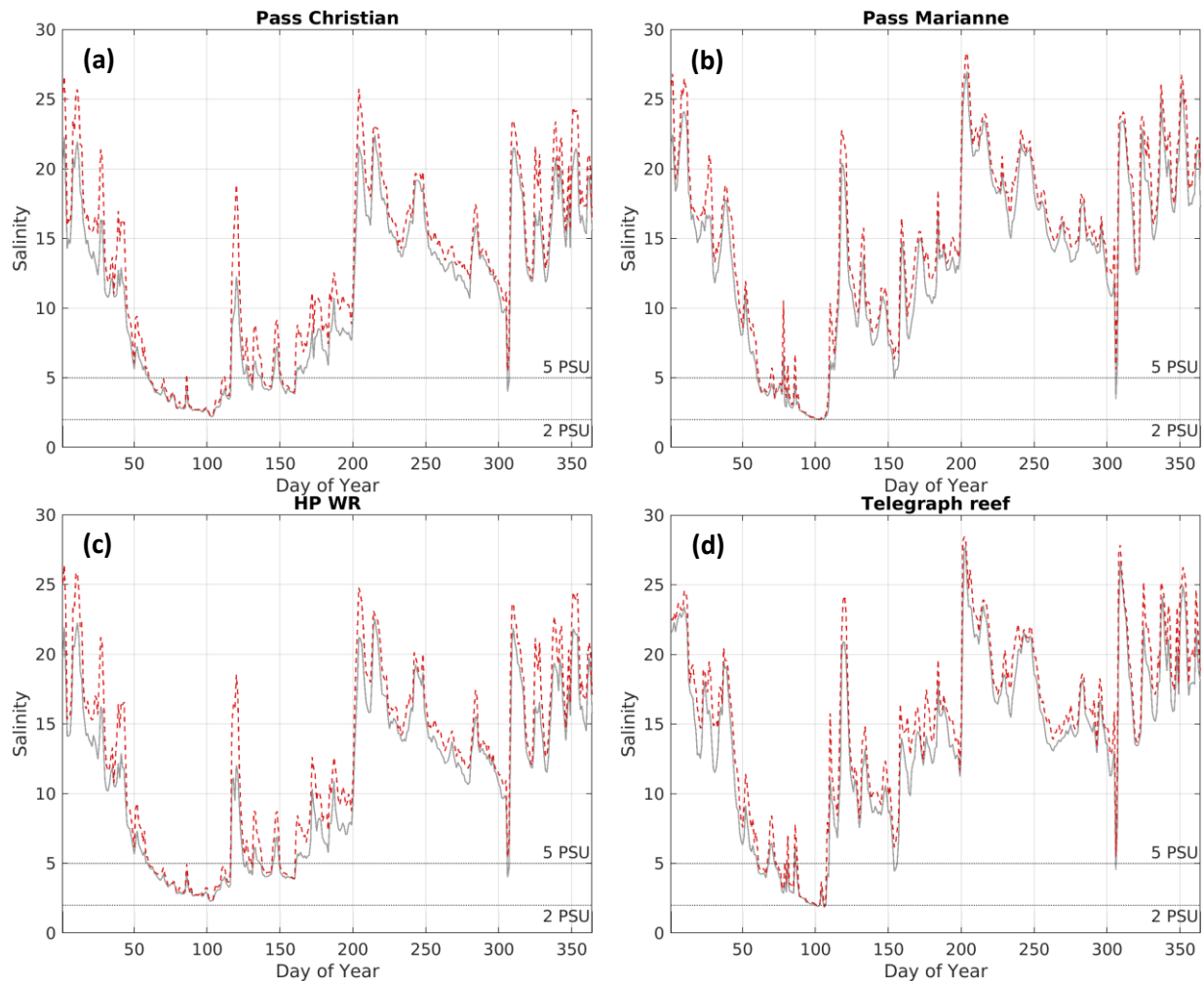


Figure 6. Daily mean salinity variation (solid line) with hourly standard deviation (dash lines) at (a) Pass Christian, (b) Pass Marianne, (c) Henderson Point, and (d) Telegraph reef locations for the 2020 scenario.

Hourly results shown in Figure 7 at the largest reefs (Pass Christian, Pass Marianne) indicate that there are multiple instances of salinity reliefs with values intermittently going above 5 especially during days

60-120 of the calendar year, covering all the opening scenarios starting on day 67. Especially at Telegraph and Pass Marianne reefs, salinity increase pulses occur every 7-10 days and hourly salinities go above 5 at days 70, 80 and 87 while the daily averaged salinities remain below 5 for most of those events especially at Pass Christian and Henderson Point. But after those pulses, salinity remains below 5 for a 3-week time period in April (days 88-108) at all reef locations and the tidal fluctuations can no longer influence the reef locations meaning the area remains under heavy influence of the strong freshwater pulse coming from Lake Pontchartrain (from the west) once the diverted volume exceeds 50% of the volume of Lake Pontchartrain.

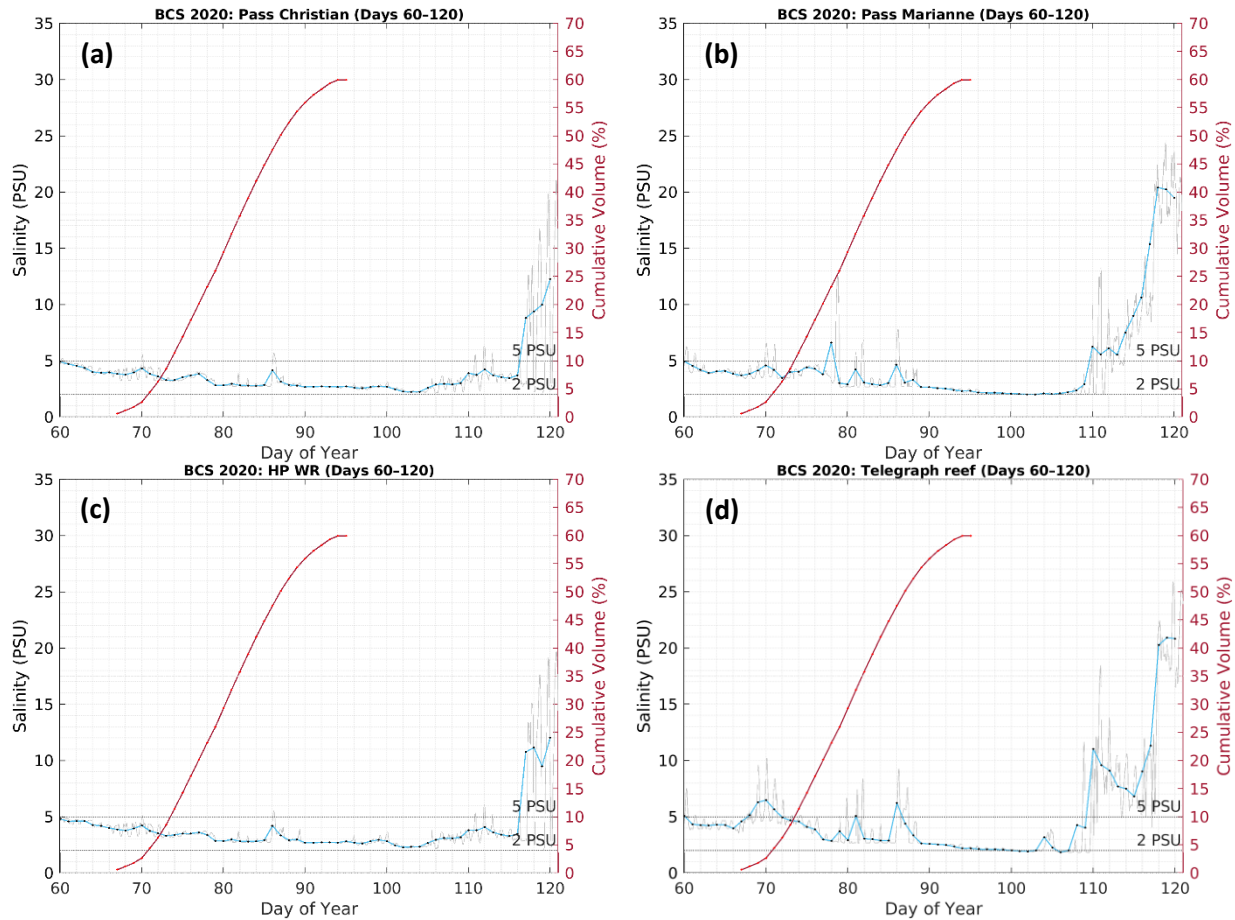
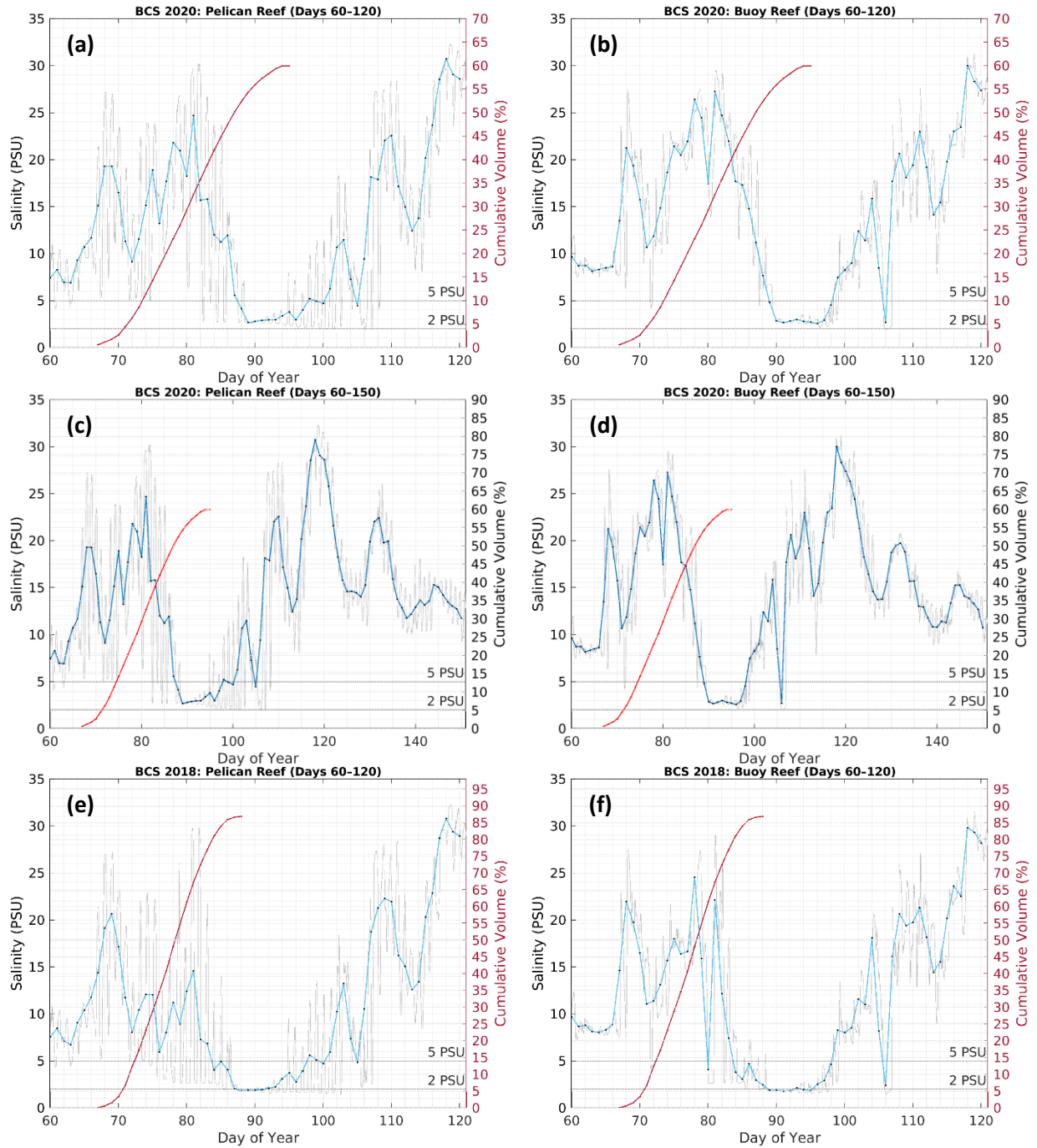


Figure 7. Daily mean salinity variation (blue line) with hourly fluctuations (grey line) at (a) Pass Christian, (b) Pass Marianne, (c) Henderson Point, and (d) Telegraph Reef locations and the cumulative volume of water (red line) diverted by BCS as a % of LPV. The 5 and 2 psu thresholds critical for oysters are shown with horizontal lines.

The salinity reliefs are more pronounced at reefs closer to the barrier island inlets such as the Pelican and Buoy reefs. Figure 8 shows the daily mean and hourly salinity fluctuations at Pelican and Buoy reefs during both 2018 and 2020 opening scenarios. It can be observed that although the daily means appear below 5 for about ten days in 2020 (from day 88 to 98) and almost two full weeks in 2018 (from day 84 to 98), hourly salinity peaks provide relief for multiple days at the beginning and end of that period hence reducing the continuous exposure to salinities below 5 to a week from day 89 to day 95. Oysters are resilient, and such intermittent reliefs might help them efficiently manage the dire conditions. The physical model allows us to observe such variability and provides such context. It is important to note here that the salinities do not fall below 10 in the Rivers-only scenario, but there is a natural decrease in

salinities from 25-30 range on day 80 to 15 on day 90. Therefore, it is always critical to monitor and account for the natural riverine input and conditions during the operations of BCS.



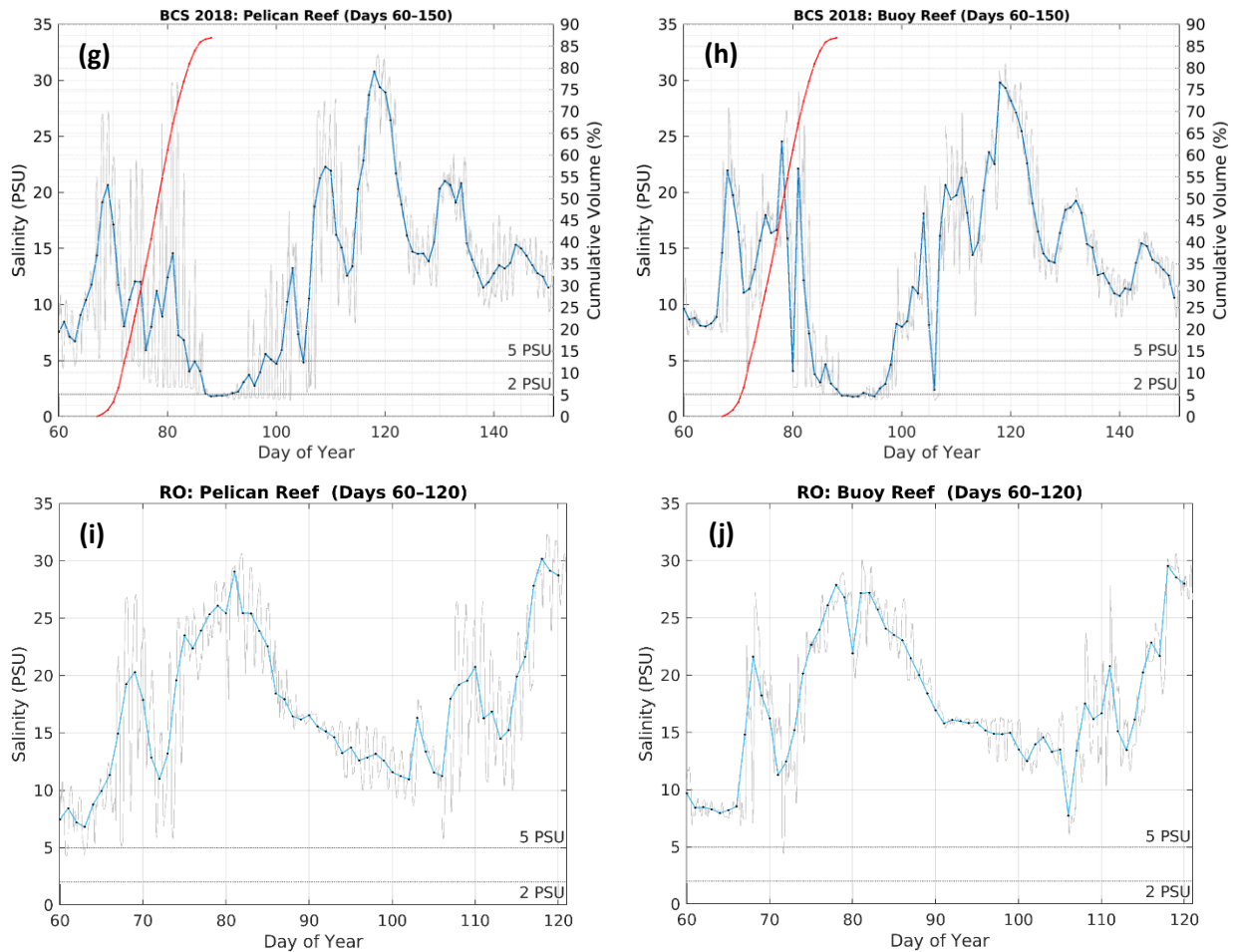


Figure 8. Daily mean salinity variation (solid blue lines) with hourly fluctuations (light gray lines) at Pelican and Buoy reef locations for 2020 (a,b,c,d) and 2018 (e,f,g,h) opening scenarios and Rivers Only scenario (i,j). Diverted volume through the spillway (solid red lines) is shown in terms of the volume of Lake Pontchartrain.

As can be seen in Figure 8, hourly variations are tidal and provide decreased salinities during ebb tide and increased salinities during flood tide providing relief to oyster reefs especially when they experience salinities between 2 and 5. These tidal reliefs provided during the shorter and more controlled 2020 and 2018 opening scenarios cannot be experienced in the stronger operation scenarios (2011 and 2019) even at those stations close to the barrier islands. This indicates that diversion operations should have both time and volume limitations to provide a chance for oyster recovery. Figure 9 shows the daily mean and hourly salinity variations at Pelican reef during 2011, 2019A, 2019B and 2019Full scenarios. It can be seen that the 2011 opening suppresses the daily tidal fluctuations much earlier at day 75 because it is the opening at the highest rate (the largest number of bays opened in the shortest amount of time at the beginning of the opening). While for all other scenarios hourly salinity goes below 5 around day 87 (day 20 of the opening), the hourly salinity goes below 5 on day 75 (day 9 of the opening) in the 2011 scenario. The accumulated increase in diverted Mississippi River water volume as a percentage of Lake Pontchartrain's volume is also shown on Figure 9. It is seen that 70% of Lake Pontchartrain volume is diverted within 9 days for the 2011 scenario, while for the 2019 scenarios this takes 15-16 days, and 100-115% is diverted on day 20 for 2019B and 2019A, respectively (Fig. 2). Once again, this means both the opening pace and the rate of release volume are critical in delaying the initiation of harsh conditions for

oysters. If the opening pace is high (e.g., 2011) a lower diverted volume (i.e., 70%) may be sufficient to push the salinities below 5 at Pelican Reef while for a more gradual opening (i.e., 2019a or B) the system can handle the freshwater pulse in such a way that it requires a larger volume (i.e., ~100%) to push the salinities below 5.

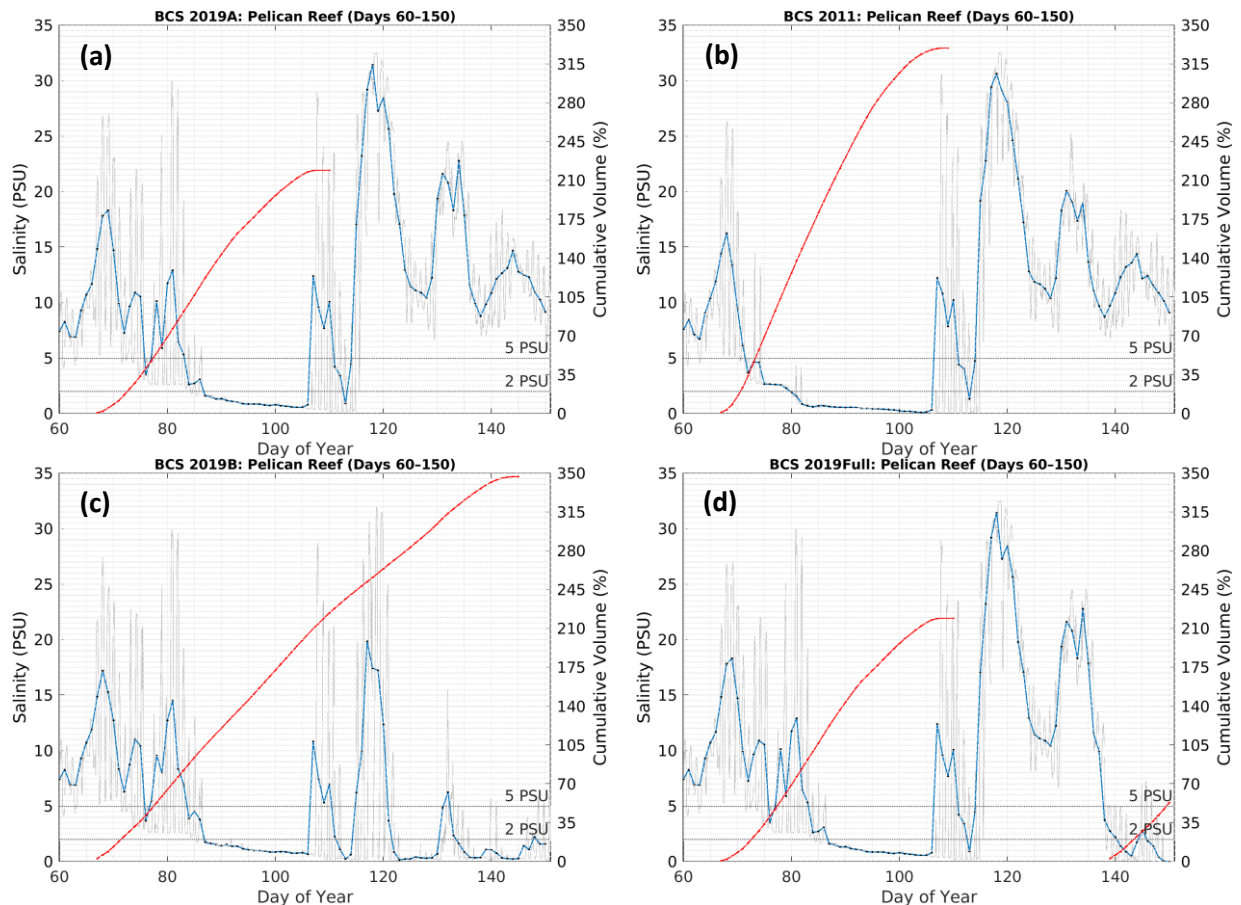


Figure 9. Daily mean salinity variation (solid blue lines) with hourly fluctuations (light gray lines) at Pelican reef location for (a) 2019A, (b) 2011, (c) 2019B, and (d) 2019Full opening scenarios. Diverted volume through the spillway (solid red lines) is shown in terms of the volume of Lake Pontchartrain.

In the 2011 scenario (shown in Figure 9), daily salinity falls below 2 on day 80 when the diverted volume exceeds 125% but is still subject to intermediate relief pulses for a few days before hourly salinity stays continuously below 2 from day 83 (160% diverted volume) until day 105. On the other hand, for the 2019 scenarios daily mean salinity goes below 2 on day 87 (120% for 2019A and 105% for 2019B) and stays below 2 until day 106. In none of these 4 stronger opening scenarios do we see the tidal pulses at Pelican reef during that period of low salinity. This indicates that the Western Mississippi Sound is completely under the influence of diverted and natural local riverine waters, engulfed in lower salinity waters, and any influence of marine waters from the inner shelf region is effectively blocked. Our model results indicate that the shorter and more gradual (lower opening pace) scenarios are required for oysters in Western Mississippi Sound to survive BCS operations.

The modeling system used in this study may also be used to forecast the impact of BCS operations to guide both the users of the spillway and the decision makers on how to control the spillway operation to minimize the negative impacts on the marine environment and particularly on the health of oysters.

### Spillway Duration Analysis

When hourly salinities are considered over the entire year, the total cumulative duration of salinities below 2 can be computed as a percentage of the entire year. In the weakest 2020 opening scenario, only Telegraph reef has salinities below 2 for around 2% of the time while other stations have salinities below 2 for less than 0.42% of the time, this is indicative of the limited impact of this conservative opening scenario on settled oysters. In the 2018 opening scenario, the largest impact was seen at Pass Marianne with 6.6% and Telegraph Reef with 6% of the time being under a salinity of 2. The cumulative time at Pelican Reef, Buoy Reef, Henderson Point and Pass Christian varied between 2.1 % to 3.7%. It can be seen that while the 2018 opening scenario is shorter than 2020, the increased diverted volume of water (86.6% in 2018 vs 59.9% in 2020) increases the duration of distressing conditions for oysters. The impact of larger openings is in the same order at all reef locations with the smallest impact at Pelican Reef and the strongest impact at Pass Christian. The 2019A opening scenario resulted in cumulative hourly salinity below 2 ranging between 6.5% and 11.6%, followed with 2011 opening scenario with the range between 8% and 12.8%, 2019B opening scenario ranging between 15.1 % and 20.4 %, and the biggest impact during the 2019Full scenario with a range between 20.6% and 35.7%. The central MS Sound stations BB and SW are only impacted by the 2019Full scenario.

We plotted the cumulative percentage as a function of operation duration and if the 2020 simulation is considered an outlier, the correlation between the increase in cumulative percentage of hourly salinities below 2 psu as an increase in the operation duration is very high with at least 0.99 at all Western Mississippi Sound reef locations. Figure 10 below shows this relationship for the 6 reef locations in Western Mississippi Sound. A strong linear relationship can be seen between the spillway opening duration and the cumulative duration of salinity below 2. The ratio between days and salinity percentage is about 0.20 for the Pelican Reef, Buoy Reef meaning about 2% of the time is added to the cumulative percentage of time below 2 psu for every 10 days of spillway operation. For example, because the spillway was open for approximately 120 days in 2019full scenario, about 24% of the entire year had salinities below 2 at those two reef locations. The ratio was higher for Telegraph Reef, Pass Marianne at and above 0.26 and the highest at Pass Christian and Henderson Point at about 0.30. Meaning 3% more time of salinity below 2 psu for every 10 days of spillway opening. According to these findings and considering the 80% biomass loss as the tipping point for settled oysters, we can tell that a 40-day opening would be sufficient for oysters at Pelican and Buoy reefs to reach a tipping point and a shorter 27-day opening would be sufficient for oysters at Pass Christian and Henderson Point to reach their tipping points. This may be the reason why oysters did not reach their tipping points for the shorter 2018 (21 days) and 2020 openings (29 days) based on the ecological model findings.

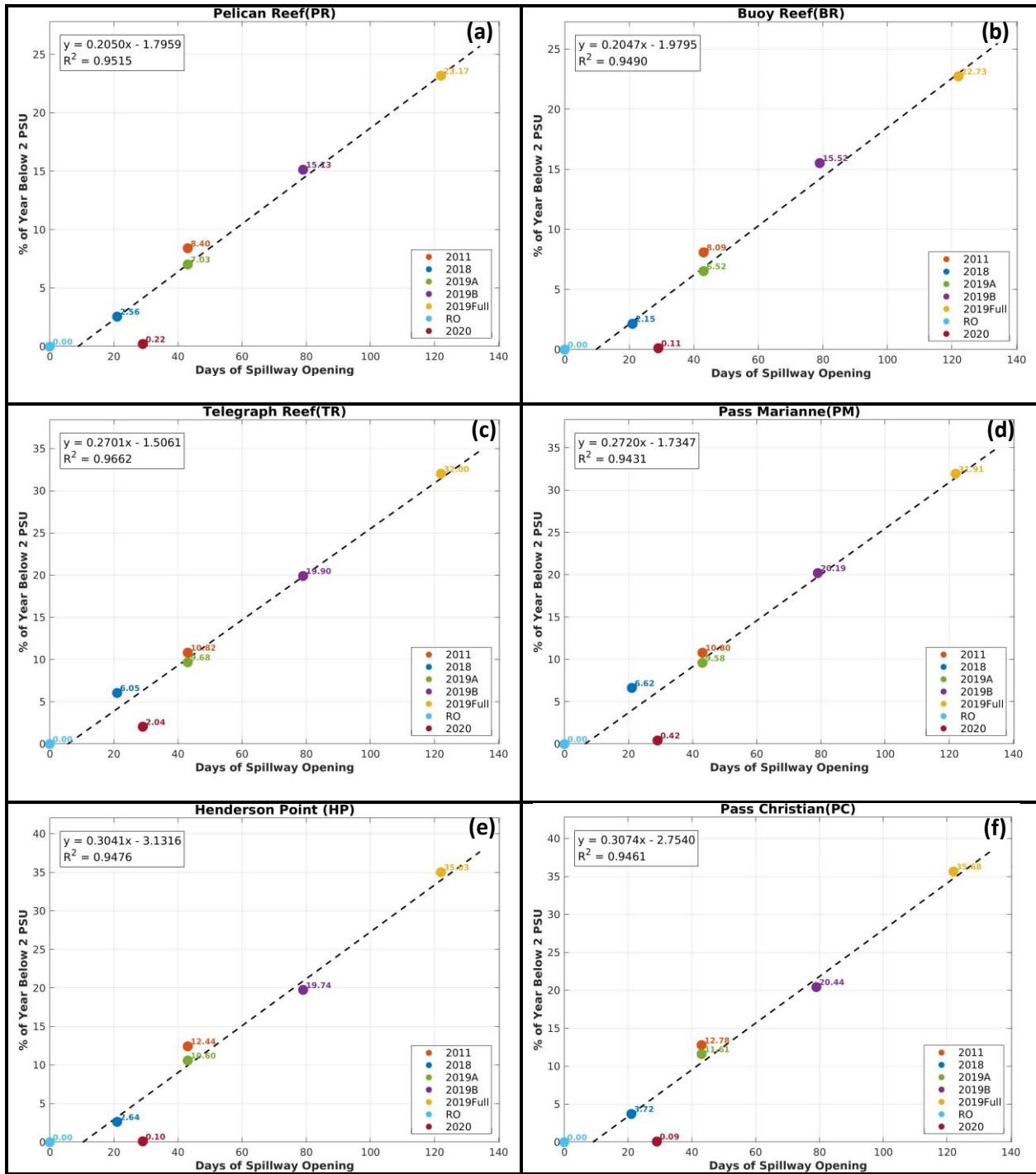


Figure 10. Relationships between number of spillway opening days and the cumulative percent of time with salinities below two for each western Mississippi Sound reef location: (a) Pelican Reef, (b) Buoy Reef, (c) Telegraph Reef, (d) Pass Marianne, (e) Henderson Point, (f) Pass Christian.

### Spillway Opening Pace Analysis

Study results show that both duration and rate of discharge are important in managing spillway operations. While the 2020 and 2018 openings were similar in duration, 21 and 29 days respectively, their rates of discharge and total released volumes are quite different. In Table 5a, we can see that the

average pace for the 2020 scenario was only 2.4% of LP volume per day (total volume 59.9% of LP) while in the 2018 scenario the average pace is 3.9% (total volume 86.5% of LP). The 2020 spillway opening was the only scenario in this study where oyster beds did not reach a hydrodynamic tipping point (14-day period of salinity below 2 psu). This suggests that there is some limit to the capacity of freshwater that can be flushed by the system each day in this climatological scenario and that the 2020 scenario does not exceed this limit.

The average and maximum rates of discharge for the 2020 scenario can be used to define a target capacity in this representative scenario. The maximum rate of BCS discharge during the 2020 opening was 3.3% of LP while the average was 2.4% per day. The influx from local rivers also needs to be taken into account. In this climatological scenario, the average rate of discharge for the rivers flowing into Lakes Maurepas, Pontchartrain, and Borgne for the first 120 days is 1% of LP volume per day. These numbers combined suggest that the average capacity of the system to mix in fresh water and maintain a salinity above 2 psu could be around 3.4% (2.4% 2020 average plus 1% river discharge) to 4.3% (3.3% 2020 maximum daily discharge plus 1% average river discharge, Figure 12). When spillway rates combined with river discharge exceed this value (4.3% per day), the system begins to fall behind. During periods when this combined discharge is much higher than 4.3%, such as in 2011 when the average discharge rate was 7.7% per day, the system not only falls behind more quickly but could also take longer to recover. This is supported by the strong correlation between the number of spillway opening days and the cumulative percent of time with salinities below two for each western Mississippi Sound reef location (Figure 10). The 2020 spillway scenario is an outlier for this correlation because on most days (25 out of 29 days) daily combined discharge falls below the 4.3% threshold. However, the R squared value for correlations between the number of days the spillway pace is greater than 3% and the percentage of days that are below 2psu at reef locations is 0.98-0.99 (Figure 11). Using the linear equations (listed in Figure 11 and Table 6) the number of days the spillway must be open in order to cross the hydrodynamic tipping point (14 days below 2 psu) can be estimated for each reef location and is found to range between 11 and 20 days (Table 6).

*Table 6. Estimated number of days the Bonnet Carré Spillway can be open at a pace >3% of Lake Pontchartrain volume per day to reach the hydrodynamic tipping point of 14 days of salinity below 2 psu.*

Reef Name	Slope	Y-intercept	R <sup>2</sup>	Number of days (x) to equal 2 weeks (y) of salinity below 2 psu
Telegraph Reef	0.2842	0.4975	0.9925	11.75
Pass Marianne	0.289	0.172	0.9882	12.68
Pass Christian	0.3262	-0.5839	0.9886	13.55
Henderson Point	0.322	-0.9607	0.9866	14.90
Pelican Reef	0.2177	-0.3561	0.9966	19.25
Buoy Reef	0.2176	-0.5486	0.9953	20.15

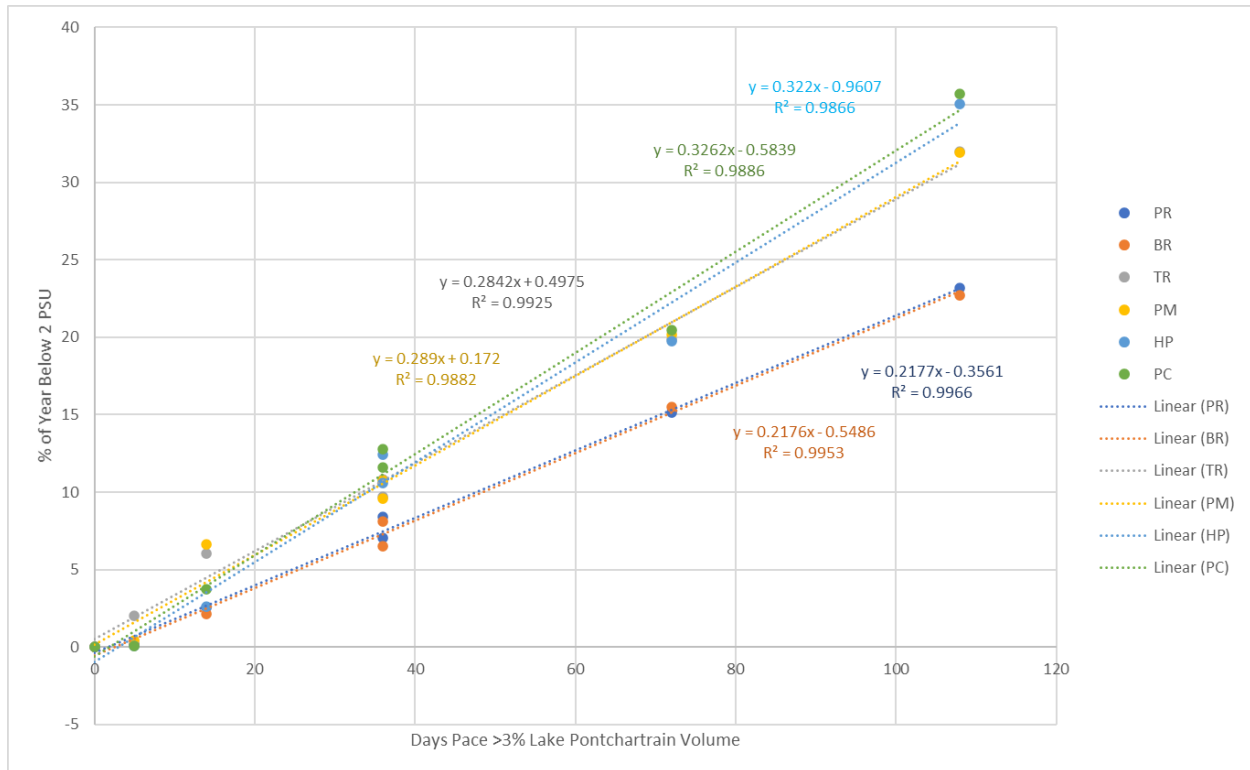


Figure 11. Correlation between the number of days the Bonnet Carré Spillway opening pace is greater than 3% of Lake Pontchartrain Volume and the percentage of days below 2 psu.

During the rivers only scenario, the Lake Pontchartrain estuary is behaving as a well-mixed (low flow) estuary where tidal fluxes are of similar or stronger magnitude as the flow driven by local riverine input. This results in weak stratification and allows for asymmetric tidal mixing to occur, enhancing estuarine circulation. As the combined flow of local rivers and BCS outpaces the tidal flow, stratification increases and suppresses vertical mixing and estuarine circulation. In the 2018 scenario, low salinity streaks start around 20 days after the opening, which is nearing the total volume of 86.6%, compared with 2011 where low salinity streaks start 12 days after the opening at a volume of around 110%. In the lower flow scenario (2018), stratification is moderate and enhanced estuarine circulation transports the lower volume of water further reaching the western Sound. In the higher flow scenario, stratification is strong, estuarine circulation breaks down, and it takes less time but for a higher volume of water to reach the Western Sound. Figure 12 demonstrates the variability of opening pace of each scenario in terms of %LPV throughout the duration of each opening. It may clearly be seen that the 2011 opening had the largest opening pace of all scenarios. 2018 scenario, while the shortest of all with 21 days also peaked with the second largest opening pace and hence a large volume was diverted to cross the tipping point at not all but some of the reefs. The 2020 scenario has the smallest opening pace leading to the smallest diverted volume. It is the only scenario below the total 4.3% LPV (combined BCS discharge+ local river discharge west of the oyster reefs) per day and is the only scenario in which the tipping point was not crossed at any reef location.

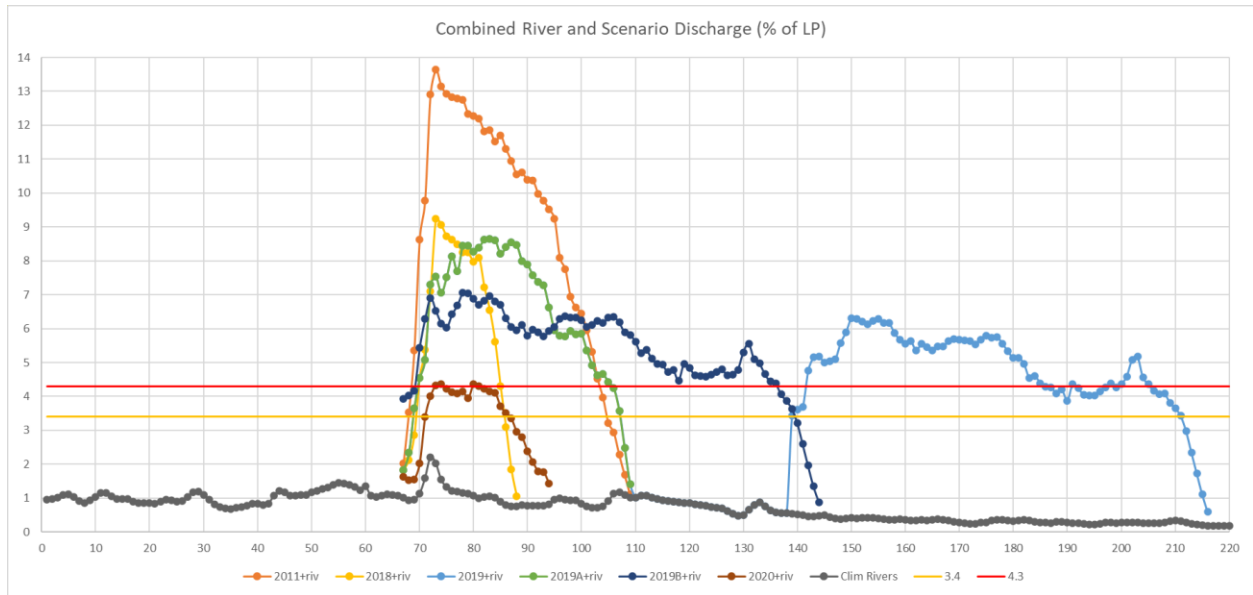


Figure 12. Combined Bonnet Carré Spillway and river volume as a function of Lake Pontchartrain volume per day for each scenario. 3.4% (horizontal yellow line) and 4.3% (horizontal red line).

## Summary and Conclusion

In this report, the hydrodynamic/water quality tipping point focuses on salinity as a hydrodynamic water quality parameter and uses the more acute and critical threshold of 2 psu. **The tipping point is defined as 14 consecutive days below 2 psu because it has been found that oysters are not able to tolerate exposure to low salinities for more than several weeks (Southworth et al., 2017; Le Peyre et al., 2013).**

The ecological assessment which utilized monthly timescales identified 2018 and 2020 as years that did not reach the ecologically defined tipping point (de Mutsert, Riddall, and Milroy, 2026). **The high resolution of the msbCOAWST model allows a detailed look into daily/hourly timescales and shows that only 2020 does not exceed the defined hydrodynamic tipping point on a daily/hourly timescale. The critical threshold of 2 psu for 14 consecutive days is exceeded for 2011, 2018, 2019A, 2019B, and 2019Full BCS opening scenarios.**

- Longest streaks were assessed with a focus on the 5 psu and 2 psu thresholds under which settled oysters experience significant stress. While all scenarios drop below 5 during the spring freshet, **only those scenarios with BCS open remain below 5 and/or drop below 2 for “streaks” of consecutive days that extend beyond the tipping point in Mississippi Sound.**
- Area of impact: In addition to the 320K square kilometers which remain under a salinity of 2 for a minimum of 2 consecutive weeks due to the natural riverine input into the system, BCS scenarios increase the area by 57.8% (2020) to 73.7% (2019 Full). The area of impact can mainly be attributed to volume since spillway operations of similar duration (43 days in 2011 and 44 days in 2019A) result in different area increases (73.7% and 69.4% respectively) depending on the volume released (329.6% in 2011 vs 219.5% in 2019A). **Limiting BCS opening volume will limit the increased area of impact.**
- Pace vs Volume vs Duration Discussion :
  - Pace: Arrival of low salinity waters following the BCS opening is proportional to the opening pace of each scenario. Scenarios where opening pace (first 20 days) is between 4% and 5.8% of Lake Pontchartrain volume (LPV) per day reach reefs in Western Mississippi Sound 5-7 days later than the 2011 scenario which has an opening pace of 9.6%. **Limiting opening pace to less than 5% of LPV per day gives fisheries managers additional time to make resource management decisions.**
  - Duration: The duration of the spillway openings in days is highly correlated with the cumulative percent of time for which salinities are below 2 at each reef location. **System recovery is delayed for longer spillway openings.**
  - Tidal influence: Tidal variations provide increased salinities during flood tide providing relief to oyster reefs experiencing salinities between 2 and 5 psu. These tidal reliefs only occur during shorter more controlled BCS operation scenarios (2020 and 2018). **Limiting the duration and volume of spillway operations allows for intermittent reliefs driven by tides and provides a chance for oyster recovery and resilience.**
  - Volume: The total volume released for the 2020 scenario which did not reach the tipping point threshold was 60% of Lake Pontchartrain volume while the total diverted volume for 2018 which did reach the tipping point for a limited number of reefs (2 out of 8) was 86.6%.

**Limiting diverted volume to less than 80% of LPV could limit the negative impacts on oyster reef health in Western Mississippi Sound.**

- Background Natural Riverine Input when BCS is open: Pace impacts the system's ability to flush additional freshwater input. 2020 is the only scenario where the opening pace is less than 3% of LPV per day and the only scenario where streaks below 2 are limited to 2 days at one reef. The climatological spring freshet volume flowing in the Western Mississippi Sound is 1% of LPV. The total volume of water coming from Pearl River is higher in BCS years (Figure A5). **Limiting the combined BCS pace and freshet volume in the Western Sound to less than 4% of LPV per day during the spring season could prevent introducing more water than the Mississippi Sound can flush, avoiding long streaks of days with salinity below 2 psu.**
- The number of days the pace is greater than 3% of LPV per day is highly correlated ( $R^2=0.99$ ) with the percentage of days annually the salinity at each reef is below 2 psu. This allows an estimation of the number of days the spillway can be open at a pace greater than 3% before the hydrodynamic tipping point is reached at each Reef. This value ranges between 11 and 20 days. **Limiting the number of days the spillway pace is >3% LPV to less than 11 days could prevent reaching the hydrodynamic tipping point at Reefs in Western Mississippi Sound.**

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## APPENDIX.

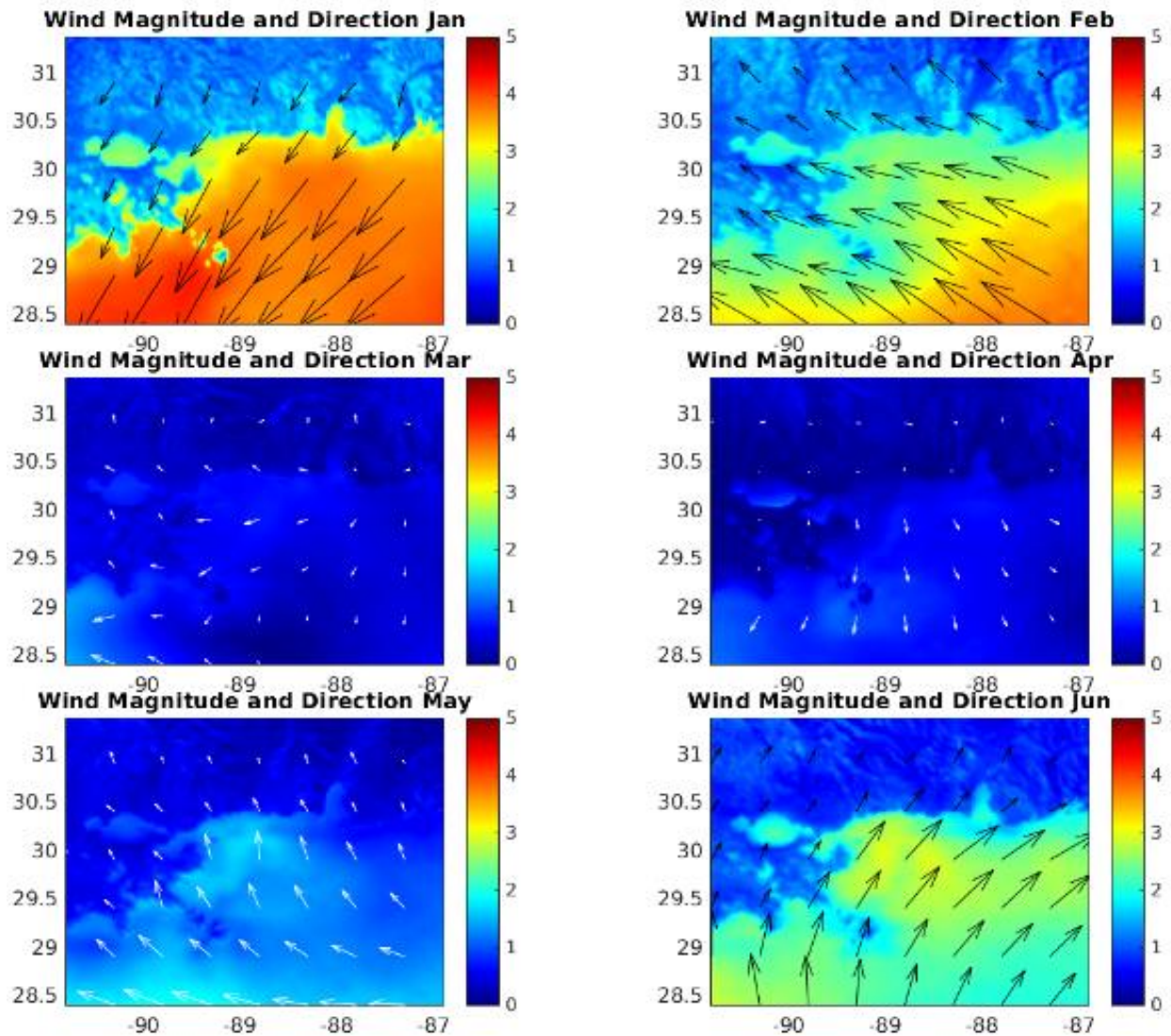


Figure A1. Spatial pattern of monthly mean wind distribution over the study region for the year 2018 estimated from HRRR (3-km spatial resolution). Wind speed (m/s) is indicated by the colored field and the scaled wind vectors reveal both wind direction and magnitude.

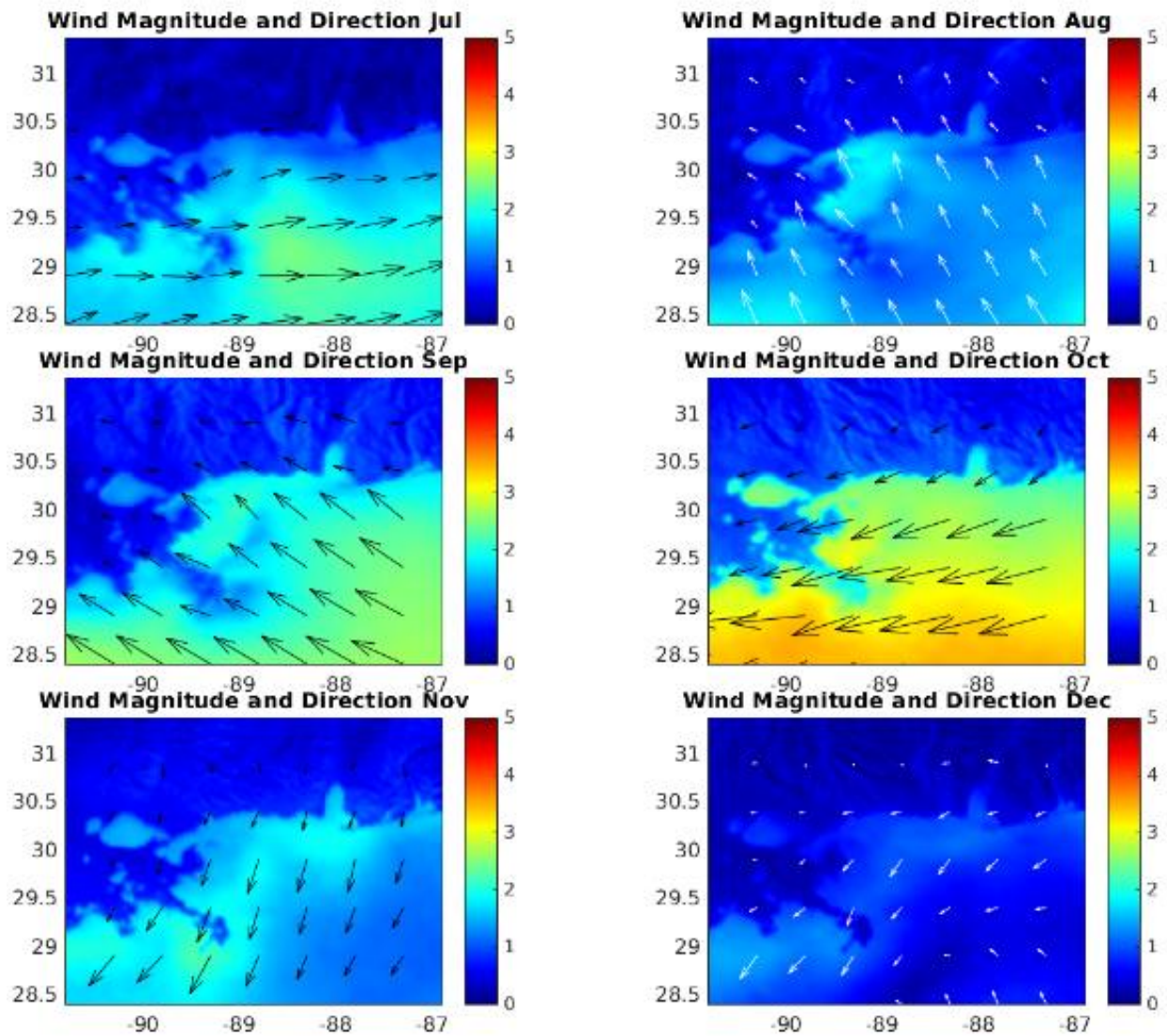


Figure A1. (continued). Spatial pattern of monthly mean wind distribution over the study region for the year 2018 estimated from HRRR (3-km spatial resolution). Wind speed (m/s) is indicated by the colored field and the scaled wind vectors reveal both wind direction and magnitude.

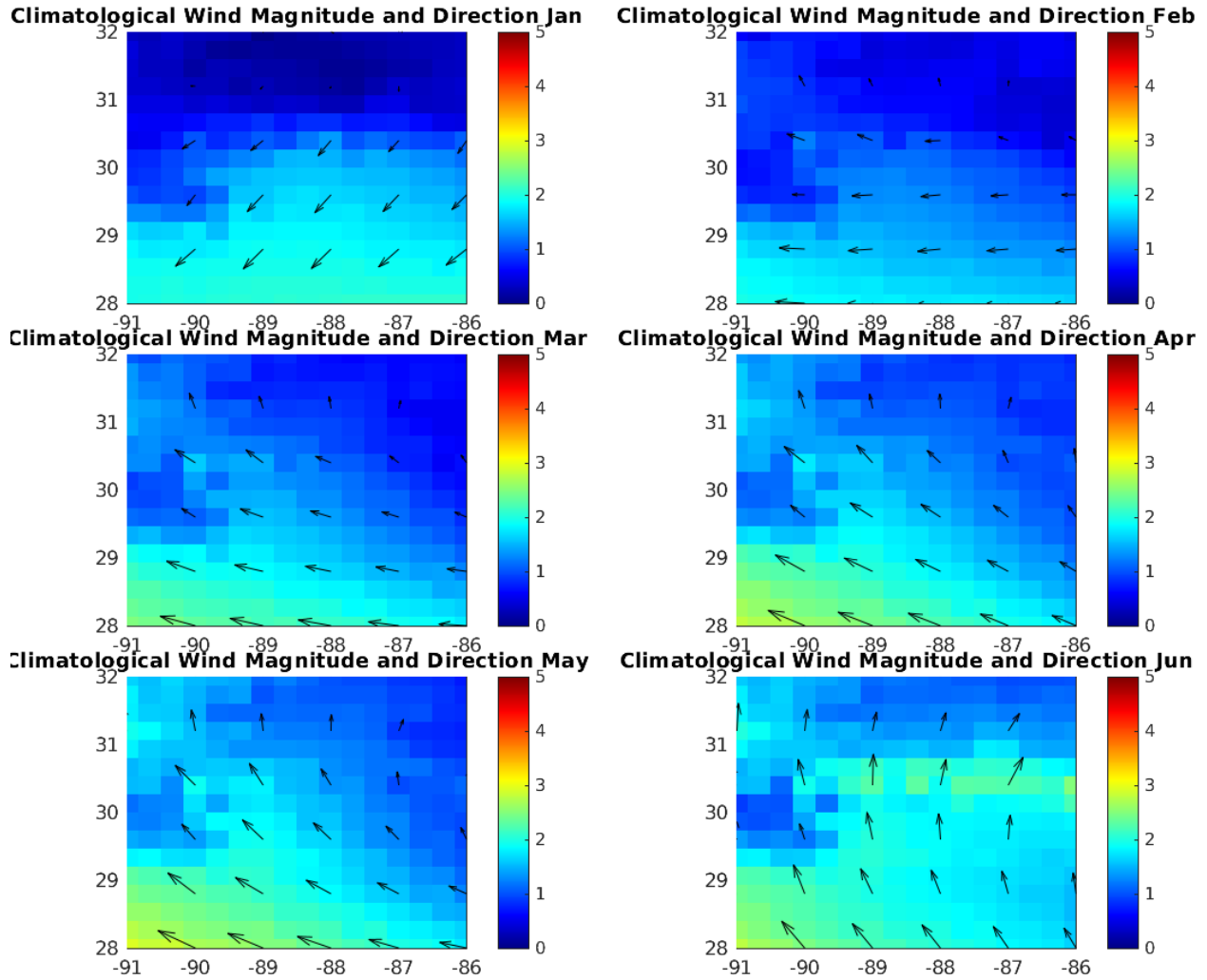


Figure A2. Spatial pattern of climatological (2010-2020) monthly mean wind distribution over the study region estimated from NARR (32-km spatial resolution). Wind speed (m/s) is indicated by the colored field and the scaled wind vectors reveal both wind direction and magnitude.

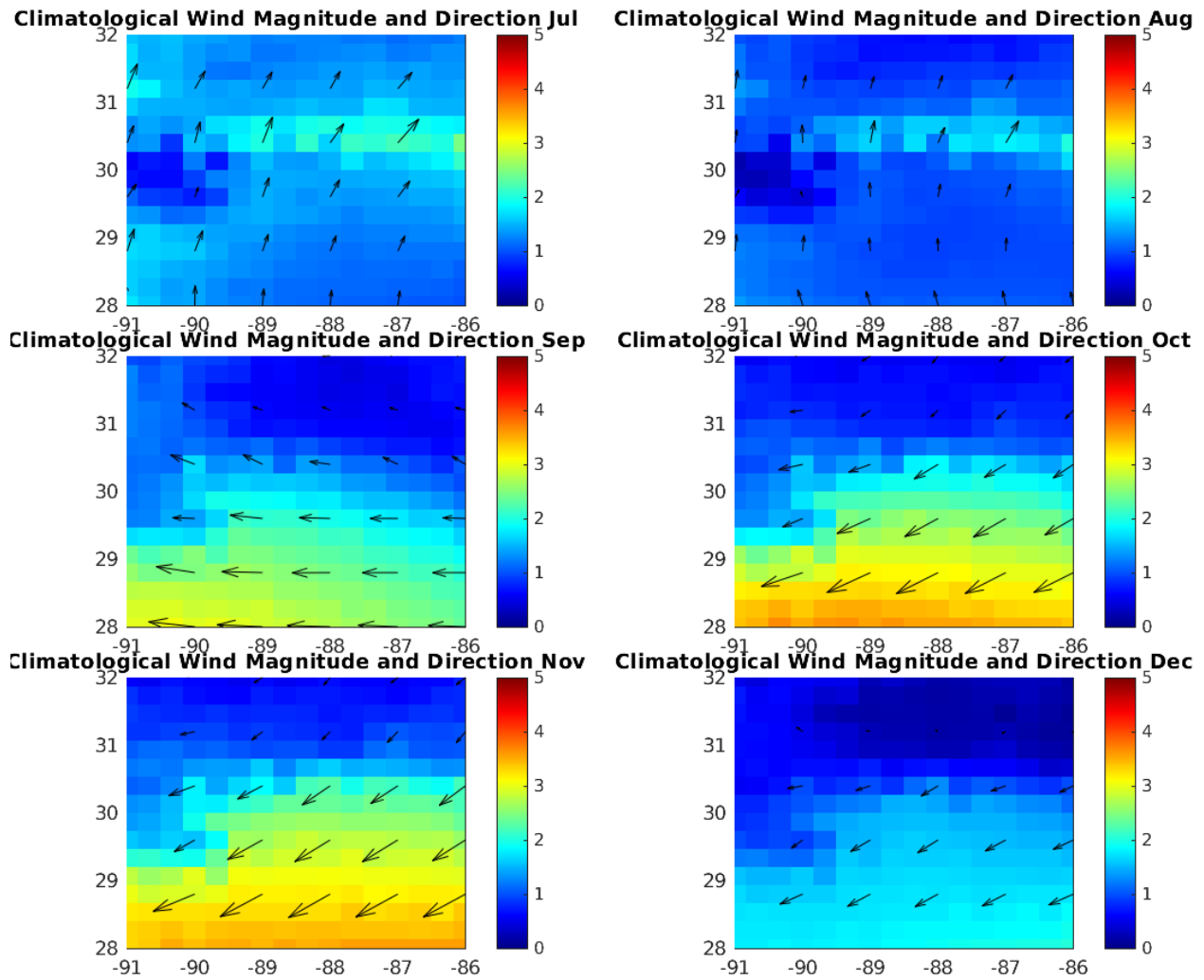


Figure A2 (continued). Spatial pattern of climatological (2010-2020) monthly mean wind distribution over the study region estimated from NARR (32-km spatial resolution). Wind speed (m/s) is indicated by the colored field and the scaled wind vectors reveal both wind direction and magnitude.

# Monthly Wind Roses - Pass Marianne Reef

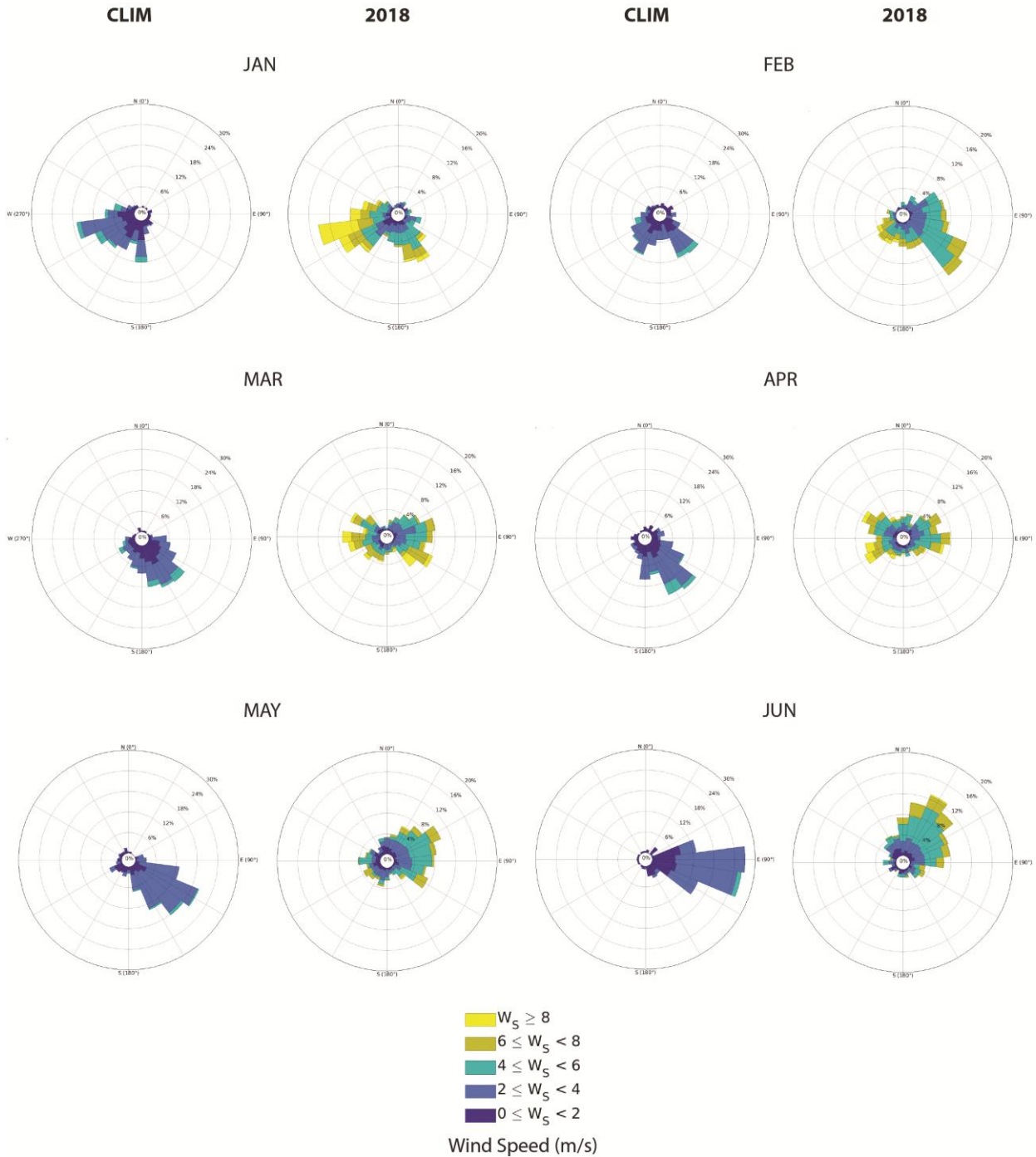


Figure A3. Wind roses from January to June for climatological (CLIM) winds extracted from NARR wind field (shown in Figure A2) compared to actual 2018 winds extracted from HRRR wind field (shown in Figure A1) at near-coastal Pass Marianne Reef location.

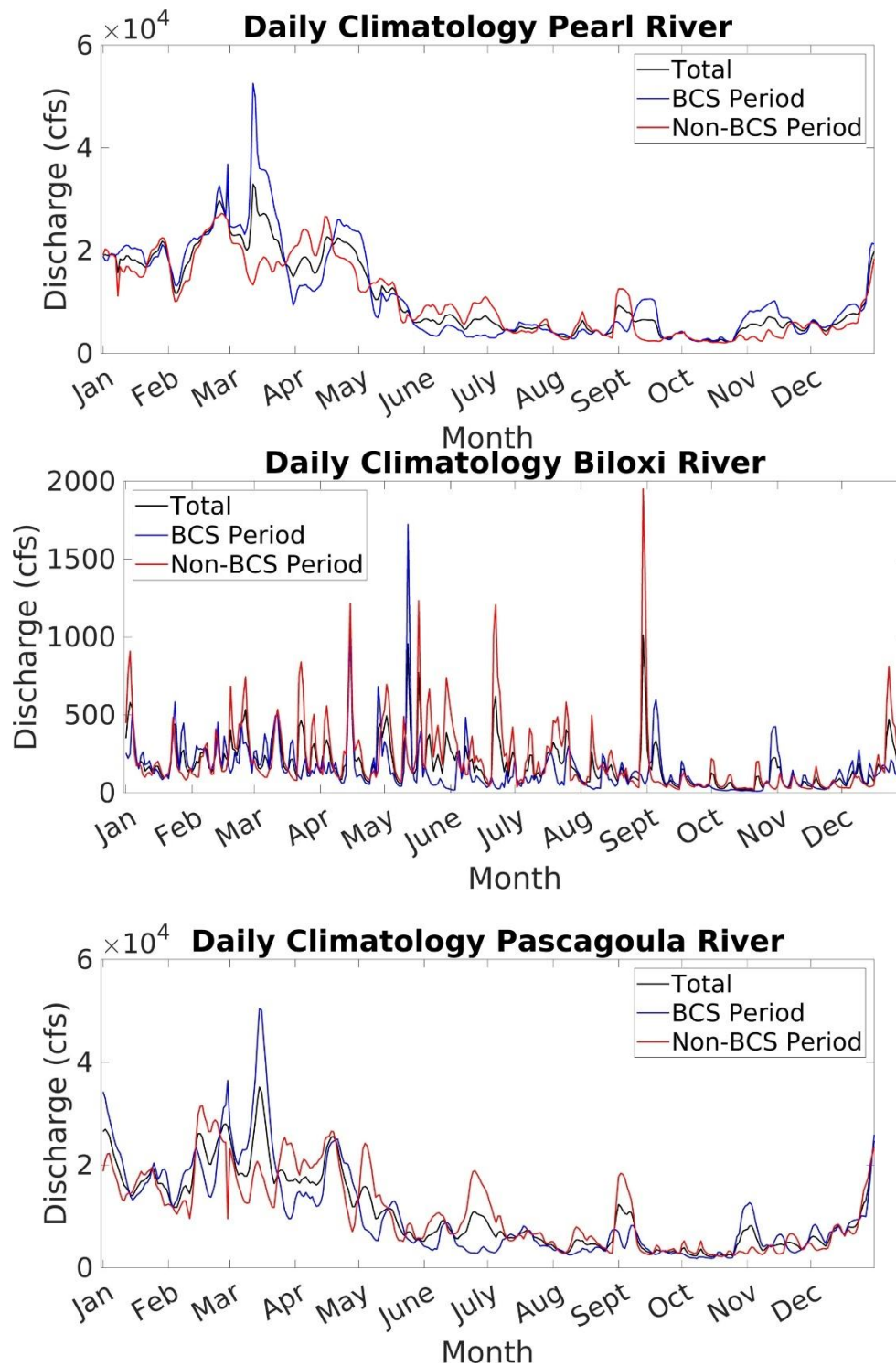


Figure A4. Daily climatological river forcing for 2011-2020 time period (black) compared to daily average discharges for BCS opening years (2011, 2016, 2018, 2019, 2020) and years with no BCS opening (non-BCS) (2012-2015, 2017) at (a) Pearl River in western Mississippi Sound (b) Biloxi River in central Mississippi Sound (c) Pascagoula River in eastern Mississippi Sound.

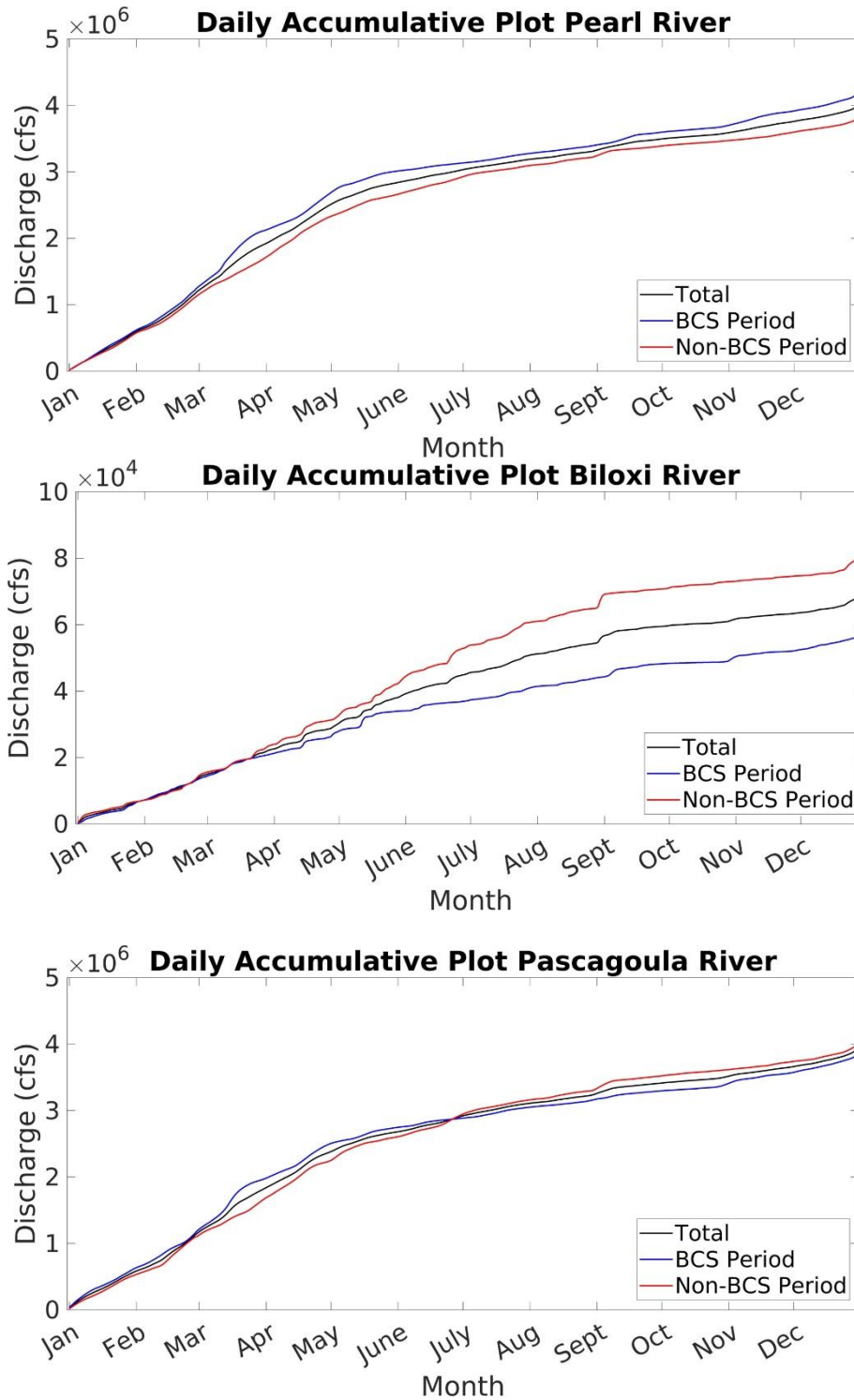


Figure A5. Daily accumulative river discharge for 2011-2020 time period (black) compared to daily cumulative discharges for BCS opening years (2011, 2016, 2018, 2019, 2020) and years with no BCS opening (non-BCS) (2012-2015, 2017) at (a) Pearl River in western Mississippi Sound (b) Biloxi River in central Mississippi Sound, and (c) Pascagoula River in eastern Mississippi Sound.

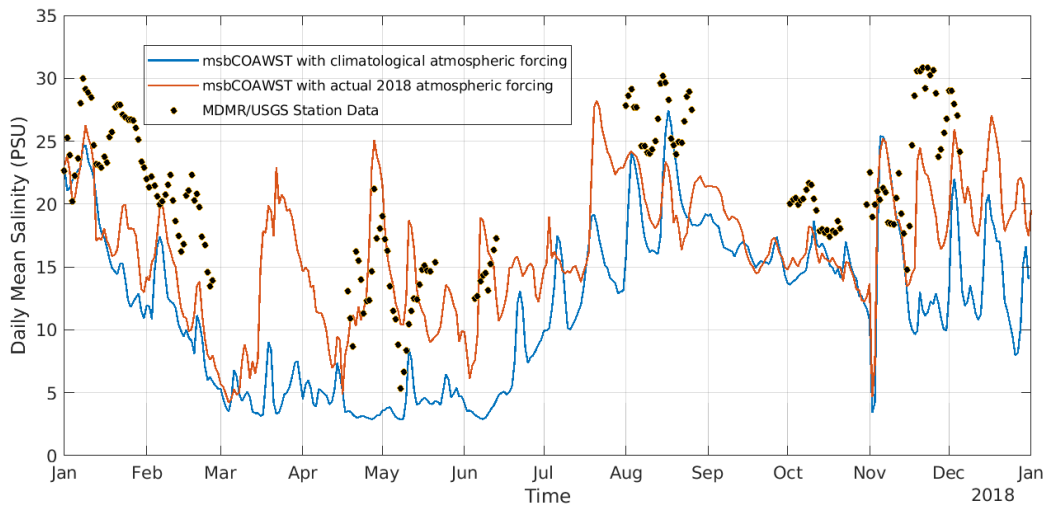


Figure A6. Daily averaged salinity from MDMR/USGS Merril Shell Bank Light station (black dots) compared to daily averaged salinities from msbCOAWST at the adjacent Pass Marianne reef using actual 2018 atmospheric forcing (red line) and using climatological atmospheric forcing (blue line).

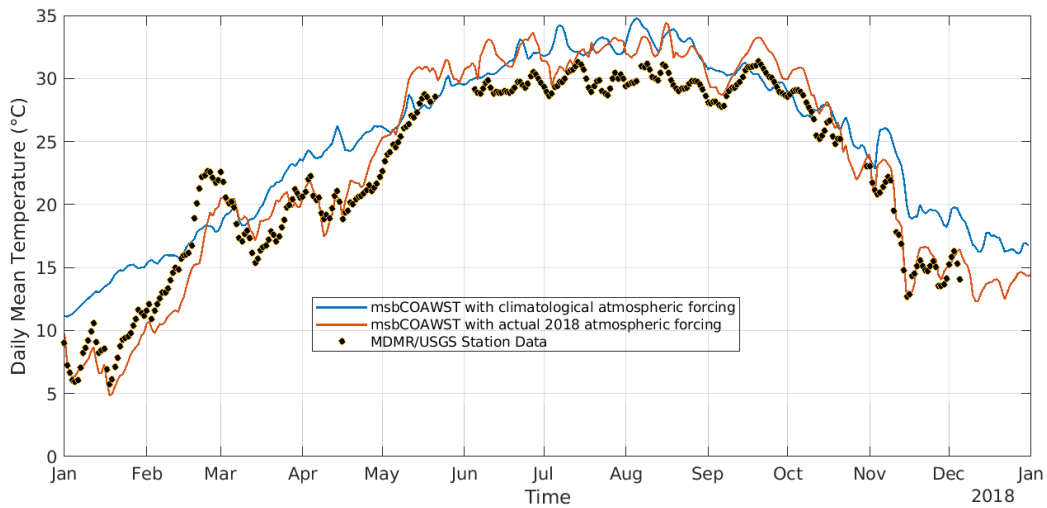


Figure A7. Daily averaged temperature from MDMR/USGS Merril Shell Bank Light station (black dots) compared to daily averaged temperatures from msbCOAWST at the adjacent Pass Marianne reef using actual 2018 atmospheric forcing (red line) and using climatological atmospheric forcing (blue line).