Hurricane impacts on turbidity and sediment in the Rookery Bay National Estuarine Research Reserve, Florida, USA

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Abstract

The resuspension and transportation of sediments affect the nutrient or contaminants cycles in water column. Therefore, hurricane-induced sediment resuspension in coastal waters may cause environment impacts on coastal ecosystems. In this study, field observed data during a hurricane event from the Rookery Bay National Estuarine Research Reserve (Rookery Bay NERR), Florida, were studied. Based on the relationship between sediment and turbidity, variations of turbidity in the Rookery Bay NERR were discussed in this paper under the impact of the Hurricane Isaac in 2012. Time series analysis indicates that Hurricane Isaac causes the substantial increase of turbidity. Traditional direct regression analysis with raw data was found to result in poor correlation ($R^2 < 0.41$) between wind speed and turbidity due to the impacts of multi-factors in coastal waters of study region during hurricane. Then Hanning Filter was used to remove tidal effect, which shows some improvement of correlations ($R^2 > 0.6$) between wind speed and turbidity. Further improvement was made by introducing a phase factor to account for the

lag time between the peak turbidity and peak wind speed, which lead to further improvement of the regression equation between wind speed and turbidity. By using Hanning Filter and phase factor, the regression equation between turbidity and wind speed fits well with observations ($R^2 > 0.96$). Different lag time between wind speed and turbidity at different locations illustrated that wind had different effects on turbidity due to the locations and water depth. Based on the approximate empirical relationship between turbidity and sediment concentration, a regression equation between wind speed and sediment concentration was derived approximately. The equation could be applied to approximately estimate the sediment concentration using wind speed during hurricane, especially with the strong wind speed above 4m/s. It can be used to provide technical supports for sediment assessment and coastal zone research under extreme climate in the study region.

Key Words: Hurricane impacts; Sediment; Turbidity; Wind; Hanning Filter; Phase factor; Estuary

1. Introduction

Under the global climate change, extreme weather such as hurricanes occur more frequently with heavier rainfall and flooding, which may cause severe changes to the environment and ecosystem, especially in the coastal areas (Scavia et al., 2002). Coastal waters are areas representing the interactions between the human activities and natural components (Liu et al., 2011). Hurricanes occurred in coastal areas could cause extensive damages. Besides financial loss, their effects on the vegetation (Lucas & Carter, 2013), landscape (Sherman et al., 2013), hydrological indices (Dresback et al., 2013) and substance transportation (Samaras et al., 2014; Huang et al., 2011) may linger for years for coastal ecosystem to recover.

In coastal waters, sediment is an important factor for aquatic ecosystems and water quality. High levels of sediment concentrations can reduce the amount of light reaching lower depths and inhibit the growth of submerged aquatic plants. Consequently it will affect species which are dependent on them, such as fish and shellfish. In addition, bed sediment is sometimes the main source of nutrients and contaminants. The resuspension and transportation of sediments participate in chemical and biological processes, and influence the

nutrient or contaminants cycles in water column, which would have great impact on ecosystem and water environment. Sediment distribution in water could be affected by tide, wave, runoff, and topography. Shi (2010) pointed out that both estuarine circulation and tidal asymmetry were important factors during the fine sediment processes in Yangtze estuary. Hsu et al. (2013) investigated the transport of fine sediment across idealized intertidal flats through numerical simulation, and it was indicated that the sediment transport was landward on the lower and upper flat and seaward in the subtidal region. Landsat and MODIS satellite images and field campaigns were used by Min et al. (2012) to analyze the suspended sediment concentration changes caused by dyke construction in the Saemangeum area on the west coast of Korea. It was revealed that the sediment concentration increased continuously with the dyke construction progressed.

Wind is an important factor for sediment resuspension and distribution, especially the strong wind during hurricanes. In coastal areas, winds can affect sediment transport and beach morphological changes (Afsoos Biria et al., 2015; Kuiry et al., 2014), which may affect the aquatic ecosystems (Xie et al., 2015). Through sediment sampling in the Mississippi Canyon axis during Hurricane Georges (Ross et al., 2009), it was pointed out that the critical bed shear stress for sediment resuspension was exceeded approximately 50% under the hurricane influence, and the sediment resuspension was the five-fold increase in trap fluxes. Using the remote sensing model to investigate the impact of Hurricane Frances on total suspended solid concentrations in Apalachicola Bay, Chen et al. (2009) demonstrated that the average concentration in the Bay was twice higher 5-days after the passage of the hurricane and the maximum concentration increased almost three times during the hurricane, which indicates that strong winds during the hurricane caused strong sediment resuspension.

Some researchers have investigated the relationship between wind and sediment by numerical simulations. Guillou et al. (2011) studied the impact of a northerly wind-generated storm on the sediment resuspension in the Dover Strait and adjacent waters by numerical simulation using coupling of the wave propagation module SWAN and the three-dimensional circulation module COHERENS. Liu and Huang (2009) applied the sediment model coupled with a 3D hydrodynamic module in the Environmental Fluid Dynamics Code model to predict the wind-induced sediment transport in Apalachicola Bay during a hurricane event. Hu et al.

(2011) applied a coupled physical and sediment transport model to perform a one-year simulation of the hydrodynamic and sediment transport processes in the Pearl River Delta and its adjacent coastal sea. The suspended sediments load and distribution were simulated considering hourly winds as meteorological conditions. Booth et al. (2000) combined environmental modeling, remote sensing, and radioisotope techniques to investigate the annual transport of particles during resuspension, redistribution and deposition process in the Barataria Basin. Zuo et al. (2009) analyzed the effects of wind-driven waves on sediment transport in the Yangshan deep-water harbor of Shanghai by considering wind speed in the complex momentum equation in a two-dimensional numerical model. Based on the numerical model, sediment transport equation is solved considering the convection, diffusion and sources/sinks terms to represent sediment behaviors including deposition and resuspension. Although the results of numerical simulations are relatively generally reasonable, numerical studies and data required for model calibration and verification generally takes considerable cost and efforts.

Direct analysis of relationship between wind and sediment concentration from field observations is another way to investigate the influence of wind on sediment. Liu et al. (2014) carried out field observation to discuss the effect of wind on near-bed sediment transport in a heavily modified coastal plain estuary of Sheyang on the China coast. It's found out that the long-shore sediment transport induced by winds exceeds the cross-shore component near the river mouth bar which indicated the noticeable importance of wave-dominated coastal processes in shaping topographic features. Nowacki and Ogston (2013) investigated the sediment dynamics in the muddy tidal flats of southern Willapa Bay, Washington under a range of seasonal and meteorological conditions, including rain and wind events. It's demonstrated that wind speed was positively correlated with minimum suspended-sediment concentration. Hoque et al. (2010) found out that the suspended sediment concentrations were higher under the northeast monsoon than that under the southwest monsoon at tidal inlets of Salut Mengkabong Lagoon through field measurements, while the quantitative relationship between wind and sediment concentrations wasn't shown. However, it is usually expensive and difficult to obtain sufficient long-term data to cover the extreme weather events such as hurricanes through field observation.

On the other hand, turbidity, as an optical property of liquids, measures the scattering or absorption of light due to material suspended in solution. It includes inorganic and organic solids, and the total suspended solid (TSS) is always considered as the main component which makes the turbidity an indicator of sediment in water column because of this close relation. Some scholars have analyzed the correlation between wind and turbidity in shallow lakes (Zheng et al., 2015; Cozar et al., 2005). However, because direct and continuous measurement of sediment concentration is very expensive, it is generally difficult to obtain long-term time series data of sediment to analysis of wind effects during hurricanes. Turbidity can be measured continuously, and is often utilized to reflect the level of sediment concentration by some researchers. Linear regression equations between turbidity and sediment concentration in the form of Eq. (1) have been presented in several research articles (Wu et al., 2012; Ziegler et al., 2014; Liu & Huang, 2009).

$$C_s = a \cdot Tur + b \quad (1)$$

Where C_s is the sediment concentration (mg/L); and the Tur is the turbidity in NTU/FNU; the coefficients a and b are constants as shown in Table 1, which vary dependent on different sediment types in different study sites. Because continuing measurement of turbidity at a field station is available, continuing data for sediment concentration can be obtained by applying Eq.(1) to convert turbidity to sediment concentrations.

Table 1 Empirical linear regression equations between turbidity (FNU/NTU) and sediment concentration (mg/L)

$C_s = a \cdot Tur + b$			
Regions	Values of a	Values of b	References
Mae Sa River, Northern Thailand	1.502	0	(Ziegler et al., 2014)
Apalachicola Bay, USA	1.861	3.383	(Liu & Huang, 2009)
Changjiang estuary, China	2.46	-54.0	(Wu et al., 2012)

Located at the northern end of the Ten Thousand Islands on the Gulf coast of Florida, Rookery Bay National Estuarine Research Reserve (Rookery Bay NERR) represents one of

the few remaining undisturbed mangrove estuaries in North America. As a nearly pristine subtropical mangrove forested estuary, water environment is especially important in the Rookery Bay NERR. In addition, the Rookery Bay NERR is located in a specific disturbance regime of hurricanes. But up to now, the effects of hurricane on sediment distribution in Rookery Bay NERR is rarely researched. Some scholars focus on the vegetation in the Rookery Bay NERR. For example, [Sheridan \(1997\)](#) compared the benthic faunal abundances and biomasses in adjacent mangrove, seagrass and non-vegetated mud habitats through sampling in Rookery Bay. The DNA hybridization assay was used by [Goodwin et al. \(2005\)](#) to detect toxic algae in coastal waters of Rookery Bay NERR. [Cremer et al. \(2007\)](#) documented the diatoms and dinoflagellate cysts identified in a sediment core and a water sample taken in Rookery Bay. Few researches about the variations of the hydrological indices have been done in the Rookery Bay NERR. [Twilley and Chen \(1998\)](#) estimated the water budgets of two basin mangrove forests in Rookery Bay considering precipitation, tides, seepage, runoff and evapotranspiration. Mass balance and groundwater salinity were analyzed to discuss the connections between the soil of basin forests and adjacent upland ecosystems. Tidal circulation and salinity variations ([Zheng & Weisberg, 2010](#)) were addressed by a three-dimensional, baroclinic numerical circulation model FVCOM to assess the water properties of complex, multi-connected estuarine systems. Under different fresh water flow rates, the salinity distributions were quantitatively discussed. These researches have analyzed the hydrological and dynamic environment in Rookery Bay, but only salinity variation was discussed due to the change of fresh water inflow as the water quality index. [Donders et al. \(2008\)](#) presented a 300-year record of changes in the hydrological cycle from Rookery Bay to gather insights into the natural variability of the coastal ecosystems in Florida versus the effects of anthropogenic impact in the area. Palynological, diatom, and sedimentological were analyzed in a sediment core to reveal significant changes in past runoff and wetland development. The results also indicated that several hurricanes have impacted on southwest Florida during the past century. [Lammers et al. \(2013\)](#) used biomarkers from terrestrial and aquatic environments to reconstruct temperature, runoff, and aquatic productivity in Rookery Bay. It reflected both local and regional environmental changes during the past 300 years. It suggested that natural climate phenomena such as hurricane activity might have added to

ongoing processes during the twentieth century. In these researches, they used long term data to analyze the effect of climate on water environment in Rookery Bay. A thorough understanding of natural climate variability is required in order to assess the impact of climate change on coastal areas. But in fact, the available instrumental records are either too short or too limited to capture the full range of natural variability.

In this paper, effect of hurricane on sediment concentration (turbidity) was investigated during a hurricane event in Rookery Bay National Estuarine Research Reserve in Florida, USA. Observed hourly data of turbidity during a hurricane event were analyzed. Because direct use raw data results in poor correlation between wind and turbidity, different data analysis methods were investigated to find a better regression equation to characterize wind effects. After measured data were filtered to remove tidal signals, regression analysis was conducted to estimate correlations between wind and turbidity. In addition, a phase factor was introduced to represent the phase lag between wind and the turbidity (or sediment concentration), which led to substantial improvement of the regression relationship. Further discussion on wind effects on sediment concentration was conducted by approximately applying a turbidity-sediment regression equation, which was derived in a nearby estuary. Excellent correlations ($R^2 > 0.96$) between wind and turbidity (and sediment) indicate that the regression equations can be used as cost-effective tools for predicting hurricane effects on coastal ecosystems to support coastal environmental management under extreme climate condition. The analysis techniques used in this study can also be as a good reference for other study sites.

2. Study site

The study area is the Rookery Bay National Estuarine Research Reserve (The Rookery Bay NERR) designated in 1978. It is at the northern end of the Ten Thousand Islands in south-western Florida as shown in [Fig.1](#). The Rookery Bay NERR represents one of the few remaining undisturbed mangrove estuaries in North America. The total estimated surface area of open waters within the boundary is 28.33 km², 64 percent of the reserve. The remaining 16.19 km² are primarily mangroves, fresh to brackish water marshes, and upland habitats. Connecting to the Gulf of Mexico, the reserve is tidally influenced with average tidal range of

0.6m. The primary freshwater source is Henderson Creek which is located at the northeastern corner of the Reserve. The creek experiences salinity fluctuations depending on tide, season, and water release. The water flow from Henderson Creek is managed to control drainage of the Belle Meade Water District.

Fig.1 The path of Hurricane Isaac during August 21st- September 1st,2012

To observe and analysis water quality and meteorological conditions, a monitoring program has been applied in the Rookery Bay NERR by the Reserve System's Centralized Data Management Office (CDMO, <http://nerrs.noaa.gov/>). It provides accurate and useful data to capture variability of water quality in the reserve. The observation sites (Station No.1-5) in the Rookery Bay NERR are shown in Fig.2 including four water quality stations and one meteorology site. Also, data from one tide gauge-Station Naples(Station No.6) which is about 8kmnorthwest away from Rookery Bay NERR, and hydrological stations of a river and a canal (Station No.7-8) are utilized to analyze the influence of hurricane. Locations and contents of monitoring at every observation sites are listed in Table 2. Based on these measured data, hurricanes effects on sediment (turbidity) in the Rookery Bay NERR were discussed in this paper.

(a) Study region in south Florida

(b) Observation stations in the study region

Fig.2 Locations of study region and observation stations in the Rookery Bay National Estuarine Research Reserve (the Rookery Bay NERR)

Table 2 Locations and contents of monitoring stations

Station number	Station name	Location	Latitude (°N)	Longitude (°W)	Contents of monitoring
1	RKBLHWQ	Lower Henderson Creek	26.03	81.73	Water quality
2	RKBMBWQ	Middle Blackwater River	25.93	81.59	Water quality

3	RKBFUWQ	Faka Union Bay	25.9	81.52	Water quality
4	RKBFBWQ	Fakahatchee Bay	25.89	81.48	Water quality
5	RKBUHMET	Upper Henderson Creek	26.05	81.7	Meteorological
6	Station Naples	Coastal waters near Naples	26.13	81.81	Tidal elevation
7	Henderson Creek	Henderson Creek	26.03	81.41	River discharge
8	Faka Union Canal	Faka Union Bay	25.57	81.3	River discharge

3. Hurricane description

The period of study is during August 21st - September 1st, 2012 when the Hurricane Isaac made its landfall. Hurricane Isaac was a tropical cyclone that spent most of its life as a tropical storm but became a category one hurricane a few hours before making landfall in southeastern Louisiana (Berg, 2013). Hurricane Isaac had maximum sustained winds of 92.6km/h while the center moved parallel to the northern coast of Cuba toward the Straits of Florida, passing south of the Florida Keys. Tropical-storm-force winds affected the Florida Keys and South Florida in rain bands. Hurricane Isaac entered the southeastern Gulf of Mexico early on August 27th, moving more slowly toward the west-northwest and northwest. From the path of Hurricane Isaac (Fig.1), it shows that the hurricane passed waters near the Rookery Bay NERR during August 26th - 27th, 2012.

4. Field observations during Hurricane Isaac in 2012

4.1 Meteorology, hydrology and turbidity

Meteorological conditions including wind speed and precipitation were observed at Station No.5 in the upper Henderson Creek as shown in Fig.3 (a-b). The averaged wind speed was about 2.4m/s in this area. During August 21st - September 1st, the highest wind speed reached to 9.1m/s in response to Hurricane Isaac. The cumulative precipitation measured in millimeters over a 24 hour period also exhibited the influence of Hurricane Isaac. The largest precipitation was approximate 38mm/h and it also occurred on August 25th. Tidal elevations were recorded at Station No.6 by National Oceanic and Atmospheric Administration (NOAA). As shown in

Fig.3(c), the tidal range was about 1.0m-1.4m as usual. But it ran up to 1.69m on August 25th. It's found out that the greatest effect of Hurricane Isaac on this area appeared on August 25th, 2012.

Fig.3 Observed wind, rainfall, and tidal elevation in the Rookery Bay NERR during Hurricane Isaac in 2012

Discharges of the Henderson Creek and the Faka Union Canal were surveyed at Station No.7 and Station No.8 by the South Florida Water Management District (SFWMD). Mouths of these two runoffs are located inside the Rookery Bay NERR. In Fig.4 (a-b), it's found out that the discharges of both the Henderson Creek and the Faka Union Canal were very small. For the Henderson Creek, the averaged discharge was about $0.3\text{m}^3/\text{s}$ before the landfall of the Hurricane Isaac, while it became $0.6\text{m}^3/\text{s}$ after that. The peak of discharge appeared on August 28th with the value of $0.94\text{m}^3/\text{s}$. The maximum discharge of the Faka Union Canal was $23.5\text{m}^3/\text{s}$ on August 28th. Due to the influence of hurricane, the averaged discharge increased from $8.2\text{m}^3/\text{s}$ to $18.9\text{m}^3/\text{s}$. Although the discharges of both the Henderson Creek and the Faka Union Canal were relatively small, the floods lasted for more than two weeks after the hurricane landfall.

Fig.4 River discharges to the Rookery Bay NERR during Hurricane Isaac in 2012

Turbidity was observed at Stations No.1, 2, 3, and 4 spanned from northwest to southeast along coastline in the Rookery Bay NERR as shown in Fig.2. Variations of turbidity during Hurricane Isaac are shown in Fig.5 (a,b,c,d). We can see Hurricane Isaac lead to the increasing turbidity concentration. The general concentration of turbidity was below 20 FNU/NTU at Station No.1, while the maximum concentration was 70 FNU/NTU during the period of Hurricane Isaac. Within one week before Hurricane Isaac, turbidity concentration at Station No.1 was unsteady with some instantaneous peak value. Compared with Fig.3(a), it is feasibly related to the fluctuation of wind speed. The variation pattern of turbidity at Station No.2 was similar to that at Station No.1. The only different is that there had two peaks in the

distribution of turbidity during Hurricane Isaac at Station No.2. One appeared on August 21st and the other was on August 25th. The peak value on August 25th was in accordance with the distributions of wind speed and rainfall data. The largest concentration of turbidity at Station No.2, with the value of 182FNU/NTU, was almost twice as that at Station No.1. At Station No.3, which is located around the mouth of Faka Union Canal, the concentration of turbidity seemed not to be impacted by the increasing discharge of runoff. The peak of turbidity concentration (104FNU/NTU) on August 25th accorded with that at Station No.1 and Station No.2. It's resulted from the strong wind due to the Hurricane Isaac. The main effect of Hurricane Isaac was the obvious increasing turbidity concentration at Station No.4, too. The peak concentration of turbidity at Station No.4 was higher than that at Station No.3.

Fig.5 Observed turbidity concentrations (FNU/NTU) at different stations in the Rookery Bay NERR during Hurricane Isaac in 2012

4.2 Traditional simple regression method using raw data of wind speed and turbidity

We firstly examined the relationship between turbidity and wind speed using raw data. Regression analysis is a statistical process for estimating the relationships among variables. Fig.6(a,b,c,d) have shown the results of regression analysis using raw data at four stations. Although the best regression fits between turbidity and wind speed were found as cubic polynomial functions at all stations, the correlations between turbidity and wind speed were extremely poor. R^2 values were in the range of 0.1-0.45 as shown in Table 3. The root-mean-square error (RMSE) is a frequently used measure of the differences between predictions and the observations. According to the predicted turbidity by regression analysis using raw data, the largest value of RMSE was 22.26 at Station No.4, and the smallest value was 7.65 at Station No.1. The values of RMSE were 16.77 and 8.57 at Station No.2 and Station No.3, respectively. The high values of RMSE indicated the scatter between predicted regression data series and the observations. Although the R^2 values at Station No.1 and Station No.3 were relatively lower than those at other two stations, the predicted values were much closer to the observations.

Fig.6 Turbidity versus wind speed during the hurricane period by traditional simple regression method directly using raw data, which show poor correlation due to tidal effects

Table 3 Regress equations between turbidity and wind speed by traditional simple regression method directly using raw data from observations, which show poor correlation and high RMSE

$Tur = a_s \cdot V^3 + b_s \cdot V^2 + c_s \cdot V + d_s$						
Locations	a_s	b_s	c_s	d_s	R^2	RMSE
Station No.1	-0.143	2.037	-7.011	20.42	0.123	7.65
Station No.2	-0.229	3.537	-10.78	21.41	0.256	16.77
Station No.3	-0.075	1.522	-6.348	17.98	0.211	8.57
Station No.4	0.182	-0.284	-1.645	10.78	0.410	22.26

Note: R^2 is the correlation coefficient, RMSE is the root mean square error.

Regression analysis has been successfully used to display relationships between water quality indices in the lake or river with rare impact factors, but the study region in this paper is coastal waters where the raw data of turbidity was affected by too many factors such as tide, runoff, wind, especially tide. Also according to the RMSE values, the raw data were quite scatter under the impacts of multi-factors in coastal waters of study region during hurricane. Because of tidal effects, it indicates that the simple regression analysis using raw data can't reveal the relationship between wind speed and turbidity in coastal waters.

5. Enhanced regression analysis of wind effects on turbidity by integrating with Hanning Filter and phase factor

5.1 Regression analysis with Hanning Filter to remove tidal signals

Through the analysis, it's found out that the poor correlations between turbidity and wind speed resulting from the simple regression on raw data might be caused by the tide influence in coastal waters. In order to specifically find out the influence of hurricane on turbidity, the observed raw data were filtered within 24 hours to avoid the impact of tide using Hanning

Filter. Hanning Filter (Thomson & Emery, 2014) is a method for smoothing a sequence of numbers in order to approximate a low-pass filter. It produces an output which is a weighted average of continuous inputs as shown in Eq.(2). Hanning Filter is an efficient solution for filter approximation, which has been widely used in engineering signal processing (Kudela et al., 2015; Huet, 2012; Girault et al., 2010; Zhang et al., 2009; Wen et al., 2009).

$$y_i = \frac{\sum_{n=i-(n-1)/2}^{i+(n-1)/2} [x_i \times w(n)]}{\sum w(n)} \quad (2)$$

$$w(n) = 0.5 \times \left(1 - \cos\left(\frac{2\pi n}{N-1}\right)\right) \quad (3)$$

where x_i is the input data series with the number of N , n is filter length, $w(n)$ is the weight factor calculated by Eq.(3).

Filtered time series data of wind speed and turbidity were shown in Fig.7 and Fig.8, respectively. After filtering, the peak value of wind speed decreased from 9.1m/s to 6.4m/s in Fig.7. The tendencies of turbidity at four stations were shown without the pulsation due to the influence of tide in Fig.8. The wind induced variations of turbidity were clearly demonstrated after the data filtering. The peaks of turbidity occurred in accordance with the wind speed, and the values were also smaller than the raw data. And it's also found out that there had a short phase lag between the wind speed and turbidity. Because the turbidity results from wind-driven resuspension from bottom and transport into water column, there needs time to transfer the driven force during wind-hydrodynamics-suspension process. It is noticed that there still existed a peak in the distribution of turbidity at Station No.2 on August 21st after data filtering. It is probably due to the effect of runoff around this area. The impacts of wind on turbidity were greater at Station No.2 and Station No.4. Those two stations were located in relatively open areas where the hydrodynamics was easily affected by wind field.

Fig.7 Time series wind speed after 24-hour filtering using Hanning Filter to remove tidal effects

Fig.8 Time series of turbidity (FNU/NTU) after 24-hour filtering using Hanning Filter to remove tidal effects

Regression analysis with Hanning Filter is applied to estimate the relationships between wind speed and turbidity in coastal waters of study region. Fig.9(a,b,c,d) has shown the results of regression analysis with Hanning Filter at four stations. After data filtering, the relationships between the wind speed and turbidity concentration were found more apparently at all stations. The regression functions for the concentrations of turbidity and wind speed all fit in the type of cubic polynomial. As shown in Table 4, the highest value of R^2 was 0.962 appeared at station No.3 where the turbidity concentration intensively related with the wind during hurricane, but the value of R^2 were lower than 0.87 (0.605, 0.767, 0.864, respectively) at other three stations. The RMSE values became lower at all stations after Hanning Filter. The highest RMSE still appeared at Station No.4 with the value of 6.46, and the smallest value was 0.9 at Station No.3. At Station No.1 and Station No.2, the RMSE values were 2.61 and 3.63, respectively. The relatively higher R^2 and lower RMSE values indicated that the correlations between wind speed and turbidity have improved apparently using regression analysis with Hanning Filter, but the results at most stations were still not satisfied based on R^2 values.

Fig.9 Regression fit of turbidity versus wind speed at different stations during the hurricane period by data analysis method with Hanning Filter for 24-hour filtering to remove tidal effects (without phase factor)

Table 4 Regress functions between turbidity and wind speed after using Hanning Filter, which show improvement of correlation and reduction of RMSE

$Tur = a_s \cdot V^3 + b_s \cdot V^2 + c_s \cdot V + d_s$						
Locations	a_s	b_s	c_s	d_s	R^2	RMSE
Station No.1	-0.172	2.996	-13.54	31.99	0.605	2.61
Station No.2	-0.029	2.051	-9.459	25.64	0.767	3.63
Station No.3	0.315	-2.616	6.444	6.895	0.962	0.90
Station No.4	0.586	-3.297	3.858	9.823	0.864	6.45

Note: R^2 is the correlation coefficient, RMSE is the root mean square error.

According to the time series data in Fig.7 and Fig.8, the peaks of turbidity and wind speed didn't exactly appear at the same moment. As the driven force, wind affects hydrodynamic conditions such as wave and current in shallow waters. Wave and current, which cause the change of bottom shear stress, could control the bottom resuspension and affect the sediment or turbidity transportation in water column. During this process, not only wind speed but also wind duration has impact on sediment distribution. The time lag between wind speed increasing and sediment resuspension may cause the unsatisfied results in Fig.9.

5.2 Integrating regression analysis with Hanning Filter and phase factor

Considering the time lag between wind speed and peak sediment concentration, a phase factor was adopted to improve the regression analysis between wind speed and turbidity. Through the time series analysis of filtered data, the phase factor in the relationship between wind speed and sediment concentration was obtained at each station. And then the phase factor was introduced into the regression analysis.

Results of the integrating regression analysis with Hanning Filter and phase factor were shown in Fig.10. The turbidity concentrations fit by the cubic regression equations of wind speed very well with the high value of $R^2 (>0.96)$ and low value of RMSE (<3.40) at all stations by the enhanced method. It is manifested that peak of turbidity generally occurs later than that of wind speed because of the resuspension process in water column due to wind-driven force. Strong wind during hurricane lead to high concentration of turbidity with phase lag at all stations except Station No.3. Phase lag between turbidity and wind speed varied with locations. At Station No.4, it was consistent with this general feature, $T_{wind} = T_{tur} - 5.75 \text{ hours}$ (T_{wind} : time for wind speed; T_{tur} : time for turbidity). Station No.4 had the highest concentration of turbidity during hurricane period. The wind caused the hydrodynamics change and resuspension process which resulted in the increasing turbidity after 5.75 hours of phase lag. The phase lags between wind speed and turbidity at other stations were as following: $T_{wind} = T_{tur} + 0.0 \text{ hours}$ at Station No.3; $T_{wind} = T_{tur} + 8.0 \text{ hours}$ at Station No.2; $T_{wind} = T_{tur} + 11.0 \text{ hours}$ at Station No.1. There has no phase lag at Station No.3. It might be because that water depth at Station No.3 was relatively shallow and it didn't cost

much time for the suspended matters to suspend with wind. The peaks of turbidity appeared early than those of wind speed at Station No.1 and No.2, which mean the turbidity concentrations at these two stations were saturated before the occurrence of hurricane. The turbidities had already reached up to the maximum value before the occurrence of the largest wind speed. From the comparison of the turbidity levels at these stations, it's illustrated that the increment of turbidity driven by wind at Station No.4 was apparently higher than those at other three stations. The phaselag became larger from southeast to northwest along the coastal line. It related to both of the location and water depth. The effects of wind field on water column have distinctions at difference locations, and wind has more significant influence at stations with lower turbidity concentrations and shallow waters.

Fig.10 Regression fit of turbidity versus wind speed by data analysis method combining Hanning Filter and phase factor

The lines of regression function for the concentrations of turbidity and wind speed at four stations during the hurricane period were in the same format of the cubic equations as shown in Eq.(4). The constant coefficients a_s , b_s , c_s , d_s and phase factor t_0 (in hours) varied with locations as shown in Table 5.

$$Tur_{(t)} = a_s \cdot V_{(t+t_0)}^3 + b_s \cdot V_{(t+t_0)}^2 + c_s \cdot V_{(t+t_0)} + d_s \quad (4)$$

Where $Tur_{(t)}$ is the turbidity concentration (FNU/UTN) at time t , $V_{(t+t_0)}$ is the wind speed in m/s after t_0 hours phase factor between wind speed and turbidity which indicates the phase lag during wind-hydrodynamic-turbidity suspension process.

Table 5 Regress functions between turbidity and wind speed by integrating regression analysis with Hanning Filter and phase factor (t_0 in hours), which further increase the correlation coefficients

$Tur_{(t)} = a_s \cdot V_{(t+t_0)}^3 + b_s \cdot V_{(t+t_0)}^2 + c_s \cdot V_{(t+t_0)} + d_s$							
Locations	a_s	b_s	c_s	d_s	t_0	R^2	RMSE

Station No.1	0.268	-2.124	4.842	11.11	-11.0	0.987	0.47
Station No.2	0.472	-3.932	12.51	0.761	-8.0	0.978	1.53
Station No.3	0.315	-2.616	6.444	6.895	0.0	0.962	0.90
Station No.4	0.732	-5.032	10.77	-0.424	5.76	0.965	3.38

Note: R^2 is the correlation coefficient, RMSE is the root mean square error.

Comparisons of R^2 and RMSE values in different regression analysis are shown in Table 6. Because there has too many factors in coastal waters especially the tide, the correlations between turbidity and wind speed were completely poor using the raw data. After using 24-hours Hanning Filter to avoid tide influence, the correlations between turbidity and wind speed were increased with relatively higher R^2 and lower RMSE values at some stations. Then after introducing the phase factor, the excellent correlations were shown obviously. It's indicated that the enhanced integrating regression analysis with Hanning Filter and phase factor is an efficacious method to reveal the effect of wind on turbidity and estimate turbidity concentration under hurricane.

Table 6 R^2 and RMSE values between turbidity and wind speed under different data analysis methods, which show the substantial improvement by using Hanning Filter and phase factor

Station number	Traditional simple regression method using raw data		Regression analysis with Hanning Filter		Enhanced regression analysis with Hanning Filter and phase factor	
	R^2	RMSE	R^2	RMSE	R^2	RMSE
1	0.123	7.650	0.605	2.61	0.987	0.47
2	0.256	16.77	0.767	3.63	0.978	1.53
3	0.211	8.570	0.962	0.90	0.962	0.90
4	0.410	22.26	0.864	6.45	0.965	3.38

Note: R^2 is the correlation coefficient, RMSE is the root mean square error.

Because of the different hydrodynamic conditions, the phase factor t_0 varied with locations. To express the relationship of wind and turbidity in the whole Rookery Bay NERR, the line of regression function for the spatial averaged concentration of turbidity and wind speed was shown in Fig. 11. The averaged turbidity concentration could be fit ($R^2=0.988$)

by a cubic equation of wind speed in the period of hurricane in the Rookery Bay NERR:

$$Tur = 0.1746 \cdot V^3 - 0.2119 \cdot V^2 + 3.1899 \cdot V + 18.6054 \quad (5)$$

Fig.11 Regression fit of turbidity and wind speeds in hurricane after using the data analysis method combining Hanning Filter and phase factor

According to survey results published by Folger (1972), the sediments in the study region and the Apalachicola Bay are both fine sand. Due to the similar characteristics of sediments, the equation of turbidity and sediment in (Liu & Huang, 2009) as shown in Table 1 was adopted to estimate the relationship between sediment concentration and wind speed during hurricane. The approximate regression fit of sediment and wind speeds was shown in Fig.12. And a simple equation of sediment concentration (C_s , mg/L) versus wind speed (V , m/s) was approximately obtained as shown in Eq.(6). It can be used to estimate the sediment concentration using wind speed during hurricane.

$$C_s \approx 0.324 \cdot V^3 - 0.394 \cdot V^2 - 5.936 \cdot V + 38.00 \quad (6)$$

Fig.12 The approximate regression fit of sediment and wind speeds using the data analysis method combining Hanning Filter and phase factor. Sediment and turbidity relationship is based on the empirical equation by Liu and Huang (2009).

As shown in both Fig.11 and Fig.12, the relationships between wind speed and turbidity and between wind speed and sediment concentration were similar. Turbidity and sediment concentration were both positively correlated with wind speed. When the wind speed was lower than 4 m/s, the variations of turbidity and sediment concentration were very slight. While if wind speed was higher than 4 m/s, the increasing turbidity and sediment concentration were apparent. During Hurricane, the wind speed is usually higher than 4 m/s. Eq.(6) is a suitable method to simply estimate the sediment concentration variation during hurricane.

Through the integrating regression analysis with Hanning Filter and phase factor, it's

found out that turbidity could fit well by a cubic polynomial equation of wind speed with high value of R^2 and low value of RMSE. After introducing the linear relationship between turbidity and sediment, sediment concentration also can be estimated by an approximate regress fit of wind speed.

Although the turbidity and sediment concentration both fit well by a cubic polynomial equation of wind speed, the results basically based on the statistical analysis through the integrating regression analysis with Hanning Filter and phase factor. There may still have some limits considering the physical characteristics. For instance: when the wind speed is lower than 3m/s, the concentrations of turbidity or sediment are both slightly growing with the decreasing wind speed using this cubic polynomial equation (Fig.11 and Fig.12). In fact, relationships between wind speed and the surface wind-shear stress, and between bed shear velocity and bottom shear stress are in quadratic function in coastal area. Therefore, other two fitting equations between sediment concentration and wind speed: quadratic function and the power function, are compared with the cubic function as shown in Table 7 and Fig.13. It's clearly shown that results of quadratic function almost coincide with that of cubic function, while the former one has relatively lower R^2 and higher RMSE values. Result of the power function is rather poor with serious deviations. It is recommended that both the second and third order polynomial equations can be used to estimate sediment concentration using wind speed, especially the wind speed is higher than 4m/s.

Table 7 Comparisons of three fitting equations of sediment concentration and wind speed: cubic function, quadratic function and power function

No.	Three fitting equations	Equations	R^2	RMSE
1	Cubic function	$C_s \approx 0.324 \cdot V^3 - 0.394 \cdot V^2 - 5.936 \cdot V + 38.00$	0.988	1.67
2	Quadratic function	$C_s \approx 3.713 \cdot V^2 - 22.03 \cdot V + 57.40$	0.986	1.81
3	Power function	$C_s \approx 0.08 \cdot (V + 5)^{2.75}$	0.907	4.89

Note: R^2 is the correlation coefficient, RMSE is the root mean square error.

Fig.13 Comparisons of three fitting equations of sediment and wind speeds: No.1 cubic

function, No.2quadratic function and No.3 power function.

6. Conclusions

Under the global climate change, hurricanes occur more frequently and cause more severe damages. Influences of hurricane on sediment in the coastal waters are important for aquatic life and should be paid more attention. Located on the gulf coast of south Florida, the Rookery Bay National Estuarine Research Reserve is a nearly pristine subtropical mangrove forested estuary. Distributions of turbidity were discussed to evaluate the sediment variation under the impact of the Hurricane Isaac in 2012. Because traditional simple regression method can't satisfy the regression analysis between wind and turbidity due to the multi-factors in coastal waters, the integrating regression analysis of wind effects on turbidity with Hanning Filter and phase factor was applied. Excellent correlations between wind and turbidity were revealed using the enhanced method. According to the empirical equation between sediment and turbidity, a strong correlation between wind and sediment concentration was obtained which could be used to simply estimate the sediment concentration variation during hurricane.

Through the data analysis, it's found out that the highest wind speed reached to 9.1m/s from the averaged value of 2.4m/s in response to Hurricane Isaac. It caused a larger tidal range of 1.69m at Station No.6 on August 25th. And the largest precipitation was approximate 38mm/h. Peak discharges of Henderson Creek and the Faka Union Canal were also found during the hurricane period. Hurricane Isaac has led to the increasing turbidity concentration. Based on the result of traditional simple regression analysis, relatively better regression functions were obtained in the period of hurricane after 24-hour data filtering by Hanning Filter to avoid the influence of tide. Through the phase lag analysis, it's pointed out that wind had different effect on turbidity due to the locations and water depth. After introducing the phase factor, the turbidity concentrations fit by the cubic regression equations of wind speed very well with the high value of $R^2(>0.96)$ and low value of RMSE (<3.4) at all stations. The enhanced integrating regression analysis with Hanning Filter and phase factor is an efficacious method to reveal the effect of wind on turbidity and estimate turbidity concentration under hurricane. Based on the linear relationship between turbidity and sediment,

sediment concentration also can be estimated by an approximate regress fit of wind speed. Relationship between sediment and wind speed is similar to that between turbidity and wind speed. An empirical regression equation was obtained to provide quick estimation of the sediment concentration in response to the strong wind effects during hurricane, especially with the wind speed higher than 4m/s.

According to the results, hurricane impacts on sediment (turbidity) were analyzed and the approximately quantitative relationships between wind speed and sediment was defined in hurricane. It could use to simple estimate the variation of sediment concentration in hurricane and provide technical supports for assessment of sediment concentration variation and coastal zone research under extreme climate in the study region. It is also a good method for coastal environmental management in similar waters.

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Figure1

Figure2a

Figure2b

Figure3

Figure4

Figure5

Figure6a

Figure6b

Figure6c

Figure6d

Figure7

Figure8a

Figure8b

Figure8c

Figure8d

Figure9a

Figure9b

Figure9c

Figure9d

Figure10a

Figure10b

Figure10c

Figure10d

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Figure12

Figure13