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Stratification variability in a lagoon system in response to a passing storm

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Abstract

Shallow lagoon systems with limited river flow and precipitation are often regarded as being well-mixed; however, stratification can occasionally occur in shallow lagoons in response to intense river runoffs and precipitation. Understanding the stratification behaviors of a shallow lagoon system is critical for future environmental assessment and management strategies. Thus, in this study, stratification and mixing mechanisms in a shallow lagoon system (the Maryland Coastal Bays) were investigated on an episodic scale during Hurricane Sandy (2012) by using a numerical model. The strength of stratification (Brunt-Väisälä frequency, N in s^{-1}) in the lagoon system varied spatially; and was determined by river flow, precipitation, winds, and remote forcing. During the pre-Sandy period (October 25–28, 2012), the bays were relatively mixed without sufficient river flow and precipitation. Driven by intense river flow from the northern creeks (peak: 82.47 $m^3 s^{-1}$), high precipitation (peak: 3.29×10^{-6} $m s^{-1}$), and strong storm winds (mean: 12.15 $m s^{-1}$) during the Sandy period (October 28–31, 2012), the water column in the northern creeks of the bays became stratified (mean N^2: ~ 0.01 s^{-2}). During the post-Sandy period (October 31–November 3, 2012), the St. Martin River among the northern creeks showed strong stratification (mean N^2: ~ 0.03 s^{-2}) due to weaker winds (mean: 5.70 $m s^{-1}$) and residual high river flow and precipitation from the Sandy period. The wind was found to be the most dominant source of mixing in the bays, while remote forcing and wind regulated the stratification near the Ocean City Inlet.

Stratification in estuaries, which has been investigated by both field observations (Peters 1997; Stacey et al. 1999; Holleman et al. 2016; Sengupta et al. 2016) and numerical modeling (Lerczak and Geyer 2004; Wang et al. 2011; Hetzel et al. 2015; Ralston et al. 2017), has been a subject of continuous research interest due to its significant influence on estuarine hydrodynamics and ecosystems (Murphy et al. 2011; Ralston and Geyer 2019). In shallow lagoon systems with limited river flow, intermittent turbulent mixing caused by winds and tides results in a lack of persistent or seasonal stratification, and these lagoon systems are often regarded as being well-mixed (Defne and Ganju 2015). However, salinity/temperature-induced stratification can occur occasionally in shallow lagoon systems during periods of relatively high river flow, rainfall, and solar radiation events (Cousins et al. 2010; Staehr et al. 2017). Though the dominant mixing mechanisms vary considerably in such lagoon systems (Gale et al. 2006), winds or tides can be the major mixing mechanisms in different regions of lagoon systems and these forcing mechanisms depend on the specific local conditions.

Previous studies have identified the main mixing mechanisms for several shallow lagoon systems around the world. Gale et al. (2006) investigated the vertical mixing processes in Wamberal Lagoon, which is located along the southeast coast of Australia, for open (maximum depth: 2 m) and closed (maximum depth: 3.5 m) states during a 3-month observational study. Their study found that rainfall causing the vertical salinity differences was the dominant stratification source due to limited river flow. In addition, the mixing mechanisms varied between the closed and open states. Both wind-induced and tidal mixing were the dominant processes that regulated vertical mixing when the lagoon system was open, while the wind was the dominant mixing mechanism when it was closed. Cousins et al. (2010) conducted a comprehensive study of vertical turbulent mixing rates and density structures based on a 2-yr-long observational dataset in Rodeo Lagoon, a choked, non-tidal, shallow coastal lagoon (maximum depth: 1.5–2.5 m) located in California. This study revealed that wind was the dominant driver of turbulent mixing in Rodeo Lagoon.

Hurricanes bring intense river flow, high precipitation, and strong winds along coastal shelves, causing a significant

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

perturbation in estuarine hydrodynamics (Du and Park 2019; Liu et al. 2020) and ecosystems (Peierls et al. 2003; Munroe et al. 2013; Gobler et al. 2019). Shallow lagoon systems are heavily influenced by relatively small but intense river flow caused by hurricanes, which results in low salinity in the lagoon systems (Steward et al. 2006). Meanwhile, strong storm winds also generate mixing that destratifies the water column (Cho et al. 2012). However, it is still unknown whether stratification can occur in coastal shallow lagoon systems on such episodic events with intense river flow, high precipitation, and strong storm winds. Moreover, if stratification occurs, many other questions regarding stratification remain unanswered, including "what is the spatial distribution of stratification in specific lagoon systems?", "what are the main mixing drivers in shallow lagoon systems during the passage of hurricanes?", and "is the stratification in shallow lagoon systems mainly salinity-induced or temperature-induced?". Answering these questions will help future environmental assessment and management strategies.

This study is designed to improve our knowledge of the storm-induced stratification behaviors and mixing mechanisms of a shallow lagoon system (i.e., the Maryland Coastal Bays) in response to a passing hurricane (i.e., Hurricane Sandy, 2012). The Maryland Coastal Bays are a restricted shallow lagoon system (~ 1–2 m) adjacent to the Atlantic Ocean with generally limited river flow (Wang et al. 2013). However, this lagoon system was severely affected by strong storm winds, intense river flow, and precipitation during Hurricane Sandy (2012) (Blake et al. 2013). Therefore, the Maryland Coastal Bays serve as a good site to examine stratification in shallow lagoon systems in response to extreme weather events. In this study, a state-of-the-art, finite-volume, and three-dimensional hydrodynamic model was used with a model nesting approach to investigate the response of stratification behaviors and mixing mechanisms in the Maryland Coastal Bays to Hurricane Sandy (2012).

Methodology

Study area

The Maryland Coastal Bays, with two unique inlets (the Ocean City Inlet in Maryland and the Chincoteague Inlet in Virginia), are a restricted shallow lagoon system (~ 1–2 m) located behind the barrier island of the Delmarva Peninsula (Fig. 1; Boynton et al. 1996; Wazniak et al. 2005), that support important habitats for commercial fish species including summer flounder (*Paralichthys dentatus*), blue crab (*Callinectes sapidus*), and black sea bass (*Centropristis striata*), and play an important role in maintaining the ecosystem balance of the

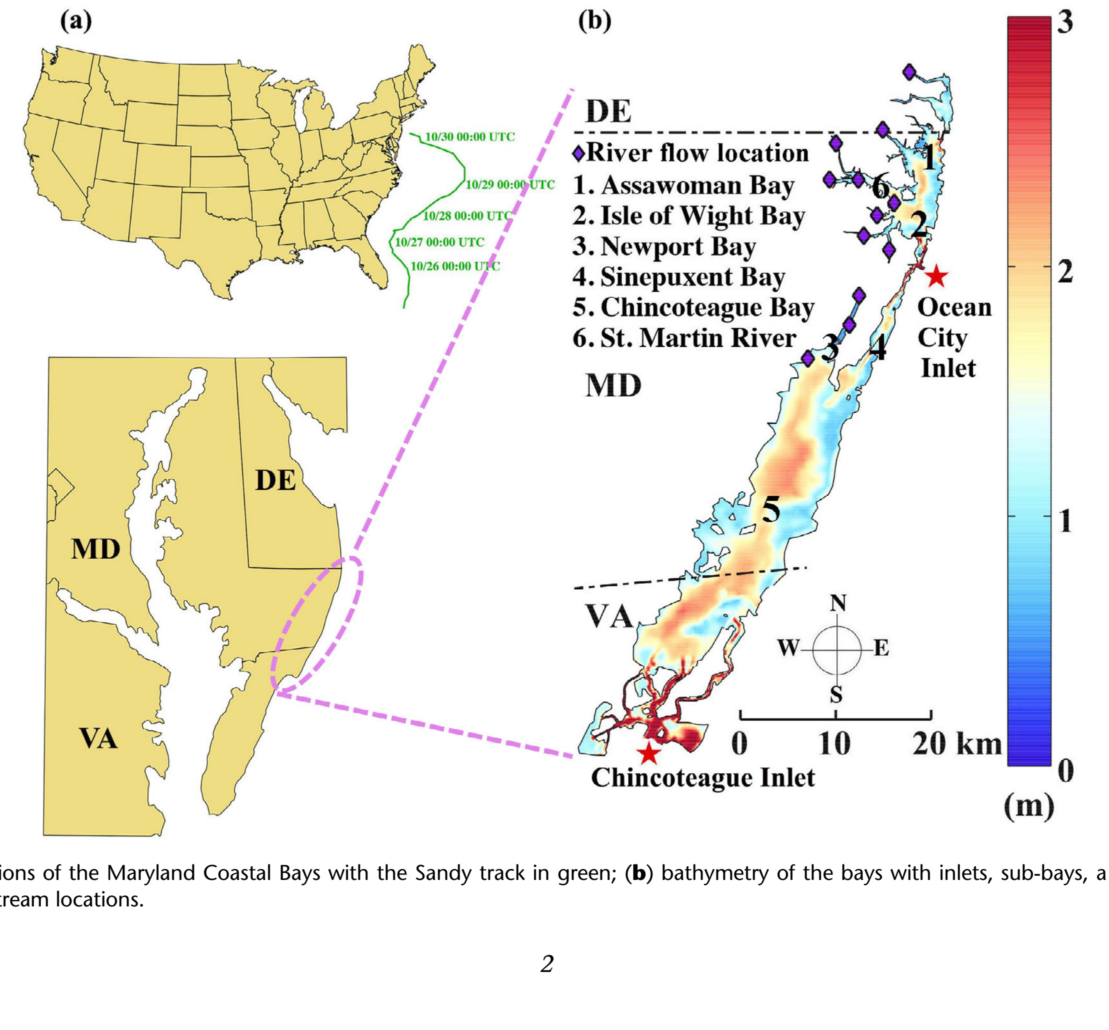

Fig. 1. (**a**) Locations of the Maryland Coastal Bays with the Sandy track in green; (**b**) bathymetry of the bays with inlets, sub-bays, a river name, and important creek/stream locations.

lagoon (Love et al. 2009). The bays include five sub-bays and one major river: Assawoman Bay, Isle of Wight Bay, Sinepuxent Bay, Newport Bay, and Chincoteague Bay, which occupies the largest portion of surface area of the Maryland Coastal Bays, and the St. Martin River (Fig. 1b). The two inlets display different inlet orientations, widths, and depths (Fig. S1e,f in Supporting Information). Tidal flushing plays a vital role in the inlet hydrodynamics (Boynton et al. 1996; Kang et al. 2017). Tidal range is found to be greater at the inlets with 1 m, and it decreases to ~ 0.2 m within the bays (Nowacki and Ganju 2018). Winds aligned with the shape of Chincoteague Bay have a great impact on the inlet exchange dynamics (Kang et al. 2017). Most parts of the bays show relatively high salinity (> 25) except in the creek areas where freshwater flow dominates (Wang et al. 2013). In this study, we defined the creeks and sub-bays toward the north of the Ocean City Inlet as the northern creeks and northern bays, respectively.

Reviews of hurricane climatology in the Maryland Coastal Bays

Hurricane Isabel (2003)

Hurricane Isabel (hereinafter referred to as Isabel) made landfall as a Category 2 hurricane near Drum Point on the North Carolina Outer Banks on September 18, 2003, and had a great impact on the Chesapeake Bay regions. However, its

Table 1. Designs of the numerical experiments.

Case name	Wind	Remote forcing	River flow	Precipitation
Sandy	On	Nested	On	On
No_W	Off	Nested	On	On
No_RF	On	Off	On	On

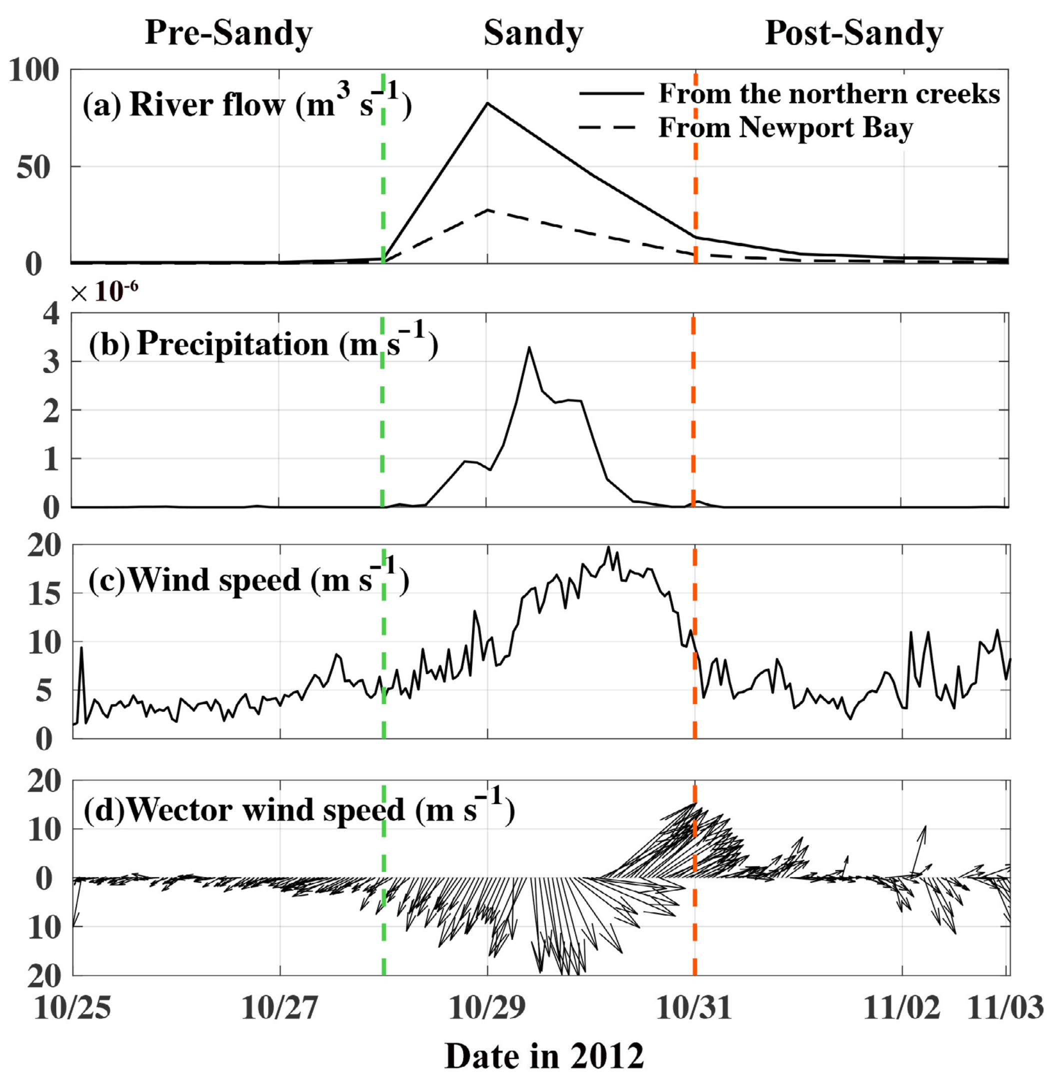

Fig. 2. Time series of (**a**) river flow; (**b**) precipitation; (**c**) wind speed; (**d**) vector wind speed in the Maryland Coastal Bays during the passage of Sandy.

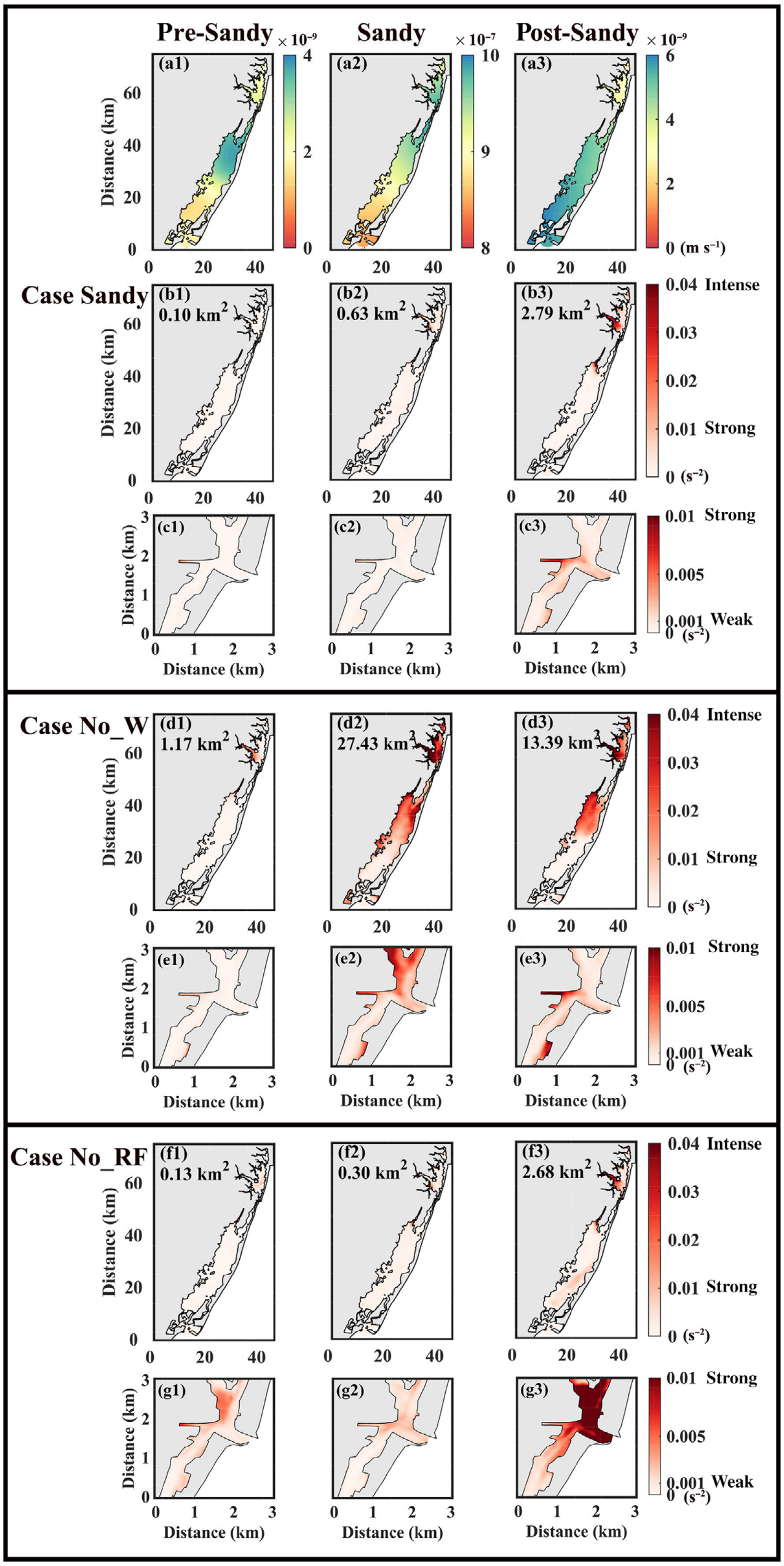

Fig. 3. (**a1–a3**) Spatial distribution of the mean precipitation and (**b1–b3**; **c1–c3**; **d1–d3**; **e1–e3**; **f1–f3**; **g1–g3**) spatial distribution of the mean stratification (N^2) with corresponding stratification-affected areas in various cases during the passage of Sandy. (**b1–b3**; **d1–d3**; **f1–f3**) and (**c1–c3**; **e1–e3**; **g1–g3**) are for the Maryland Coastal Bays and the Ocean City Inlet, respectively.

effects were weaker along the Maryland shorelines. Isabel generated 0.6–1.2 m storm surges along the Maryland shorelines with 101.60–177.80 mm rainfall in east-central Maryland (Beven and Cobb 2004). No observational wind data were available for the Maryland Coastal Bays during the passage of Isabel.

Hurricane Irene (2011)

On August 27–28, 2011, Hurricane Irene (hereinafter referred to as Irene) moved northward along the U.S. East Coast and passed over the Maryland Coastal Bays. Winds gusted up to 19 m s^{-1}, and a 0.7 m storm surge was recorded at the Ocean City Inlet from the National Ocean Service gauge. Although the maximum rainfall reached 45.72 mm for the nearby watershed, the average rainfall in the Maryland Coastal Bays during the passage of Irene was only 6.60 mm, which indicates that the bays were spared the heavy rainfall that other regions received (Eyes on the Bays, Maryland Department of Natural Resources 2011).

Hurricane Sandy (2012)

Hurricane Sandy (hereinafter referred to as Sandy) was one of the most destructive hurricanes in U.S. history, which also brought huge impacts to the Maryland Coastal Bays. Sandy developed in the Caribbean Sea on October 22, 2012, passed through the Mid-Atlantic Bight, and made landfall as a Category 1 hurricane on the New Jersey coast on October 29, 2012 (Fig. 1a; Beudin et al. 2017). According to observational data, the National Ocean Service gauge at the Ocean City Inlet measured a storm surge of 1.32 m with a maximum observed wind gust of approximately 25.72 m s^{-1}. This storm surge had the worst impact along the eastern shore of Maryland since Hurricane Gloria in 1985, destroying a large portion of a 30.48 m fishing pier in Ocean City (Blake et al. 2013). During the passage of Sandy, the heaviest rainfall (127–177.80 mm) among the Sandy-impacted areas occurred in the eastern shores of Maryland, Virginia, and southern Delaware, causing intense river flow into the Maryland Coastal Bays (Blake et al. 2013).

Impacts on wind speed, storm surge, and rainfall in the Maryland Coastal Bays during Sandy were found to be much stronger compared to other hurricanes recorded in this area. For that reason, Sandy was chosen to study the stratification behaviors of the Maryland Coastal Bays in response to a severe passing storm.

Model description and validation

This study applied the Finite Volume Community Ocean Model (FVCOM; Chen et al. 2006) used by Kang and Xia (2020) to investigate the Sandy-induced stratification behaviors in the Maryland Coastal Bays. FVCOM accurately follows the irregular coastline and complex bathymetry of the bays using unstructured horizontal grids and vertical sigma coordinates. The Smagorinsky turbulent closure parameterization was used to solve the horizontal turbulence mixing, and the vertical turbulence mixing was determined by the Mellor-Yamada level 2.5 turbulent closure model. Detailed model settings (with a model nesting method to provide the necessary remote forcing for storm surge simulation) and simulation performances of the hydrodynamic responses of the Maryland Coastal Bays to Sandy were addressed by Kang and Xia (2020).

Table 2. Stratification level.

Stratification level	N^2 values range (s^{-2})	Condition
Negligible	10^{-5}–10^{-3}	Mixed
Weak	10^{-3}–10^{-2}	Relatively mixed
Strong	>0.01	Stratified
Intense	>0.04	Highly stratified

Designs of the numerical experiments

Considering the importance of the heavy rainfall during Sandy and its potential influence on stratification, precipitation was taken into account in this study. The detailed external forcing, observational data, and the corresponding model performances with the inclusion of precipitation were fully addressed in Supporting Information. In the Maryland Coastal Bays, the major river flow mainly comes from the creeks (Fig. 1b). During the passage of Sandy, river flow from the northern creeks influenced salinity at the Ocean City Inlet, dropping it from 32 to 28 after October 31, 2012 (Kang and Xia 2020). In contrast, salinity at the Chincoteague Inlet was high and stable (~ 32) because of the long distance between the river and the inlet (Fig. 1b). Since salinity and temperature are crucial for determining stratification, this study mainly focused on the St. Martin River from the northern creeks and the Ocean City Inlet to elucidate the stratification characteristics and mixing mechanisms in the Maryland Coastal Bays.

Stratification and mixing mechanisms in the Maryland Coastal Bays were thoroughly examined during the passage of Sandy. Three periods were defined for this study, based on various river flow, precipitation, and wind characteristics (Fig. 2). From 00:00 UTC on October 25, 2012 to 00:00 UTC on October 28, 2012 (the pre-Sandy period), the bays received limited river flow and precipitation, and the mean wind speed was 4.12 m s^{-1} (Fig. 2). From 00:00 UTC on October 28, 2012 to 00:00 UTC on October 31, 2012 (the Sandy period), the bays were collectively driven by relatively intense river flow, high precipitation, and strong storm winds (Fig. 2). The river flow from the northern creeks was very high, reaching a peak of 82.47 m^3 s^{-1}, and the peak precipitation was 3.29×10^{-6} m s^{-1} (Fig. 2a,b). Strong storm winds reached a peak of 19.75 m s^{-1} with a mean of 12.15 m s^{-1} (Fig. 2c). From 00:00 UTC on October 31, 2012 to 00:00 UTC on November 3, 2012 (the post-Sandy period), river flow and precipitation decreased significantly, and winds became weaker with a mean of 5.70 m s^{-1} (Fig. 2). To understand the effect of wind and remote forcing on stratification in the bays, a series of numerical experiments were conducted with each individual external force (wind or remote forcing) (Table 1).

Results

Density stratification (Brunt-Väisälä frequency, N in s^{-1}) was expressed as the squared buoyancy frequency, $N^2 = -g\rho_0{}^{-1}(\partial\rho/\partial z)$. Here, g is the gravitational acceleration, ρ is the density determined from salinity and temperature, and $\partial\rho/\partial z$ is the density shear along the vertical coordinate.

Spatial distribution of stratification in the Maryland Coastal Bays

Stratification in the bays showed distinct characteristics during the passage of Sandy (Fig. 3b1–b3,c1–c3). The stratification levels used in this study are listed in Table 2. Here, based on N^2 values in the bays during the passage of Sandy, the 97th percentile N^2 value (0.04 s^{-2}) was defined as the critical value for intense stratification. The areas corresponding to this value were defined as the stratification-affected area.

During the pre-Sandy period, the entire bays were relatively mixed and the stratification-affected area was 0.10 km^2 (Fig. 3b1). A stratified water column (mean N^2: ~ 0.01 s^{-2}) occurred in the creeks as a result of intense river flow and precipitation during the Sandy period and the stratification-affected area increased to 0.63 km^2 (Fig. 3b2). Strong stratification (mean N^2: ~ 0.03 s^{-2}) was mainly concentrated in the St. Martin River and the stratification-affected area increased to 2.79 km^2 during the post-Sandy period (Fig. 3b3). This increase was caused by the combination of weaker winds, as compared to those during the Sandy period, and the residual effects of high river flow and

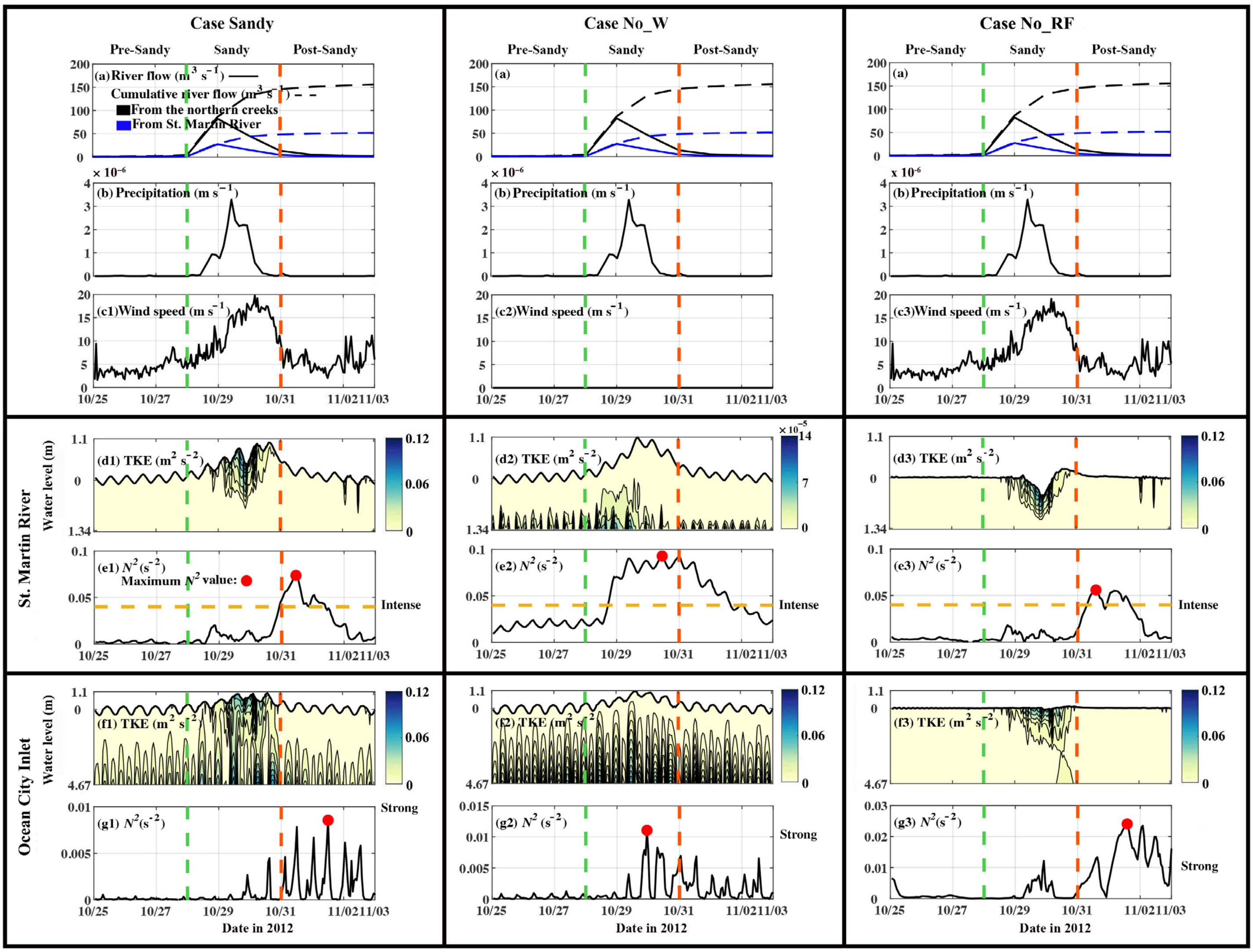

Fig. 4. Time series of (**a**) river flow, cumulative river flow from the northern creeks and the St. Martin River; (**b**) precipitation in the bays; (**c1**–**c3**) wind speed in the bays; (**d1**–**d3**, **e1**–**e3**) TKE and N^2 values at the St. Martin River; (**f1**–**f3**, **g1**–**g3**) TKE and N^2 values at the Ocean City Inlet in various cases during the passage of Sandy. Yellow dashed lines in (**e1**–**e3**) stand for the intense stratification level. Stratification levels are labeled in (**e1**–**e3** and **g1**–**g3**).

precipitation from the Sandy period (Fig. 2). Most parts of the southern Maryland Coastal Bays, particularly the main stem of Chincoteague Bay, showed negligible and weak stratification ($\sim 10^{-5}$–3×10^{-3} s^{-2}) during the passage of Sandy, owing to their shallow nature (~ 1–2 m) and limited river flow (Figs. 1b, 3b1–b3). The water column at the Ocean City Inlet was mixed with negligible stratification during both the pre-Sandy period (mean N^2: $\sim 10^{-5}$ s^{-2}) and the Sandy period (mean N^2: $\sim 10^{-4}$ s^{-2}), and showed weak stratification (mean N^2: $\sim 2 \times 10^{-3}$ s^{-2}) during the post-Sandy period (Fig. 3c1–c3). The long distance between the river and the Chincoteague Inlet resulted in a limited riverine impact on the Chincoteague Inlet, thus leading to a relatively mixed water column (mean N^2: $\sim 10^{-4}$ s^{-2}; peak N^2: 2.67×10^{-3} s^{-2}) during the passage of Sandy (figures were not included in this study since stratification at the Chincoteague Inlet was weak).

Without winds (case No_W), stratification strengthened around the creeks and the north of Chincoteague Bay (Fig. 3d1–d3). Correspondingly, the stratification-affected area expanded significantly, including the entire St. Martin River, the nearby Isle of Wight Bay, Newport Bay, and the north of Chincoteague Bay, overall reaching 27.43 km^2 during the Sandy period and 13.39 km^2 during the post-Sandy period (Fig. 3d2,d3). From the spatial precipitation distribution, heavy rainfall was mainly concentrated in the northern bays and north of Chincoteague Bay during the Sandy period (Fig. 3a2). Correspondingly, strong stratification (N^2: ~ 0.01–0.03 s^{-2}) occurred in the north of Chincoteague Bay during the Sandy and post-Sandy periods without the wind-induced mixing (Fig. 3d2,d3). Meanwhile, the combined effects of precipitation and peak river flow resulted in intense stratification in the northern creeks during the Sandy (mean N^2: ~ 0.07 s^{-2})

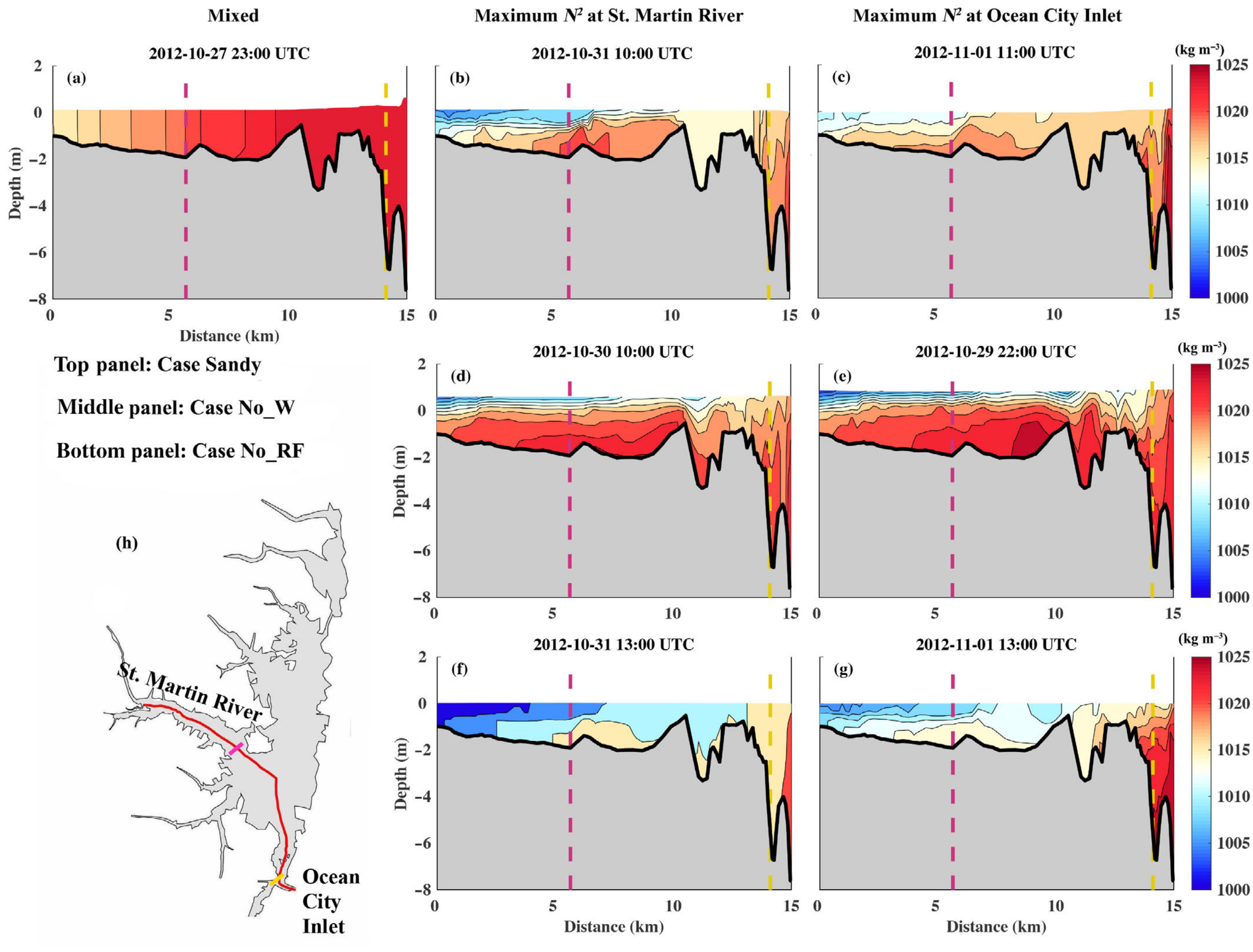

Fig. 5. Snapshots of the density profile along the St. Martin River-Ocean City Inlet transect: (**a**) in a mixed condition; (**b**, **d**, **f**; **c**, **e**, **g**) in the maximum N^2 condition at the St. Martin River and the Ocean City Inlet under different forcing. Pink and yellow lines in (**a**–**h**) mark the St. Martin River and the Ocean City Inlet areas, respectively.

and post-Sandy periods (mean N^2: ~ 0.05 s^{-2}) without the wind-induced mixing (Fig. 3d2,d3). Negligible stratification occurred at the Ocean City Inlet during the pre-Sandy period (mean N^2: ~ 10^{-4} s^{-2}), followed by weak stratification (mean N^2: ~ 2 × 10^{-3} s^{-2}) during the Sandy and post-Sandy periods in case No_W (Fig. 3e1–e3). The water column at the Chincoteague Inlet was relatively mixed (mean N^2: ~ 10^{-4} s^{-2}; peak N^2: 3.69 × 10^{-3} s^{-2}) without sufficient river flow from nearby in case No_W (figures were not included in this study since stratification at the Chincoteague Inlet was weak).

Without the effects of remote forcing (case No_RF), the spatial distribution of the stratification and stratification-affected areas were similar to those in case Sandy (Fig. 3b1–b3,f1–f3). The stratification-affected area in the bays corresponded to values of 0.13 and 0.30 km^2 in the pre-Sandy and Sandy periods, respectively (Fig. 3f1,f2). When winds became weaker during the post-Sandy period, strong stratification (mean N^2: ~ 0.03 s^{-2}) occurred at the northern creeks with a stratification-affected area of 2.68 km^2 (Fig. 3f3). Stratification at the Ocean City Inlet increased from ~ 10^{-4} s^{-2} during the pre-Sandy period and ~ 2 × 10^{-3} s^{-2} during the Sandy period to ~ 0.01 s^{-2} during the post-Sandy period (Fig. 3g1–g3). In contrast, the water column at the Chincoteague Inlet was relatively mixed (mean N^2: ~ 10^{-3} s^{-2}; peak N^2: 4.69 × 10^{-3} s^{-2}) without the impact of sufficient adjacent river flow (figures were not included in this study since stratification at the Chincoteague Inlet was weak).

Discussion

Considering the aforementioned spatial distribution of stratification in the Maryland Coastal Bays during the passage of Sandy, this study focused on the key stratification areas of the St. Martin River and the Ocean City Inlet. Thus, the time series of river flow, precipitation, wind speed, turbulent kinetic energy (TKE), and stratification (N^2) at these two locations were extracted to explain the detailed mixing mechanisms in the bays during the passage of Sandy (Fig. S1d,e in Supporting Information).

N^2 and mixing mechanisms at the St. Martin River

The St. Martin River was relatively mixed during the pre-Sandy period (mean N^2: 1.88 × 10^{-3} s^{-2}), due to limited river flow and precipitation (Fig. 4a,b,e1). Even though strong storm winds generated high TKE values (peak: ~ 0.12 m^2 s^{-2}) at the St. Martin River during the Sandy period, the water column became stratified (mean N^2: ~ 0.01 s^{-2}) because of the high cumulative river flow from the northern creeks and strong precipitation (Fig. 4a,b,c1,d1,e1). During the post-Sandy period, stratification at the St. Martin River intensified and reached a maximum value of 7.37 × 10^{-2} s^{-2} on October 31 at 10:00 UTC due to weaker winds (mean: 5.70 m s^{-1}) and residual effects of the high river flow and precipitation from the Sandy period (Fig. 4a,b,c1,d1,e1, and Fig. S5a in Supporting Information).

In case No_W, TKE at the St. Martin River significantly decreased and the maximum TKE value was only ~ 1.40 × 10^{-4} m^2 s^{-2}, owing to attenuated remote forcing from the coastal ocean to the bays (Fig. 4c2,d2). Correspondingly, the N^2 values increased and reached a maximum value of 9.28 × 10^{-2} s^{-2} (Fig. 4e2 and Fig. S5a in Supporting Information). This maximum N^2 value occurred on October 30 at 10:00 UTC, 24 h ahead of the date and time of the maximum N^2 value in case Sandy due to a lack of wind-induced mixing (Fig. S5a in Supporting Information). During the post-Sandy period, N^2 values slowly decreased under the effect of weak bottom tidal intrusions (Fig. 4d2,e2). However, when forced by winds in case No_RF, N^2 showed a similar variation pattern as it was forced by both wind and remote forcing in case Sandy (Fig. 4e1,e3). The maximum N^2 value (5.60 × 10^{-2} s^{-2}) occurred approximately 3 h later compared to that in case Sandy (Fig. 4e3 and Fig. S5a in Supporting Information). These results indicate that wind force was the dominant mixing source at the St. Martin River inside the bays. Our results also supported the outcomes of a similar study in Rodeo Lagoon, a choked, non-tidal lagoon system in California, which proved that wind was the dominant driver of mixing in that area (Cousins et al. 2010).

N^2 and mixing mechanisms at the Ocean City Inlet

A higher TKE occurred at the Ocean City Inlet bottom compared to that at the St. Martin River bottom (Fig. 4d1,f1). The water column at the Ocean City Inlet was well-mixed (mean N^2: ~ 10^{-5} s^{-2}) in the pre-Sandy period under the combined effects of weak rainfall and limited river flow from the northern creeks reaching the Ocean City Inlet (Fig. 4g1). During the Sandy period, high TKE values (~ 0.12 m^2 s^{-2}) aligned with storm winds at the surface of the water column (Fig. 4c1,f1). Additionally, tidal intrusion from remote forcing generated bottom mixing at the Ocean City Inlet (Fig. 4f1). These two mixing mechanisms combined their effects and extended over the entire water column, thus resulting in a well-mixed column at the inlet (mean N^2: ~ 10^{-4} s^{-2}; Fig. 4f1,g1). During the post-Sandy period, stratification at the Ocean City Inlet strengthened with a mean value of ~ 2 × 10^{-3} s^{-2}, due to high river flow from the northern creeks reaching the inlet and the residual effect of strong precipitation from the Sandy period (Fig. 4a,b,g1). Under weaker winds (mean: 5.70 m s^{-1}) and remote forcing, the N^2 values at the Ocean City Inlet oscillated between 0 s^{-2} and the peak value of 8.56 × 10^{-3} s^{-2} that occurred on November 1 at 11:00 UTC (Fig. 4c1,f1,g1, and Fig. S5b in Supporting Information).

Without wind-induced mixing (case No_W), TKE was mainly generated by remote forcing, and its maximum value dropped to ~ 0.06 m^2 s^{-2} (Fig. 4f2). The water column at the Ocean City Inlet remained well-mixed (mean N^2: ~ 10^{-4} s^{-2}) due to limited precipitation during the pre-Sandy period (Fig. 4g2). During the Sandy period, the corresponding N^2 values increased and oscillated between ~ 0 s^{-2} and a high value of 1.11 × 10^{-2} s^{-2}, under the effects of strong precipitation and high river flow from the northern creeks (Fig. 4a,b,g2). The maximum N^2 value reached $1.11 \times 10^{-2}\ s^{-2}$ on October 29 at 22:00 UTC at the Ocean City Inlet, 61 h ahead of that in case Sandy owing to a lack of sufficient wind-induced mixing from the surface of the water column (Fig. S5b in Supporting Information). Since only remote forcing occurred during the post-Sandy period, stratification values slowly dropped (Fig. 4g2).

Without the effects of remote forcing (case No_RF), the water column at the Ocean City Inlet was well-mixed (mean N^2: ~ $10^{-4}\ s^{-2}$) during the pre-Sandy period (Fig. 4g3). Strong wind-induced forcing during the Sandy period generated high TKE at the surface of the water column, resulting in a relatively well-mixed condition (mean N^2: ~ $2 \times 10^{-3}\ s^{-2}$; Fig. 4c3,f3,g3). During the post-Sandy period, N^2 values increased to a maximum value of $2.41 \times 10^{-2}\ s^{-2}$ on November 1 at 13:00 UTC, 2 h after the maximum N^2 value at the Ocean City Inlet in case Sandy (Fig. 4g3 and Fig. S5b in Supporting Information). This was due to the residual intense river flow from the northern creeks, strong local precipitation during the Sandy period, and a lack of sufficient mixing from both the surface and the bottom of the water column (Fig. 4a, c3,f3). From the time series of TKE and N^2 among various cases at the Ocean City Inlet, it can be concluded that both wind and remote forcing regulated the mixing at the Ocean City Inlet. This is consistent with the findings of Gale et al. (2006) who verified that wind-induced and tidal mixing were the primary agents that regulate the vertical mixing when Wamberal Lagoon was open.

Density, salinity, and temperature profiles along the St. Martin River-Ocean City Inlet transect

A mixed water column at the St. Martin River appeared during the pre-Sandy period in case Sandy (Fig. 4e1). A snapshot of the density profile along the St. Martin River-Ocean City Inlet transect on October 27, 2012 at 23:00 UTC showed a vertically mixed condition due to limited river flow and precipitation (Fig. 5a,h). The density profile snapshots along the transect on the date and time of the maximum N^2 value at the St. Martin River showed a distinct density difference between the surface (~ 1005 kg m^{-3}) and the bottom (~ 1020 kg m^{-3}) of the water column at the river in case Sandy (Fig. 5b). Similarly, distinct density differences between the surface and the bottom of the St. Martin River also occurred in cases No_W and No_RF (Fig. 5d,f). Similarly, the density profile snapshots along the transect on the date and time of the maximum N^2 value at the Ocean City Inlet showed different densities at various water depths at the inlet (Fig. 5c,e,g). Likewise, the snapshots of salinity and temperature profiles along the transect in response to different times showed a similar trend (Figs. S6, S7 in Supporting Information).

To evaluate the individual effects of salinity and temperature on stratification in the Maryland Coastal Bays, we assessed two different cases to calculate the density and the corresponding stratification: (i) constant salinity and variable temperature, and (ii) constant temperature and variable salinity. Stratification in response to Sandy was mainly salinity-induced rather than temperature-induced in the Maryland Coastal Bays, further discussion of which can be found along with Fig. S8 in Supporting Information.

Conclusions

This study investigated the response of stratification behaviors in a lagoon system (the Maryland Coastal Bays) to Hurricane Sandy (2012) using FVCOM based on a series of idealized experiments with the inclusion of precipitation. Stratification and mixing mechanisms in the Maryland Coastal Bays were examined during the pre-Sandy (October 25 00:00 UTC, 2012 to October 28 00:00 UTC, 2012), Sandy (October 28 00:00 UTC, 2012 to October 31 00:00 UTC, 2012), and post-Sandy periods (October 31 00:00 UTC, 2012 to November 3 00:00 UTC, 2012). The major conclusions of this study are as follows:

Stratification in the bays showed distinct characteristics during the passage of Sandy. During the pre-Sandy period, the bays were relatively mixed without sufficient river flow and precipitation. During the Sandy period, the water column at the northern creeks, particularly at the St. Martin River, became stratified (mean N^2: ~ 0.01 s^{-2}) due to strong storm winds (mean: 12.15 m s^{-1}), intense river flow (peak: 82.47 $m^3\ s^{-1}$), and strong precipitation (peak: 3.29×10^{-6} m s^{-1}). Stratification in the St. Martin River intensified (mean N^2: ~ 0.03 s^{-2}) during the post-Sandy period as a result of weaker winds (mean: 5.70 m s^{-1}) and residual intense river flow and precipitation from the Sandy period. Other parts of the bays showed negligible or weak stratification (N^2: ~ 10^{-5}–$3 \times 10^{-3}\ s^{-2}$) owing to their shallow nature (~ 1–2 m) and the limited river flow during the passage of Sandy. Strong precipitation and high peak river flow from the northern creeks caused weak stratification at the Ocean City Inlet. The response of stratification in the Maryland Coastal Bays to the passage of Sandy was mainly salinity-induced rather than temperature-induced. The wind was found to be an important source of mixing at the northern creeks inside the bays. In addition, wind and remote forcing also regulated the inlet vertical mixing at the Ocean City Inlet during the storm.

Limited and discrete observational data for the model validation, in particular, the lack of sufficient observational vertical and salinity data along the St. Martin River-Ocean City Inlet transect may be a potential limitation to the final results in this study. This is one reason why a comprehensive coastal ocean observation system is required in the Maryland Coastal Bays to provide more detailed and continuous data for future studies (Liu et al. 2015). The effects of stratification on the dynamics of biological processes (i.e., larval transport and water quality dynamics) in the Maryland Coastal Bays also require further study. The modeling method used in this study will be useful to study the hydrodynamic responses of other shallow bays and lagoon systems such as Great South Bay in New York, Barnegat Bay in New Jersey, Tampa Bay in Florida, and Perdido Bay in Alabama and Florida to hurricanes. Such studies would provide the hydrodynamic data for potential ecological studies in shallow lagoons and would be helpful for future environmental assessment and management strategies.

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Conflict of Interest

None declared.

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