Inflow of shelf waters into the Mississippi Sound and Mobile Bay estuaries in October 2015

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Abstract.

The exchange of coastal waters between the Mississippi Sound (MSS), Mobile Bay and Mississippi Bight is an important pathway for oil and pollutants into coastal ecosystems. This study investigated an event of strong and persistent inflow of shelf waters into MSS and Mobile Bay during October 2015 by coupling in-situ measurements, satellite ocean color and ocean model predictions. NCOM model forecast predicted high salinity shelf waters continuously flowing into the Mobile and MSS estuaries from October 18 to 27, while low salinity waters were trapped inside MSS and did not flush out until the passage of several frontal systems in late October. The October 2015 chlorophyll-a anomaly was significantly low inside and outside the MSS for the 2003-2015 time series. Similar low chlorophyll-a anomalies were only seen in 2003. The October 2015 mean in-situ salinities were upto 8psu higher than means from 2007 to 2014, and some estuarine stations showed persistent salinities above 30 psu for almost a month in agreement with model predictions. October 2015 was associated with low fall seasonal discharge, typical of fall season, and wind which was persistently out of the East to Southeast $[45\text{-}180]^{\circ}$. These persistent wind conditions were linked to the observed anomalous conditions.

Keywords. Coastal circulation, MODIS chlorophyll-a, NCOM, salinity anomaly, wind forcing, Mississippi Sound and Mobile Bay

1. Introduction.

The CONsortium for oil spill exposure pathways in Coastal River Dominated Ecosystems (CONCORDE) studies the ecosystem dynamics and characterization of the complex 4-dimensional physical, geochemical and bio-optical fields in the Mississippi Bight influenced by pulsed river discharge. A key question addressed by CONCORDE is: Despite the fluvial input into the Mississippi Sound and Mobile Bay, how can oil and other pollutants enter the Sound and Bay from the shelf and reach the coastal mainland, as it did during the Deepwater Horizon/Macondo Well oil spill.[1] This study focuses on a particular set of meteorological events that resulted in shelf waters being forced into the Mississippi Sound, and so provides a scenario where an offshore oil spill, or other toxic event, could affect the Mississippi Sound and coastal mainland.

The first CONCORDE cruise occurred on October 27 to November 7, 2015, shortly after the passage of tropical cyclone Patricia's remnants over the study area. Patricia had dissipated over the Sierra Madre mountains in Mexico after its landfall on the coast of southwestern Mexico as a category 4 hurricane, but interacted with an upper-level baroclinic trough, and reformed as a baroclinic cyclone.[2] The cyclone moved north-northeast from south Texas to southeast Louisiana from 12:00 UTC October 25 to 00:00 UTC October 27, 2015, then turned north paralleling the Louisiana/Mississippi state line until 00:00 UTC October 28, 2015. After it reached northwest Mississippi, the system then moved east over north Alabama. The unusual path created wind patterns favorable to storm surge water elevations of 0.6-1.2 m in coastal Louisiana, Mississippi, and Alabama. By 00:00 UTC October 30, 2015, a cold front reached the study region with widespread rainfall, and shifted the winds to an offshore component, conducive to flushing estuaries such as Mobile Bay.

Navy Coastal Ocean Model (NCOM) circulation model predictions and satellite Moderate Resolution Imaging Spectroradiometer (MODIS) imagery were analyzed during the CONCORDE pre-cruise preparation in October 2015 and identified strong and persistent easterly-southeasterly surface currents transporting offshore waters onto the shelf from October 18 to 26, 2015. During the same time period, a prolonged inflow of saline offshore waters into the Mississippi Sound and Mobile Bay occurred through the barrier island passes. This event lasted until the passage of Patricia's remnants and subsequent systems over the region and was atypical in its extended duration of more than 7 days as well as in intensity, and right before the beginning of the cruise. Such an influx of offshore waters into coastal areas could be crucial in the case of an oil spill or toxic bloom event allowing toxins to reach the crucial coastal habitats.

The coastal waters of the northern Gulf of Mexico (nGoM) are characterized by rich and diverse ecosystems such as salt marshes and wetlands which are extremely valuable for nursery habitats, oyster reefs, and fisheries in general.[3-6] Toxic events, such as oil spill and harmful algal bloom events are detrimental for coastal ecosystems and fisheries of the Louisiana (LA), Mississippi (MS) and Alabama (AL) coast. In the aftermath of the Deepwater Horizon (DWH) oil spill event, oil and dispersants reached the coastline in the nGoM and resulted in environmental damage in the Gulf States.[7-9] Advection of *Karenia brevis* harmful algal blooms (HABs) from the Florida Panhandle have episodically reached the Mississippi Sound,[10-11] and most recently a *Karenia brevis* bloom reached the Mississippi Sound during fall of 2015 causing the closure of oyster beds for several weeks and alerting the coastal managers of the potential implications of these episodic events. Although, the Mississippi Sound and Mobile Bay coastal habitats are separated from the open shelf by the barrier islands, they are not immune to advection of pollutants from offshore waters. Coastal and estuarine ecosystem can be impacted if offshore waters from the shelf are transported into the estuarine system via the barrier island inlets during such toxic events.

Salinity levels within coastal areas of Mississippi and Alabama are generally high (>32 psu) in open water areas located south of the barrier islands, and low (<20 psu) in near-coastal areas inside the Mississippi Sound and Mobile Bay estuaries due to freshwater sources flowing into the systems.[12-16] Total mean discharge from rivers into the Mobile Bay and the Mississippi Sound is low in the fall season so the resulting freshwater plumes onto the inner-shelf region of nGoM would be minimal.[17] Although estuarine waters can impact the coastal water,[18] the shelf is generally dominated by high salinity offshore waters and westward currents during the fall months.[19-20] The connection and interaction between the estuaries and shelf waters in the nGoM occurs through the multiple barrier island inlets approximately 15-km south of the mainland. Surface salinity records from stations near the barrier islands indicate that the inflow and intrusion of high salinity GoM waters into the Mississippi Sound and Mobile Bay, i.e. north of the barrier islands, all along the water column happen episodically.[12] In general, these saltwater inflow events are observed to be short-lived, i.e. on the order of hours and usually less than a day. However, the potential impact of oil spills, HABs, or similar events on coastal and estuarine ecosystems could be intensified if offshore shelf waters were transported into these systems via the barrier island inlets during such toxic events on the shelf.

There have been earlier studies focusing on the oceanography, hydrology and ecology of the Mississippi Bight and Sound.[15-17, 21-23] The Mississippi Sound is a primarily well mixed semi-enclosed estuary, also showing characteristics of a partially well mixed estuary and locally a stratified estuary.[12] August-October is a low-inflow/high salinity period and the persistent southerly and southeasterly winds and low discharge causes strong vertical stratification in the Mobile Bay and Mississippi Sound.[17] Kjerfve[24] showed that 1-week period meteorological events control water exchanges between the estuary and Gulf. Dietrich et al., [25] studied surface trajectories of oil transport along the northern Gulf of Mexico coastline with a coupled numerical model system of SWAN and ADCIRC (ADvanced CIRCulation model), and showed that if a hurricane happens during an oil spill, oil could move from the shelf to further north into the Mississippi Sound towards the mainland coastline.

Many of these studies focused on the shelf and recent data from the estuarine system has been limited. Thus, the interaction and connection between the less saline, colder estuarine waters and more saline, warmer shelf waters are not well understood, especially during inflow events when GoM waters intrude into the estuarine systems. In this study, the goal is to synthesize ocean model forecasting products and in-situ coastal ocean measurements with ocean color satellite imagery, to understand the mechanisms that bring offshore saltier waters into the Mississippi Sound and Mobile Bay for extended periods. These mechanisms including coastal ocean circulation, river discharge and meteorological forcing will be examined to improve the understanding of potential transport pathways of offshore sources of oil and toxins into coastal systems and intrusion of shelf waters into the estuaries.

2. Data and Methods.

2.1. Study area

The study area is within the Mississippi Bight located in the nGoM (Fig.1). The Mississippi Bight coastal plain is broad and of low relief which allows large estuarine systems to intrude inland.[15-16] This complex coastal ecosystem is defined by a series of barrier islands that separate the estuarine system from the Gulf of Mexico. The barrier islands are separated by inlets and protect the shallow lagoons of Mobile Bay, Mississippi Sound, Chandelier Sound and Breton Sound.[26] Our study was focused on the Mississippi Sound and Mobile Bay which have water depths less than 6 meters and a mainly diurnal tide of less than 0.6 m. The Mississippi Sound is a shallow (average 3m deep) elongated estuarine basin that connects to the Gulf of Mexico thru a series of passes between five barrier islands, i.e. Cat, Ship, Horn, Petit Bois and Dauphin islands.[12,24,27] Although, the geographical boundaries of the Mississippi Sound are often a source of debate, the eastern and western boundaries are nominally Mobile Bay and Cat Island.[27] Most of the fresh water fluxes into the Mississippi Sound are due to the Pascagoula and Pearl river, however other smaller rives (i.e., Biloxi, Tchouticabouffa, Jourdan and Wolf), small bayous, and even Mobile Bay and Mississippi River contribute to the fresh water inputs into the Sound.[12,17] The Mobile River may contribute fresh water to the eastern side of the Sound, while the western Mississippi Sound may receive fresh water from Mississippi River especially when the Bonnet Carre spillway is open[12, 24, 28] and also from other rivers thru Lake Borgne and Pontchartrain. Based on salinity, Eleuterius[12] defines the Sound as well-mixed from July to December, with vertical homogeneity reaching a peak on October which is the time period of interest. Adjacent to MSS is Mobile Bay, a wide, shallow and highly stratified estuary. The main freshwater sources for Mobile Bay are the Mobile and Tensaw Rivers.[14]

2.2. Ocean circulation model

The solution of a regional application of the Navy Coastal Ocean Model (NCOM) for the entire Gulf of Mexico (GOM) was subset for the Mississippi Bight. NCOM is a Boussinesq model that solves the hydrostatic primitive equations.[29-31] The spatial resolution of the model is 1-km in the horizontal and the water column is resolved by 50 levels in the vertical. Locations with 250 m and shallower depths were resolved by 35 sigma levels and additional 15 fixed z-levels were used for depths below at deeper locations. The model incorporates a realistic bathymetry derived from the Naval Research Laboratory 2-minute database. Atmospheric forcing is provided hourly from a 17-km resolution operational application of COAMPS (Coupled Ocean Atmosphere Mesoscale Prediction System).[32-34] Boundary conditions, i.e. temperature, salinity, velocities and elevation, are provided from the global operational HYCOM (Hybrid Coordinate Ocean Model). In addition, tidal boundary conditions are gathered from the global OTIS (Oregon State University Tidal Inversion Software) solution.[35-36] In this specific version of NCOM, monthly climatological river forcing was used for the major rivers in the area, i.e. Mississippi, Pearl, Pascagoula, Mobile Rivers. A daily assimilation cycle is used followed by 72 hour forecasts. Three-hourly model outputs of temperature, salinity, velocities and surface elevation were produced by NCOM and the solution only from the first 24 hour of each 72-hr forecast period was used in the analysis. Model predictions were 40-hr moving averaged to eliminate the tidal signal while comparing with the measurement data.

2.3. Ocean color satellite imagery

Satellite derived chlorophyll-a was obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Aqua Satellite. MODIS Level-3 standard mapped image (SMI) chlorophyll-a monthly means and climatology were downloaded from the NASA-Ocean Biology Processing Group website (https://oceancolor.gsfc.nasa.gov/cgi/l3) at 4km spatial resolution.[37] A thirteen-year monthly climatology for the month of October was developed by averaging all chlorophyll-a data for October months of each year from 2003 to 2015. Chlorophyll-a monthly anomalies were calculated by subtracting those calculated monthly

October climatology from each October mean from 2003 to 2015 in the Mississippi Bight (Fig. 1). The chlorophyll-a anomaly data was extracted along two latitudinal transects inside (30.27° N) and outside (30.15 °N) the Mississippi Sound as shown in Figure 1 (red lines). One-way analysis of variance and a pairwise multiple comparison test were used in Matlab to determine whether the monthly anomaly of October 2015 was significantly different from the other years (2003-2014).

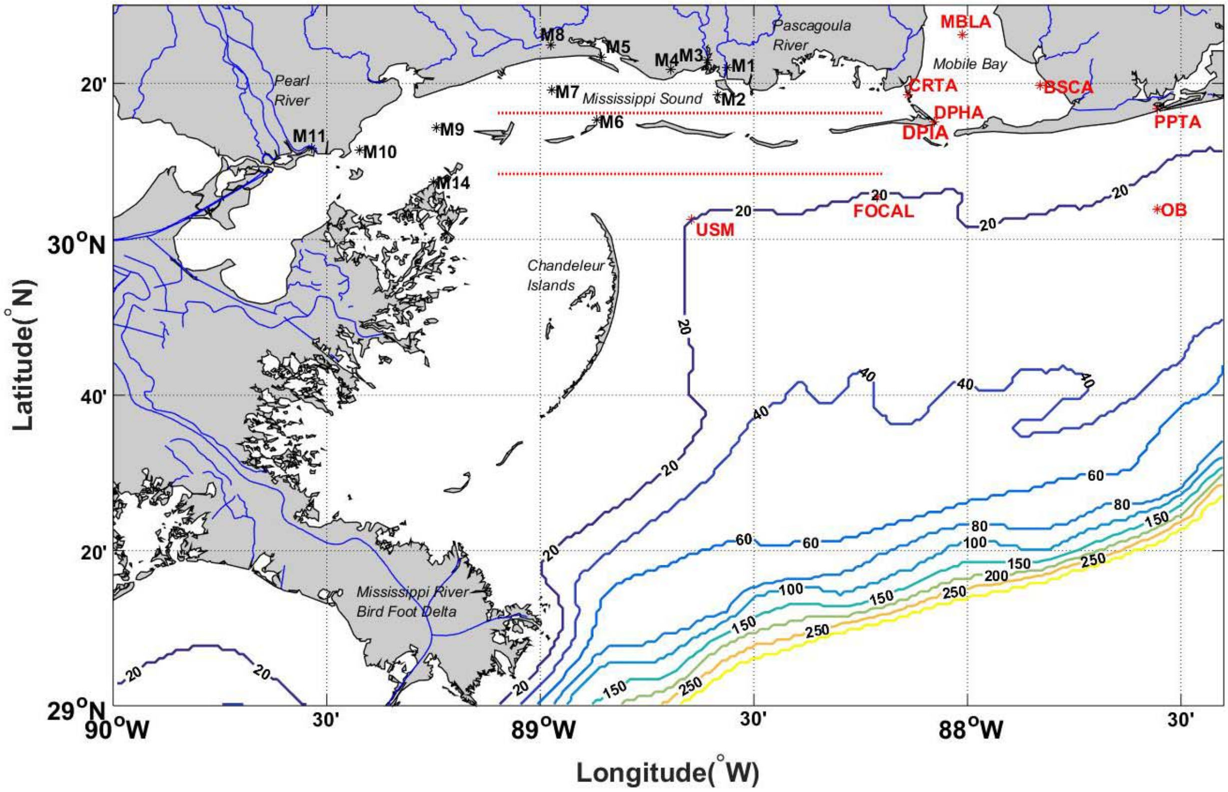

Figure 1. Study area map with MDMR/USGS stations (black labels) and NOAA/NDBC stations and buoys (red labels) in the Mississippi Bight. Contour lines represent the isobaths. The red dotted lines represent the transects used to extract the chlorophyll-a anomalies from satellite imagery. Blue lines on land represent the rivers.

2.4. In-Situ Measurements:

The Mississippi Department of Marine Resources (MDMR) provides data from real-time hydrological monitoring stations operated in partnership with the U.S. Geological Survey (USGS) in the Mississippi Sound.[38] Figure 1 shows the locations of the MDMR/USGS stations (black labels). The instruments are mounted near the sea-floor and measure temperature, salinity and pressure (water level). The National Oceanic and Atmospheric Administration's (NOAA) National Data Buoy Center (NDBC) both operates coastal marine stations in the area, and serves data from other organizations, that continuously monitors meteorological and oceanographic conditions in the coastal GoM. The locations of NOAA/NDBC stations used in this study area are shown in Figure 1 (red labels). Stations in Alabama waters around Mobile Bay estuary with continuous salinity records were used, i.e. Dauphin Island, AL (DPHA and DPIA), Perdido Pass, AL (PPTA), Middle Bay Light, AL (MBLA), Bon Secour, AL (BSCA), and Cedar Point, AL (CRTA). Besides, wind data from an offshore buoy 44 nm southeast of Mobile Bay Main Pass near Orange Beach, AL, at 28m depth. Salinity data from the University of Southern Mississippi Buoy (NDBC Station 42067) and current data from the FOCAL (Fisheries Oceanography in Coastal Alabama) mooring, both at the 20 m isobath on the inner-shelf, were also used. Table 1 provides the coordinates, names and measurements used from each station. River discharge data was obtained from four USGS stations from the Alabama, Mobile, Pascagoula and Pearl Rivers. Note that the stations were not included in Figure 1, however the coordinates can be found in Table 1.

Table 1. List of stations coordinates and measurements used for Salinity (Sal.), Temperature (Temp.), Water Level (W.L.), Wind, Currents and River discharge.

Station ID , Location	*Latitude(N)*	*Longitude(W)*	*Organization*	***Measurements***
M1, Pascagoula River	30°22'04.0"	88°33'47.0"	MDMR/USGS	Sal., Temp., W.L.
M2, MS Sound, Round Island	30°18'29.0"	88°35'02.0"	MDMR/USGS	Sal., Temp., W.L.
M3, West Pascagoula River	30°22'57.7"	88°36'30.4"	MDMR/USGS	Sal., Temp., W.L.
M4, Graveline Bayou	30°21'46.4"	88°41'41.0"	MDMR/USGS	Sal., Temp., W.L.
M5, Biloxi Bay	30°23'18.0"	88°51'26.0"	MDMR/USGS	Sal., Temp., W.L.
M6, MS Sound, East Ship Island	30°15'16.0"	88°52'08.0"	MDMR/USGS	Sal., Temp., W.L.
M7, MS Sound, Center Sound	30°19'07.0"	88°58'20.0"	MDMR/USGS	Sal., Temp., W.L.
M8, Back Bay of Biloxi	30°24'56.0"	88°58'33.0"	MDMR/USGS	Sal., Temp., W.L.
M9, Merrill Shell Bank Light	30°14'17.0"	89°14'34.0"	MDMR/USGS	Sal., Temp., W.L.
M10, St. Joseph Island Light	30°11'27.0"	89°25'20.0"	MDMR/USGS	Sal., Temp., W.L.
M11, East Pearl River	30°11'41.0"	89°32'03.0"	MDMR/USGS	Sal., Temp., W.L.
M14, MS Sound, Grant Pass	30°07'22.0"	89°15'01.0"	MDMR/USGS	Sal., Temp., W.L.
DPHA/Dauphin Island, AL	30°15'05.0"	88°04'40.0"	NOAA/NDBC	Wind
DPIA/Dauphin Island, AL	30°15'05.0"	88°04'40.0"	NOAA/NDBC	Sal., W.L.
CRTA, Cedar Point, AL	30°18'30.0"	88°08'22.0"	NOAA/NDBC	Salinity
PPTA, Perdido Pass, AL	30°16'44.0"	87°33'21.0"	NOAA/NDBC	Salinity
BSCA, Bon Secour, AL	30°19'43.0"	87°49'46.0"	NOAA/NDBC	Salinity
MBLA, Mobile Bay, AL	30°26'15.0"	88°00'41.0"	NOAA/NDBC	Salinity
42067, USM Buoy	30°02'33.0"	88°38'50.0"	USM/NOAA/NDBC	Sal., Temp.
FOCAL Buoy	30°05'24.6"	88°12'41.6"	FOCAL	Currents
42012, Orange Beach Buoy, AL	30°03'55.0"	87°33'19.0"	NOAA/NDBC	Wind
2428400, Alabama River	31°36'54.0"	87°33'02.0"	USGS	River discharge
2470629, Mobile River	31°00'56.0"	88°01'15.0"	USGS	River discharge
2479310, Pascagoula River	30°36'38.0"	88°38'29.0"	USGS	River discharge
2489500, Pearl River	30°47'35.0"	89°49'15.0"	USGS	River discharge

3. Result and Discussion.

In this section, the NCOM ocean model predictions are synthesized and analyzed together with satellite imagery from MODIS-Aqua, and in-situ measurements from MDMR/USGS stations, NOAA/NDBC stations and buoys/moorings described in the previous section to understand the dynamics and mechanisms leading to the inflow of high salinity shelf waters into the Mobile Bay and the Mississippi Sound.

3.1. NCOM Model salinity and currents

In-situ instruments provide reliable oceanographic and meteorological measurements, however they are spatially limited, therefore the kinematics and dynamics between stations are unknown. The ocean model provides continuous predictions allowing us to fill these gaps and understand the spatial and temporal variability of our study region. NCOM model predictions for sea surface salinity and surface currents covering the Mississippi Bight and Sound were used to understand the dynamic processes and chronological meteorological and oceanographic events that forced offshore saline waters towards the Mississippi Sound during October 2015. NCOM surface salinity in Figure 2 shows inflow of saline shelf waters into the Mobile Bay and Mississippi Sound through the multiple barrier island inlets from October 19 to 28, 2015. Due to strong easterly and southeasterly currents, low salinity estuarine waters were predicted to be trapped inside the Sound until the passage of Patricia's remnants on October 27, 2015.

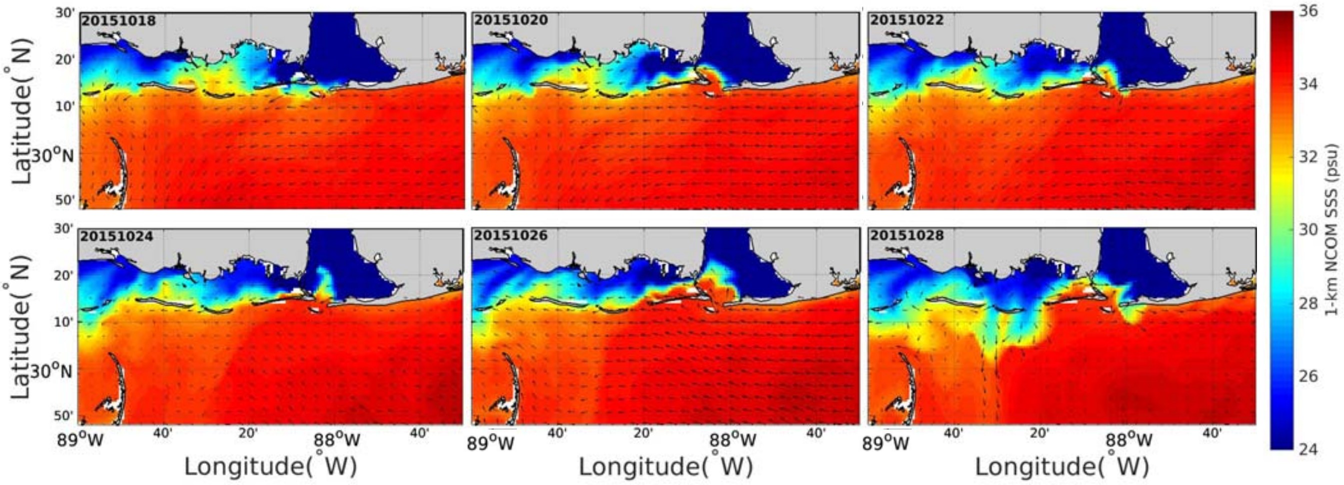

Figure 2. NCOM predictions of sea surface salinity and surface currents in the study area on a) October 18, 2016, b) October 20, 2016, c) October 22, 2016, d) October 24, 2016, e) October 26, 2016, f) October 28, 2016.

Velocity measurements (not shown here) at an inner shelf mooring FOCAL station, located approximately 20 km southwest of the Mobile Bay Main Pass, showed that the currents were directed onshore, mainly in the NW direction from October 18 until the instrument was buried due to Patricia's remnants on October 27, 2015. Model results show that the higher salinity shelf waters reached the southern coastline of almost all barrier islands, entered the estuarine system mainly via the Mobile Bay Main Pass and mixed with estuarine waters until it was transported west into the Mississippi Sound via Grant Pass (Pass Aux Heron) [Figs. 2(b),(c),(d) and (e)]. A secondary inflow was seen via the Horn Island Pass on October 19, 2015 [Fig. 2(a)]. Because of the wind reversal associated with Patricia's remnants, estuarine waters were expected to be flushed out of the Mississippi Sound and Mobile Bay as seen on October 28, 2015 [Fig. 2(f)].[39] Satellite imagery following passage of Patricia's remnants (Fig. 4 in Dzwonkowski et al., [39]) also showed high chlorophyll-a concentrations due to strong mixing, sediment re-suspension and increased biological activity in the freshwater plumes on the inner-shelf.

Hovmoeller diagrams of NCOM sea surface salinity along three chosen transects [Fig. 3(a); dash lines] around the barrier island inlets are shown in Figure 3. Figure 3(a) shows a zoomed-in map of the Mississippi Sound barrier islands and passes. The southern-most transect is outside the Sound along 30.2°N and is aligned with Pelican, Petit Bois and West Ship islands [Fig. 3(b)]. The salinity along the eastern side of the transect (>88.3°W) shows salinities of inner-shelf waters above 32 psu, reaching and exceeding 34 psu. Lower salinity waters were predicted by the model to flush out of the Mobile Bay in between October 11 and October 18, 2015 and later from October 27 to November 3, 2015 after the passage of Patricia's remnants and the subsequent cold front on October 30, 2015. The flushing of lower salinity water from the

Sound starting from October 27, 2015 was predicted to be stronger from the inlets around the Petit Bois Island most likely via both the Horn and Petit Bois Passes. Lower salinity estuarine waters were predicted to continuously flush out of the Ship Island Pass during the entire month of October, while the intensity of flushing decreased in between October 18 and 27, 2015.

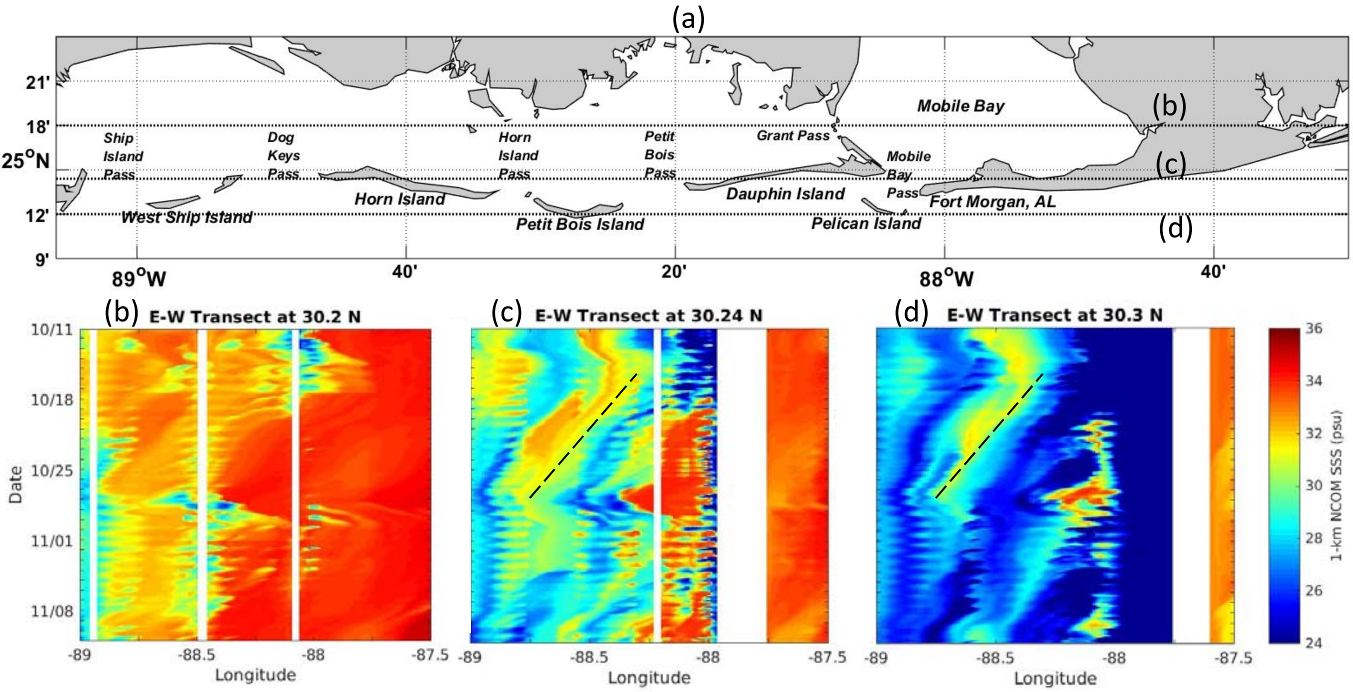

Figure 3. a) Map of the Mississippi Sound showing the major barrier islands and passes. NCOM predictions of sea surface salinity in between October 11 and November 11, 2015 through transects: b) outside the Sound along 30.2°N (30°12'N), c) along the passes at 30.24°N (30°14'24"N), and d) inside the Sound along 30.3°N (30°18'N). Transect locations are shown in (a) as dash lines.

Figure 3(c) shows the NCOM sea surface salinity through a transect north of Mississippi barrier islands at 30.24°N crossing Dauphin Island and Fort Morgan, AL [Fig. 3(a); dash line]. This transect may be considered as the transition in between estuarine waters and shelf waters because it shows the signature of both lower salinity estuarine waters (<25 psu) and higher salinity shelf waters (>34 psu). The model predicted strong northward transport of high salinity waters thru Mobile Bay Main Pass starting from October 18, 2015 and the inflow associated with this transport seems to prevent the flushing of Mobile Bay estuarine waters onto the shelf. The diagonal pattern of low salinity waters from October 18 to October 27, 2015, shown in Figure 3(c), suggests that the blockage of outflow at the Mobile Bay Main Pass and the strong easterly winds and currents caused the estuarine waters to be transported west from Mobile Bay towards the Mississippi Sound. Therefore, it is likely that the low salinity waters flushing out of the Horn Island and Petit Bois passes on October 27, 2015 could possibly be Mobile Bay estuarine waters transported westward during the 10 day period leading to the Patricia's remnants passage over the study area.

The last transect [Fig. 3(a); dash line] is inside the Mississippi Sound and Mobile Bay at 30.3°N. Low salinity (<30 psu) estuarine waters dominated throughout the time period as shown in Figure 3(c). The model predicted high salinity shelf waters reaching this transect north of Mobile Bay Main Pass starting from October 19, 2015 with increasing intensity towards October 27, 2015. The salinity through this transect also showed an earlier high salinity inflow via the Petit Bois Pass mixed with estuarine waters. These relatively high salinity waters (~30 psu) were observed to be transported west between October 18 and October 27, 2015 possibly due to westward transport of Mobile Bay estuarine waters.

3.2. In-situ measurements in the Mississippi Sound and Mobile Bay

Figure 4 shows 40-hr low pass signal of wind measurements at Orange Beach buoy (Fig. 1; OB), water level and salinity measurements (blue solid lines) at the Dauphin Island station (Fig. 1; DPIA) compared to the model predictions (red dot-dash lines) during the October 2015. Figure 4(a) and 4(b) show that the variability and magnitude of the wind forcing, provided to NCOM from COAMPS solution, compares well with the measurements. Starting from October 16, 2015 the wind was predominantly southeasterly and easterly until a strong wind reversal happened due to Patricia's remnants on October 27, 2015.

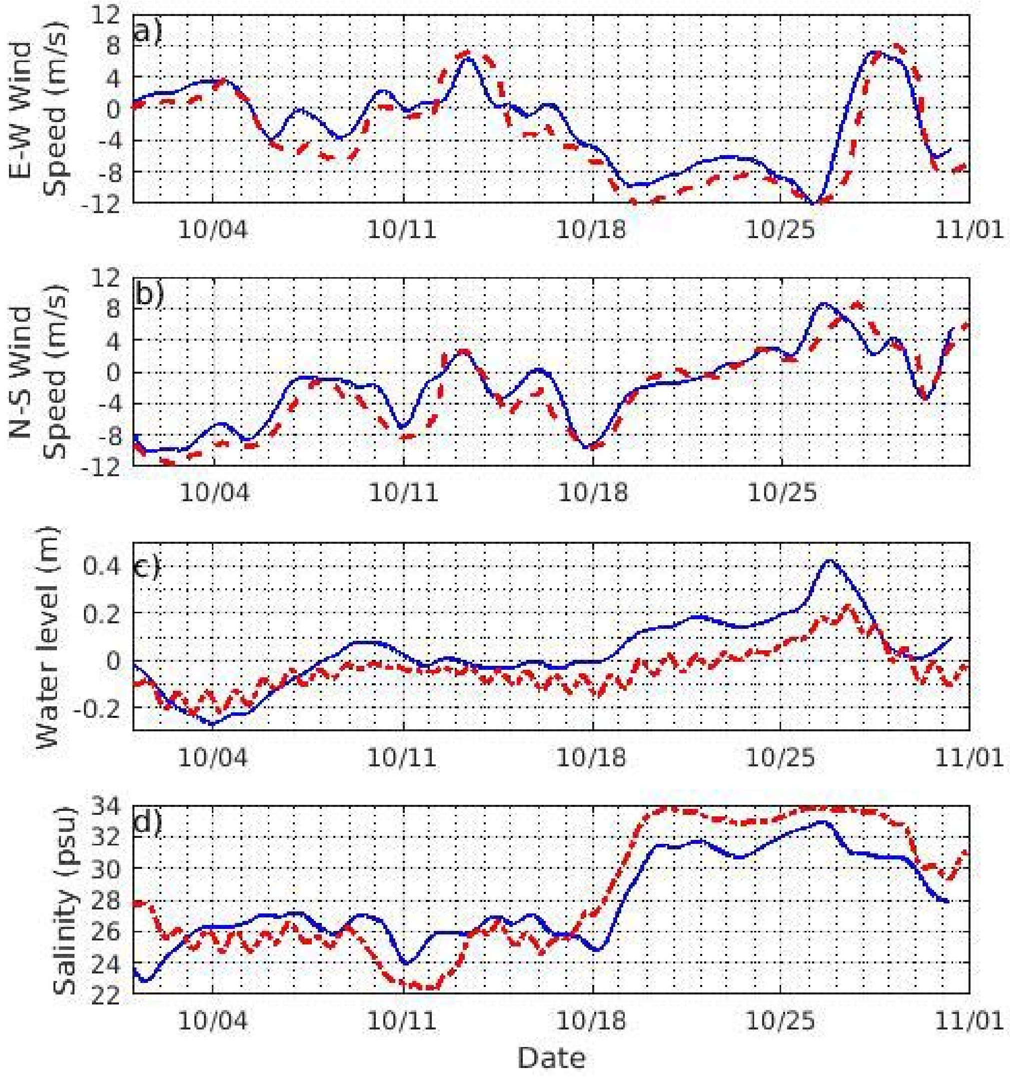

Figure 4. Measurements (solid blue) vs. NCOM model predictions (red dot-dash) of a) E-W wind speed at the Orange Beach buoy, b) N-S wind speed at Orange Beach buoy, c) water level at Dauphin Island station (DPIA), and d) salinity at Dauphin Island station (DPIA)

Figure 4(c) shows that the model predictions of the water level peak and flushing were very close to the measurements, however the peak magnitude is smaller than the observed at the Dauphin islands stations. The water surface elevation increased inside the Mississippi Sound and Mobile Bay because of the trapping of estuarine waters combined with the Patricia's surge. The salinity prediction of the model [Fig. 4(d)] was also in line with the measurements such that the salinity began to increase on October 18, 2015 and peaked at 33 psu during Patricia's influence. Salinity then decreased with Patricia's wind shift followed by several cold fronts, with a value of 22 psu by early November 2015. The model salinity peak is 34 psu, and while the initial drop to 28 psu agrees with the measurements, the modeled salinity later drops to 26 psu in November, which is higher than the measured minimum of 22 psu. Overall, the model predictions agreed reasonably well with the measurements and validated the model's capability to represent the dynamics in the region.

Salinity measurements at the USM Buoy (results not shown here), located at the 20m isobath (Fig. 1; USM), showed that the salinity at the inner-shelf exceeded 30 psu in July 2015 and stayed over 30 psu until the end of the calendar year. Moreover, the USM Buoy measurement showed that the salinity in October remained over 33.5 psu for the majority of October 2015 until a 2 psu drop from 34.5 to 32.5 psu occurred due to the movement of Patricia's remnants over the area. Figure 5(a) shows salinity measurements at the Dauphin Island station (Fig. 1; DPHA) between 2013 and 2015 and Figure 5(b) shows the salinity for 2015 only. Salinity increased during the spring and summer for all years and peaked during the fall months. If 30 psu is considered a critical threshold of very high salinity at this station, it may be said that salinity exceeded this threshold episodically and for short intervals. In fact, fall 2015 is the only time period when the salinity exceeded and persisted over 30 psu for an extended period of time (7.5 days) and over 29 psu for 11 days. Figure 5(b) shows that salinity records at Dauphin Island station, DPHA, remained over 30 psu for most of the second half of the month. A similar salinity increase was also observed in other stations in the Mississippi Sound.

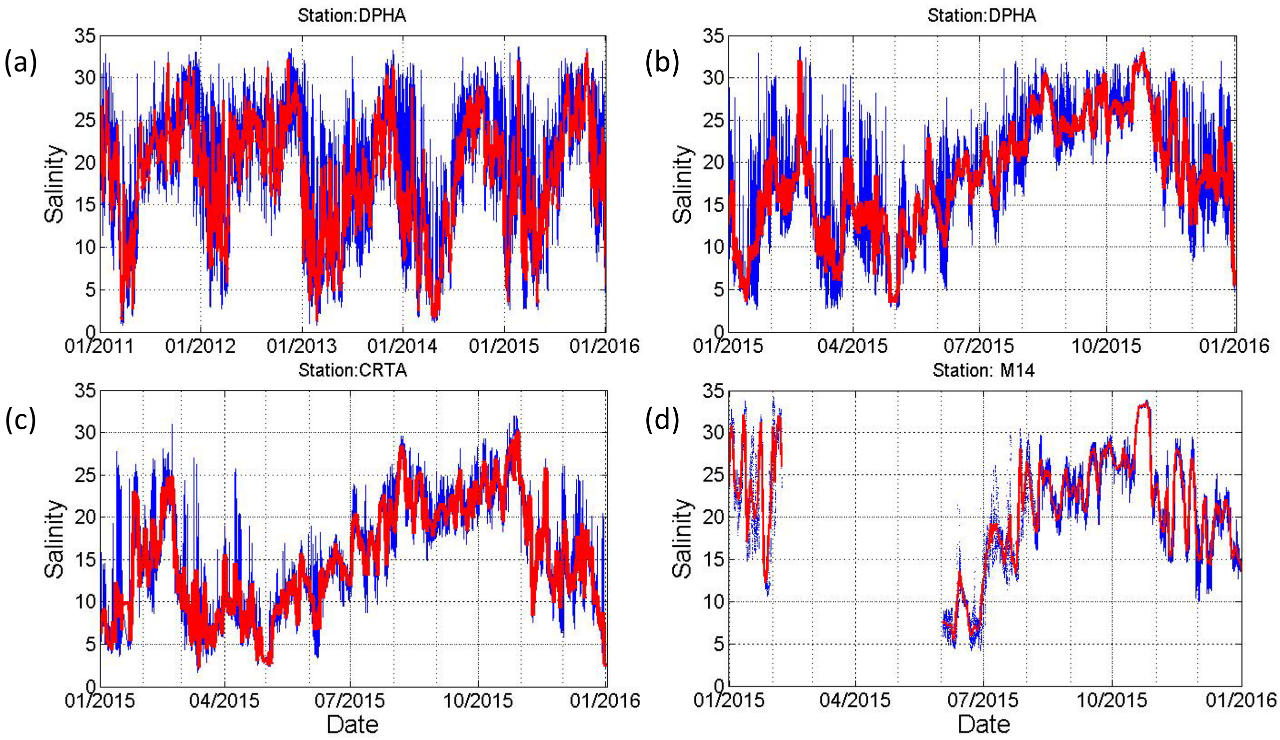

Figure 5. Salinity measurements at a) Dauphin Island, DPHA station from 2013 to 2015 and a subset for only 2015 data for stations at: b) Dauphin Island, AL (DPHA), c) Cedar Point, AL (CRTA), and d) Grant Pass, Mississippi Sound (M14).

The salinity measurement at CRTA station (Fig.1) on the eastern side of the Sound close to Mobile Bay is shown in Figure 5(c). Since this station is north of the barrier islands and inside the Sound, the peak salinity was lower than the DPHA station due to the proximity to low salinity freshwater sources and mixing inside the estuarine system. However, while the salinity at this station reached 25 psu episodically, it exceeded 25 psu on October 2015 and similar to DPHA, it stayed over this value for more than a week. Figure 5(d) shows the salinity measurements at MDMR/USGS station M14 which is on the western end of the Mississippi Sound. The salinity exceeded 30 psu in mid-October and stayed above 30 psu for the same late-October duration shown in the other stations. The fact that similar salinity fluctuations were seen not only at the DPHA but also at CRTA and M14 at both ends of Mississippi Sound indicates that the inflow of saline waters was a system-wide event impacting the entire Sound.

Since high salinity events in the Mississippi Sound are indicative of intrusions of high salinity shelf water, these events have important implications for potential transport of larvae, pollutants and toxic algae into the Mississippi Sound. An important question then is to understand whether the high salinity signal observed in October 2015 is atypical or not. To do that, the October 2015 event was compared with October conditions in other years. An anomaly study on salinity measurements was conducted for these purposes. A 10-year monthly climatology of salinity values was generated using salinity from near-bottom temperature and conductivity measurements at MDMR/USGS stations. Monthly mean salinities were calculated for the entire time series at each station. Monthly anomalies were calculated as the difference between the monthly climatology (average from 2007 to 2015) and the monthly mean value of each year. Figure 6 shows the salinity anomalies for the last 5 years (2011-2015). Inter-annual fluctuations are apparent. Elevated salinity shown as positive salinity anomaly peaks in late summer and fall months (August to October) in 2014 and 2015 at all stations, and early summer - months (May to July) in 2011 and 2012 at most stations. The highest positive salinity anomaly was seen in October 2015 (shown in red) at all MDMR/USGS stations across the Mississippi Sound. Monthly anomalies for temperature and water surface elevation measurements at MDMR stations (not shown here) were also calculated. Temperature anomalies showed no significant difference in between years at all stations. October 2015 had one of the highest sea surface elevation anomalies (up to 50 cm higher water level) during the 2011-2015 time frame due to the passage of Patricia's remnants.

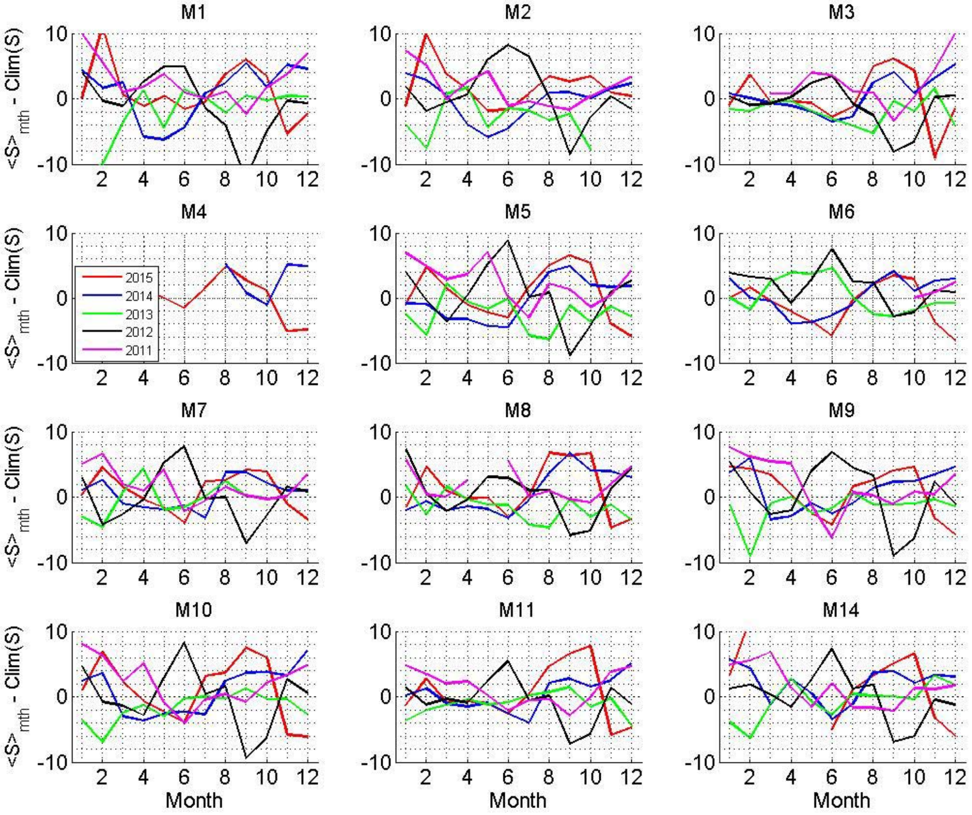

Figure 6. Monthly salinity anomalies from 2011 to 2015 at the MDMR stations in the Mississippi Sound.

Figure 7(a) shows the October in-situ mean salinities and variability from 2007 to 2015 at the MDMR/USGS stations and the NOAA/NDBC stations in the Sound. October mean salinities were the highest in 2015 at all stations. This proves that October 2015 had more saline offshore water inflow into the Mississippi Sound and Mobile Bay and towards the station locations. The highest salinities of October 2015 were measured at Mississippi Sound stations; M2, M6, M7, M14, DPHA and PPTA. Stations M2, M6, M7 and M14 were either near the barrier island inlets (M6, M14) or relatively away from the coastline and freshwater sources (M2, M7).

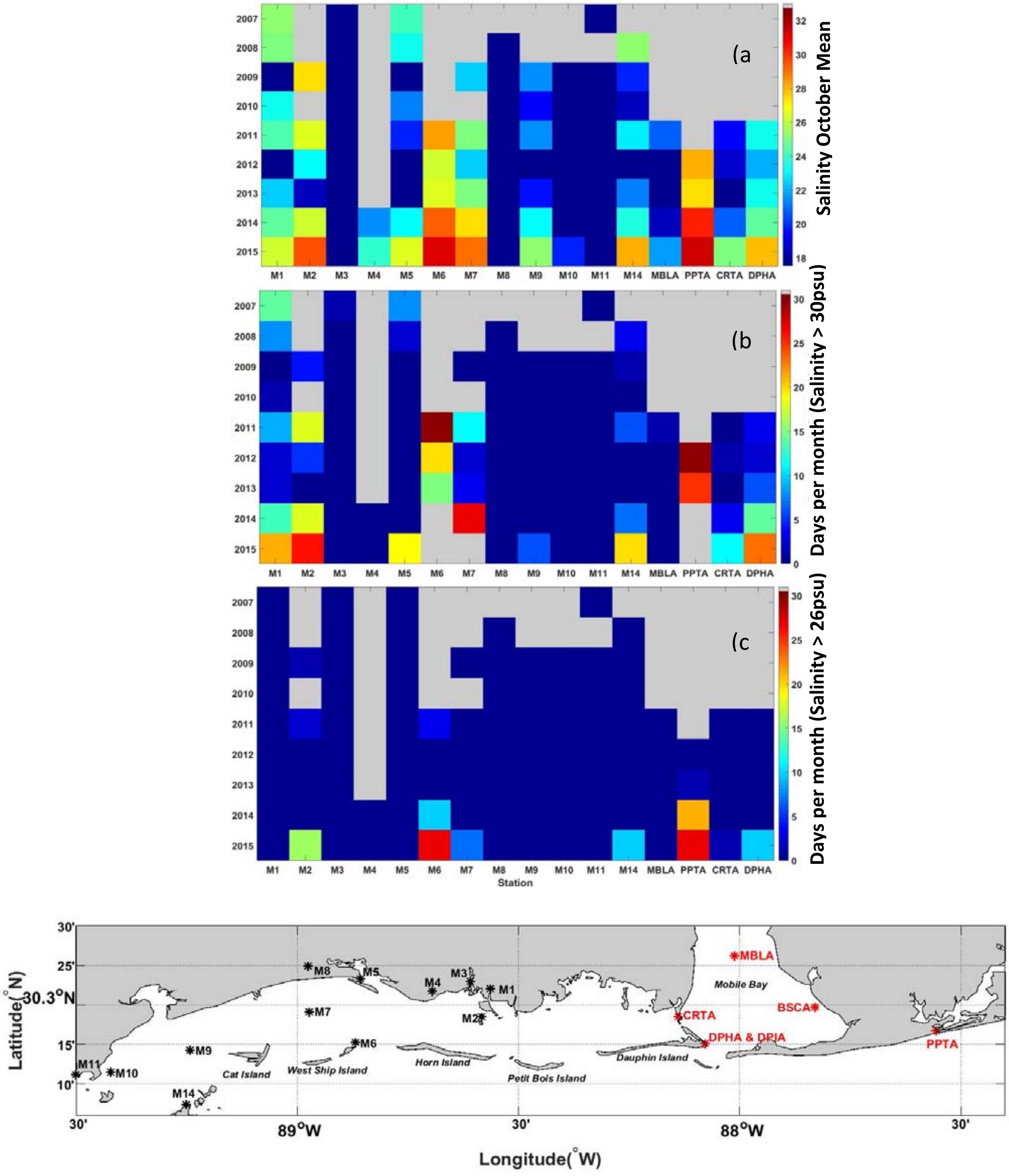

Figure 7. a) October mean salinities from 2007 to 2015 at the MDMR/USGS and NOAA/NDBC stations. Number of days when the October mean salinities exceed b) 30 psu c) 26 psu at all the stations. Gray areas indicate no data. d) Study area showing station locations.

DPHA at Dauphin Island is exposed to saline offshore waters via the exchange through the Mobile Bay Main Pass while PPTA at Perdido Pass is already located at the Gulf of Mexico coastline directly exposed to the inner-shelf waters. While the monthly mean salinity is an indicator of how salinity intensity, it is also important to know for how long salinity exceeded a certain threshold. Figure 7(b) shows the number of days in October in which salinity exceeded 30 psu. It is clear that 2015 had the most number of days, especially at those stations with the highest monthly mean salinities mentioned above. For M6 and PPTA, the salinity exceeded 30 psu for over 25 days in October 2015, followed by M2 where the salinity exceeded the 30 psu threshold for at least 15 days. At M7, M14 and DPHA, measured salinity exceeded 30 psu for at least 10 days in October 2015 and did not exceed this threshold in any of the other years with available salinity measurements.

Some stations, e.g. M3, M4, M8, M10, M11 and MBLA, were never exposed to salinities above 30 due to proximity to freshwater sources, therefore a lower salinity threshold of 26 psu was tested at all stations between 2007 and 2015. Figure 7(c) shows that the salinity values exceeded 26 psu at least at one station each year but the exceedance frequency was the highest in 2015. Measured salinity exceeded the 26psu threshold more frequently in October months of 2014 and 2015. It was found that the salinity exceeded this value for most if not all days in the month of October at the only open water station PPTA. The exceedance ratio was also high at M6 and M7, followed by M2, DPHA and M14. While the salinity never exceeded 30 psu at M1 and M5, it exceeded 26 psu for more than two weeks at M1 and M5. Figure 7 highlights that October 2015 was different than earlier years and that the salinity in all these coastal stations were higher than usual within the 9-year time-period of 2007 to 2015.

3.3. Ocean color data

The anomaly analysis using the NCOM salinity and the salinity exceedance analysis on the in-situ measurements demonstrated that October 2015 was a high salinity event at multiple stations across the system from Mobile Bay to western Mississippi Sound. Satellite ocean color chlorophyll-a imagery was used to determine the corresponding surface biological response associated with the anomalous surface salinity conditions, over the broader region. MODIS-Aqua October monthly chlorophyll-a anomaly fields were calculated for the Mississippi Bight from 2003 to 2015 and shown in Figure 8. The October 2015 monthly chlorophyll-a anomaly has a negative anomaly (less chlorophyll-a than the monthly climatology) across the entire Mississippi Sound except only very near the Mississippi river outlets in the Bird Foot Delta. The only other year with negative chlorophyll-a anomaly to such a great extent was 2003. The other years at least have a positive anomaly either outside the Mississippi Sound on the shelf or inside the Sound. The reason for most years to have positive chlorophyll-a anomaly either inside the Mississippi Sound or just south of the barrier islands is probably high chlorophyll-a associated with the freshwater sources inside the Sound and plume waters coming out of the estuarine system. Figure 9 shows the October monthly chlorophyll-a anomaly of each year along transects (Fig. 1; red lines) inside the Sound [Fig. 9(a)] north of the barrier islands and outside the MMS [Fig. 9(b)]. Ocean color data clearly shows that October 2015 has the largest negative chlorophyll-a anomaly both inside and outside the Mississippi Sound. It is important to notice that 2015 is not the only year with such high negative chlorophyll-a anomaly (-4.0 to -5.0 mg/m^3) at both transects. October 2003 had a similar chlorophyll-a anomaly.

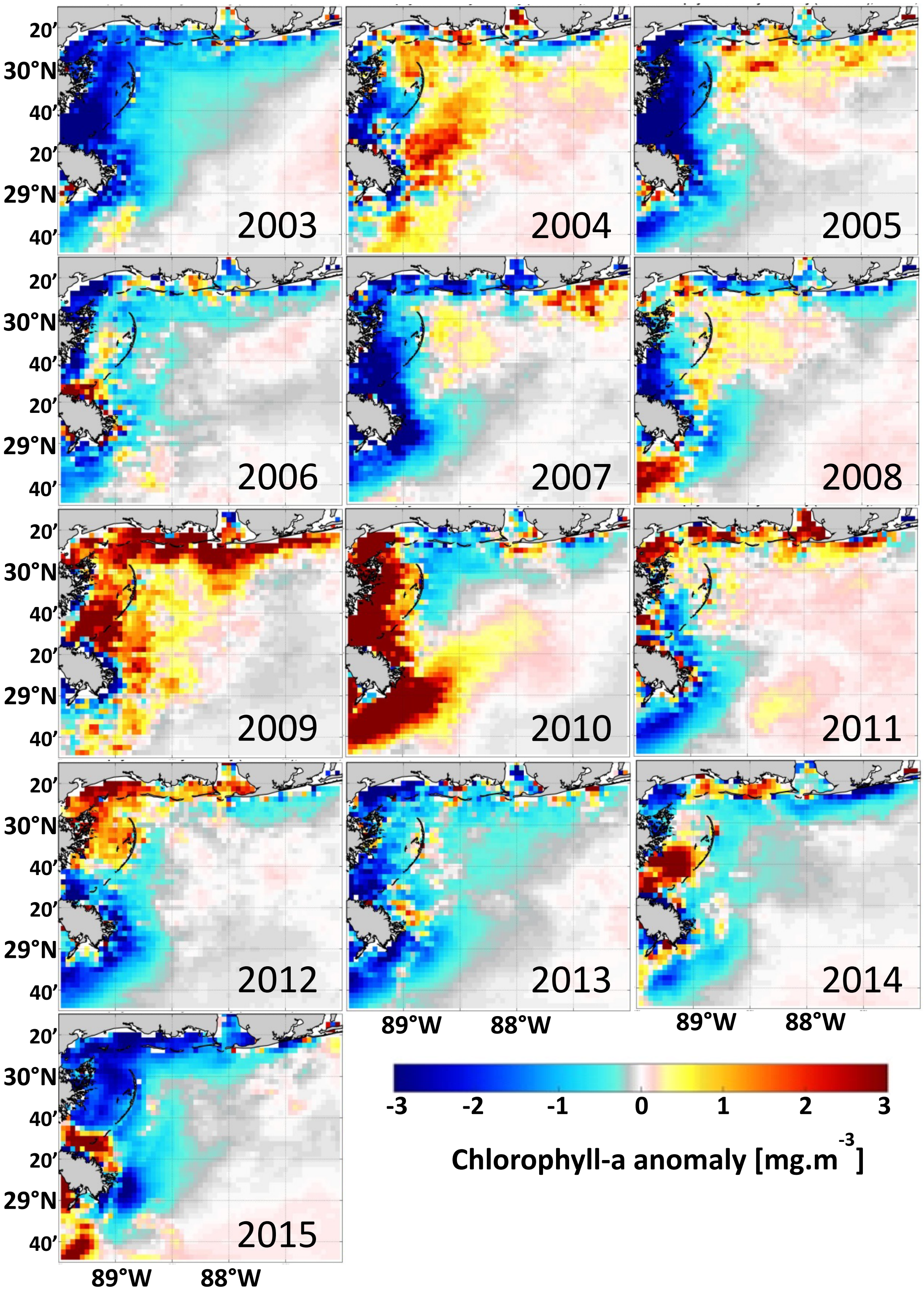

Figure 8. October monthly mean MODIS chlorophyll-a anomaly in the Mississippi Bight from 2003 to 2015.

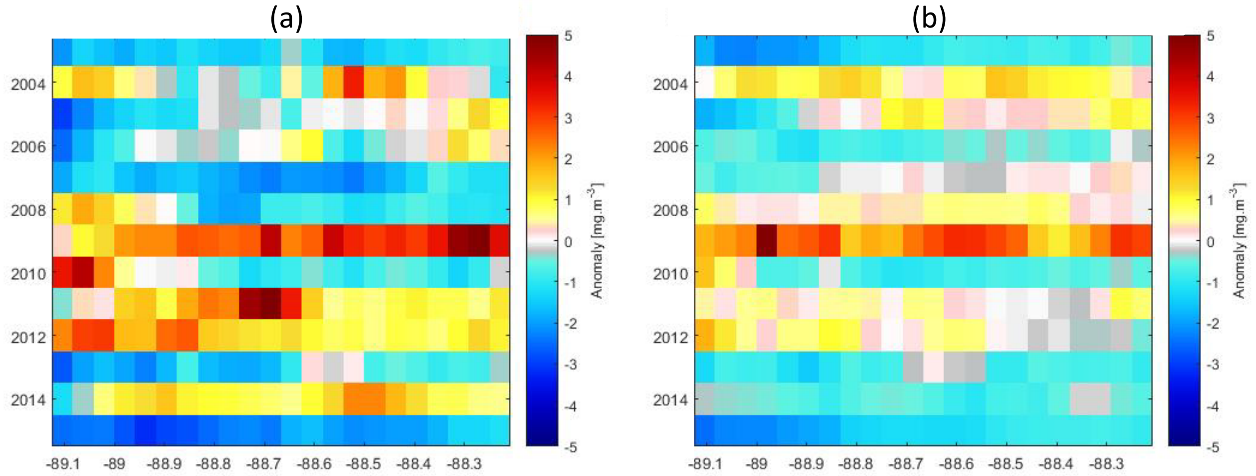

Figure 9. October monthly mean MODIS chlorophyll-a anomaly from 2003 to 2015 along a transect a) inside the Mississippi Sound, b) outside the Mississippi Sound. See Figure 1 for transect locations.

While chlorophyll-a anomaly is generally positive inside the Sound due to freshwater dominance that brings sediment and nutrients, it is generally negative outside the Sound due to offshore water dominance. October 2007 and 2013 had low chlorophyll-a anomalies (-1.0 to -3.0 mg/m^3) inside the Sound similar to October 2015, but not necessarily as negative chlorophyll-a anomaly as October 2015 outside the Sound. So, the negative chlorophyll-a anomaly outside the Sound may be attributed to the fact that the shelf was covered by low chlorophyll-a/less turbid offshore saline waters outside the Sound in October 2015 and the estuarine low salinity-high chlorophyll-a and turbid waters were not flushed out of the Mississippi Sound preventing the formation of high chlorophyll-a plumes during most of the month.

A one-way analysis of variance (ANOVA) was performed on the October monthly mean values to see the difference in chlorophyll-a anomaly by year followed by a multiple comparison test on the monthly mean chlorophyll-a anomaly to determine which pairs of group means were significantly different. Outside the Mississippi Sound, the October 2003 anomaly was the only one similar to October 2015 and all the other years were significantly different. Inside the Mississippi Sound, the multiple year comparison showed that October 2003 and October 2007 were similar to October 2015 with low chlorophyll-a. The other 10 years were found to be significantly higher chlorophyll-a than 2015, but October 2013 was statistically similar to October 2015 in transect lines both inside and just outside the Mississippi Sound.

3.4. Meteorological and hydrological data

It is important to understand the forcing mechanisms that generated the high positive salinity anomaly along with the low negative chlorophyll-a anomaly in October 2015. For this reason, the meteorological data (i.e., wind, water level) and hydrological data (i.e., discharge from freshwater sources into the Mississippi Sound and Mobile Bay) were analyzed to understand the balance between high salinity/low chlorophyll-a offshore waters and the low salinity/high chlorophyll-a freshwater sources.

The role of wind forcing was assessed using a a correlation analysis between the wind measured at Orange Beach Buoy (Fig.1; OB) and the adjusted water level (i.e., inverse barometer effects removed) and salinity data at the Dauphin Island station (Fig.1; DPIA). The component of the wind forcing with the maximum correlation was determined by calculating a lagged correlation between wind vector component contribution at 5° intervals and the scalar parameter of interest (water level or salinity) during the month of October. The highest correlations between the wind component and water level were along the orientation of 290-330°/110-150° (i.e., NW/SE axis) with r-values of 0.90-0.93 with lags of 12-23 hours. Similarly, the highest correlations between the wind component and salinity were along the orientation of 315-350°/135-170° (i.e., NNW/SSE axis) with r-values of 0.80-0.92 with lags of 0-2 hours. These results are consistent with the combined effects of coastal Ekman circulation driving coastal set-up and set-down via along-shelf wind forcing as well as direct wind forcing from the north/south component in the shallower coastal areas where the Ekman boundary layers would be expected to overlap (i.e., water is being directly pushed onshore contributing to the coastal setup or setdown). The wind-driven changes in coastal water level result in estuarine-shelf exchange that alter the estuarine salinity as observed. Salinity is somewhat more sensitive to the N/S component as indicated by the more NNW/SSE orientation and shorter lag time (i.e., direct wind response would be expected to be faster than the local Coriolis timescale). This correlation analysis shows that the wind forcing was the primary driver of the low frequency salinity variability during this time period and that wind generally from the Southeast quadrant are favorable for high salinity intrusion events.

The correlation analysis (above) showed positive correlation between wind and salinity in the 40-215° interval with decreasing correlation for directions larger than 180°. Given that Southerly to Easterly winds could drive salinity intrusions, the wind from the 45-180° direction is considered to be favorable for forcing the transport of saline offshore waters towards all the barrier islands around the Mississippi Sound including the N-S oriented Chandeleur islands. In particular, thirteen years (2013-2015) of wind measurement data for the month of October at Dauphin island station (Fig.1; DPHA) were analyzed. An important factor to consider is the wind persistence for a non-stop consecutive time. Consecutive winds in certain directions will force saline offshore waters towards the Mississippi Sound and Mobile Bay as well as prevent estuarine waters to flow out of the Sound and Mobile Bay. We found that the number of consecutive hours in Octobers since 2003 with the winds within the 45-180° interval was the highest in 2015 with 204 consecutive hours. This is approximately an 8.5-day time period between October 19 and 27, 2015. October 2013 winds follow with 143 consecutive hours, October 2004 with 132 and October 2007 with 122 consecutive hours of wind within the favorable 45-180° interval. The October monthly chlorophyll-a anomaly for 2003 and 2007 were statistically similar to October 2015, however the October 2013 salinity anomaly was not as high as 2015. Unfortunately, there were no salinity measurements available from 2007 to compare.

It is not only the persistence of wind from favorable directions but also the strength of the wind that will impact the intensity of forcing. Therefore, wind roses were created for those time periods when the wind at DPHA station were consecutively within the 45-180° interval to visualize the directional spread within the interval along with the wind speed as shown in Figure 10. The time period in which the wind was within the 45-180° interval is shown below the wind rose of each year. The wind speed exceeded 15 m/s only in October 2015 (Fig.10; at the bottom), 2004 and 2006; and for all these years wind was from E-SE for more than %50 of the favorable wind window. While the wind speed was high in 2006, the number of consecutive hours was lower (64 hours). On the other hand, 2004 winds were strong but Figures 8 and 9 indicate that this was a high chlorophyll-a year possibly due to high freshwater discharge both from the Mississippi River onto the shelf and/or from other sources into the Mississippi Sound.

Figure 11 (a) shows the river discharges measured at USGS stream gages at Pearl, Pascagoula, Alabama and Mobile Rivers (see Table 1 for station locations). In 2015, the river discharge was lowest in August, September and November at all river systems in the area. Both, the Pearl and Mobile rivers are a good indicator of the variability of freshwater input intensity in our region because they of their discharges into the Mississippi Sound and Mobile river, respectively. Therefore, the October discharge from 2007 to 2015 for those two rives were analyzed in Figure 11(b) to 11(i). October 2009 was not shown in Figure 11 due to extremely high discharge offsetting the y-axis. Measurements from the Pascagoula and Alabama rivers were not shown in Figure 11 due to their similarity to Pearl and Mobile river discharges, respectively.

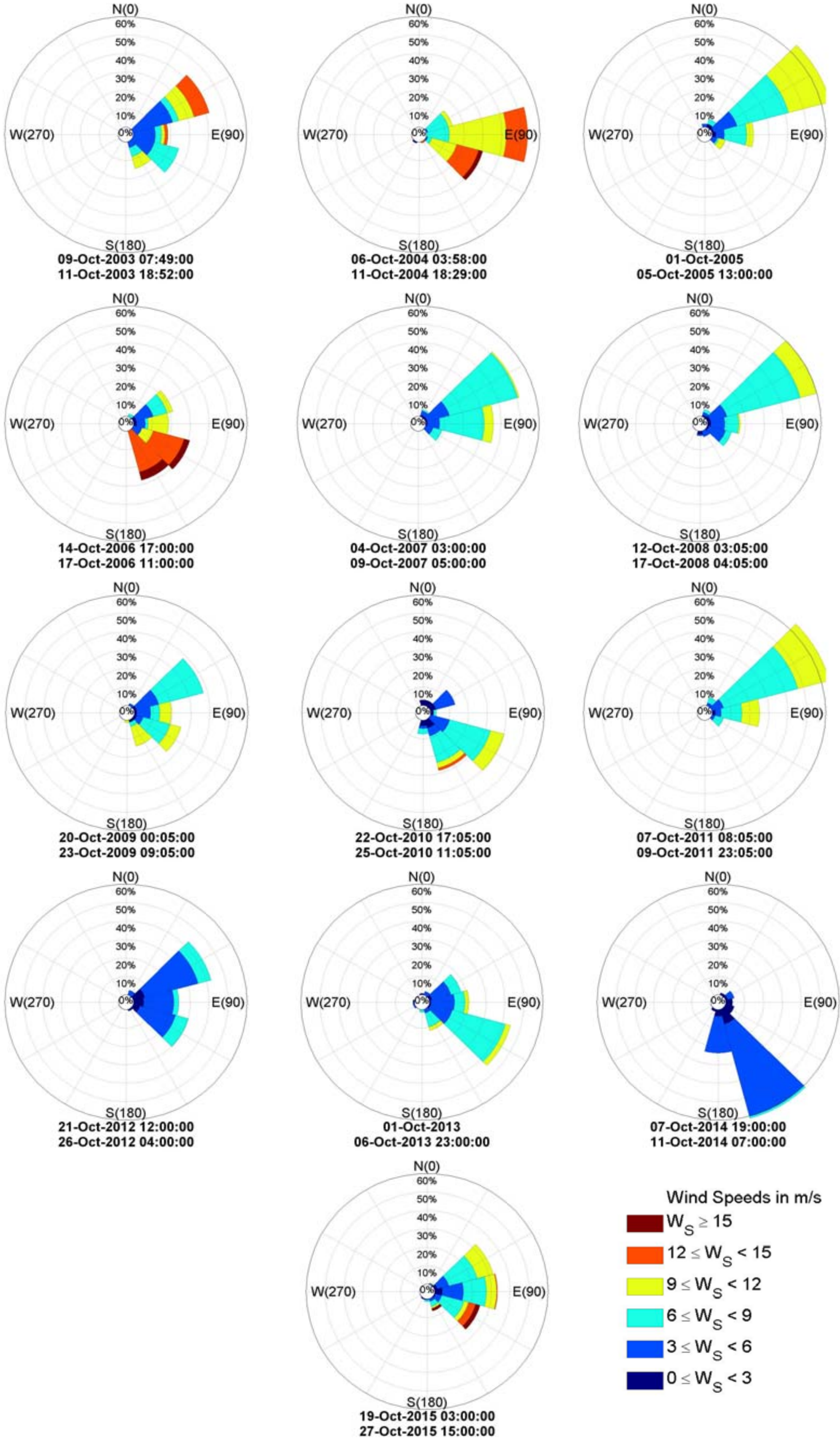

Figure 10. October wind roses from 2003 to 2015 during the time windows when the wind was uninterruptedly from the [45-180°] direction interval.

The discharge at Pearl River was seasonally low and around 50 m^3/s for almost all years and generally less than 250 m^3/s for Mobile River. Mobile River showed higher fluctuations within October 2015, however discharge variations were similar for both rivers. At Pearl River, October 2007 and 2010 had the lowest discharges along with 2015 until discharge peaks after passage of T/S Patricia remnants in late October 2015. At Mobile River, the discharge was very low between October 19 and 26, 2015 but the lowest October discharge year was 2010, followed by 2011. While high freshwater input into the Mobile Bay and Mississippi Sound is expected to decrease the likelihood of having elevated salinities inside the estuarine system; similarity in the intensity of discharge for all years implies that the low rainfall and low discharge in the area were not a significant contributing mechanism for the increased salinities inside the Mississippi Sound and Mobile Bay while the wind over the area is the primary driver for the inflow event.

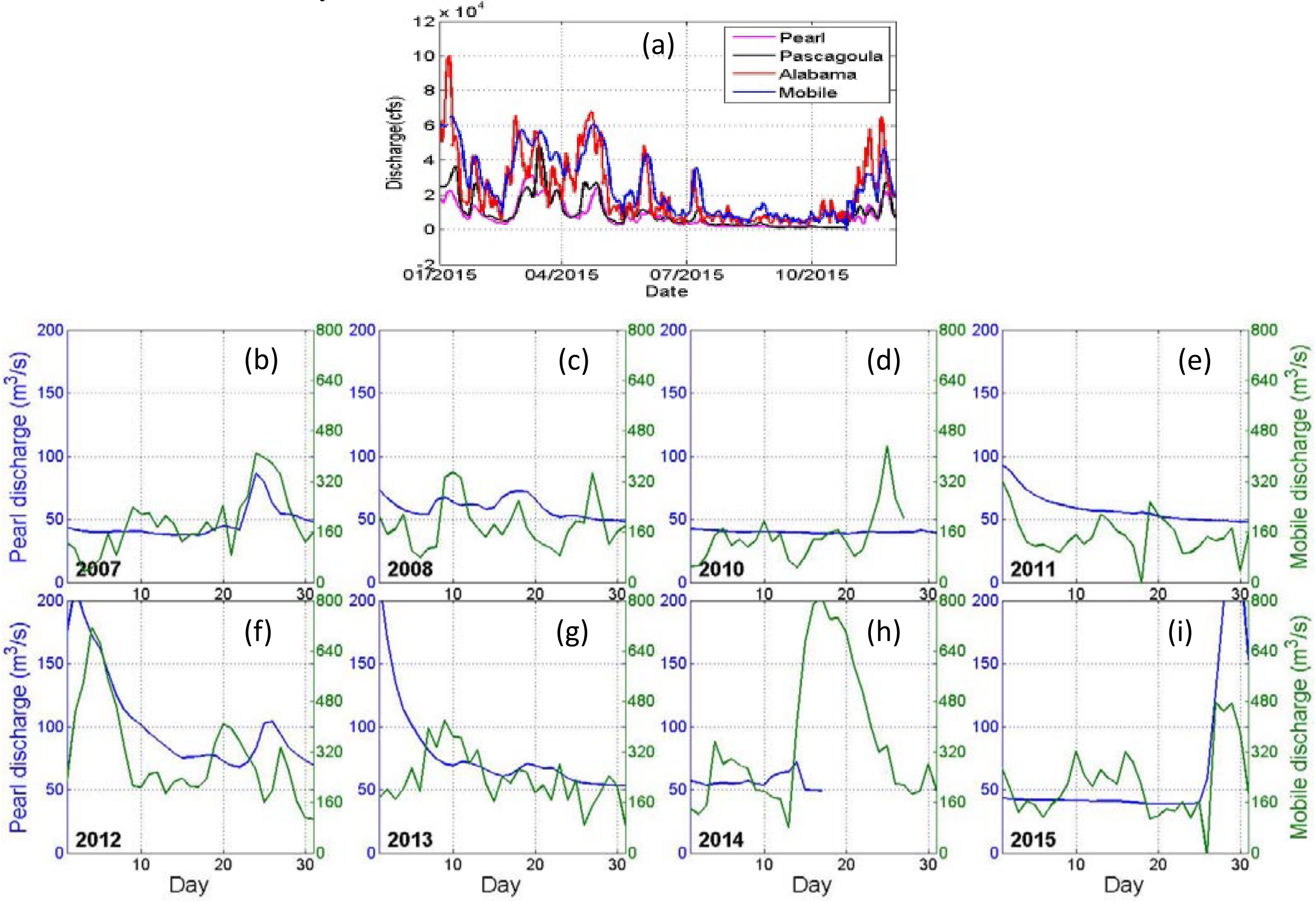

Figure 11. (a) Calendar year 2015 discharge measurements at Pearl, Pascagoula, Alabama and Mobile rivers. (b) to (i) October discharge measurements at Pearl River (blue) and Mobile river (green) from 2007 to 2015.

4. Conclusion.

This study brought model forecast products, in-situ measurements, and satellite imagery data together to study an episodic strong and persistent inflow and intrusion of high salinity offshore Gulf of Mexico waters into the Mississippi Sound and Mobile Bay estuarine systems. In-situ measurements showed elevated salinity measurements at coastal stations for an extended period (from October 18 to October 27) before the T/S Patricia's remnant passage. Monthly anomalies of salinity, temperature and water level were calculated from 2011 to 2015 in the Sound. All stations inside the Mississippi Sound had the highest positive salinity anomalies during October 2015 suggesting an excessive influx of saline shelf waters into the Sound. Model predictions of surface salinity and current fields showed an inflow of shelf waters into the estuarine system mainly via the Mobile Bay Main Pass due to strong easterly/southeasterly currents on the shelf. Patricia's remnants in late October further enhanced the positive salinity anomaly. This strong inflow into Mobile Bay possibly prevented the flushing until the passage of Patricia's remnants and several cold fronts.

MODIS-Aqua monthly chlorophyll-a anomalies were calculated from 2003 to 2015 using monthly means and climatology to define the biological response to the physical processes in before the passage of Patricia's remnants. The October 2015 chlorophyll-a anomaly had the lowest (negative) anomaly both inside the Mississippi Sound and outside on the Mississippi Bight shelf indicating a reduced biological activity in near-surface waters. A multi-comparison test of all the October chlorophyll-a monthly anomalies revealed that all years except 2003 were significantly different than 2015 for both inside and outside the Mississippi Sound. The chlorophyll-a anomaly for October 2007, showed a similar chlorophyll anomaly to 2003 and 2015 inside the Mississippi Sound. Unfortunately, the limited salinity dataset for 2007 does not allow us to make a definitive conclusion, however the low chlorophyll-a anomaly could be due to low discharge and weaker westward transport (NCOM model current data for 2007 not shown). The anomaly analysis on both in-situ measurements and satellite imagery combined with the model forecast fields indicated that the high salinity offshore waters were brought onto the entire Mississippi Bight shelf and the currents transported them into the estuaries where both low salinity estuarine waters and high salinity shelf waters were transported west due to strong easterly currents. A salinity exceedance analysis at all stations showed that October 2015 had the highest salinity records at many stations across the Mississippi Sound showing that this episodic event was a system-wide event.

An analysis on the hydrology and meteorology of the study area showed that the river flow was seasonally low during the time of the shelf water intrusion event before it peaked due to the heavy precipitation of the Patricia's remnants and subsequent cold fronts. The inflow event preceding the passage of T/S Patricia's remnants followed by Patricia's wind shift allowed the flushing of the estuarine waters onto the shelf creating plumes on the inner-shelf and mid-shelf accompanied with strong mixing and resuspension due to the storm. The highest correlation between wind and salinity was found for the wind from [45-180]° direction interval. The correlation between wind and water level was also high in the interval showing that the coastal set-up and the rise in October 2015 were mainly due to onshore shelf wind forcing. Easterly, southeasterly and southerly winds were persistent in October 2015 during the 8-day time period leading to this wind shift. An analysis on the uninterrupted wind from [45-180]° direction for all years showed that October 2015 had the longest duration for this wind interval which is possibly favorable to create currents that will allow the influx of shelf waters into Mississippi Sound and the blockage of estuarine waters in the Sound.

After the DWH oil spill event, special attention has been directed to the circulation and dynamics near susceptible costal ecosystems such as the estuaries within the Mississippi Bight. Their valuable fisheries and nursery habitats could be negatively impacted or even collapse in the case of toxic oil/dispersant or harmful algal blooms events. The Mississippi Sound and Mobile Bay are river discharge dominated systems, although the exchange with saline Mississippi Bight Shelf waters is tide-dominated and occurred frequently on short-time episodic events. Results show that the Mississippi Sound and Mobile Bay are not only limited to short-time episodic events (hours to few days), but strong and persistent (>10 days) inflow of saline Mississippi Bight Shelf waters occur. October seems to be a favorable month for extended intrusion of offshore waters type of event, so special attention needs to be considered for an oil spill during this time frame. The results conclude that Mississippi Sound was exposed to elevated salinities for over 10 days due to intrusion of shelf waters during this October 2015 event, which if happened in the case of oil spill this could be detrimental to the coastal habitats and local fisheries.

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