ABSTRACT

QIAN, HUI. Ocean Circulation Dynamics and Transport Connectivity in the Intra-Americas Sea on Inter-annual, Seasonal, Synoptic and Inertial Time Scales. (Under the direction of Dr. Ruoying He.)

Coastal circulation dynamics and associated connectivity in the Intra-Americas Sea (IAS) has drawn increased attention, but are often constrained by the sparsity of observations both in space and time. A systematic study of IAS circulation from low to high frequency is needed. To do this, both extensive in-situ observations and a high-resolution, eddy-resolving circulation model were utilized to study the circulation variability and associated transport connectivity from annual, seasonal down to synoptic and inertial time scales.

First, over the course of four years, the seasonal to inter-annual variability in transport connectivity were studied. Through the quantification of connectivity matrix using the statistically more comprehensive Lagrangian probability density function (LPDF) method, we showed that the area covered by connectivity envelopes for the IAS coral reef hotspots was larger than what previous defined using mean circulation only (e.g., Roberts, 1997). Results suggested that current variability in addition to the mean condition is important in modulating the particle dispersal pattern, and should be considered when constructing the Marine Protected Area and considering population connectivity.

In addition, ocean circulation dynamics were also investigated on synoptic time scales.
The impact of two consecutive hurricanes, Gustav and Ike, in 2008 on the upper ocean circulation dynamics and particle dispersal were examined. Results showed that at synoptic time scale, upper ocean circulation also plays important role in altering the material transport, especially during the passage of hurricanes when wind forcing played a critical role. Strong vertical motions associated with strong Ekman pumping stirs up vertical water column as shown in the particle dispersal displacement, which may have significant impact on fisheries habitats in the subsurface.

Furthermore, the upper-ocean near-inertial oscillations during the passage of Hurricane Ida in November 2009 in the Gulf of Mexico were studied. The upper ocean response is evidenced by both in-situ observations and a numerical particle tracking approach. Two groups of moorings in the GOM, one in the Loop Current area and the other on Campeche Bank have been employed in this study. Results showed that the near-inertial oscillations varied region by region due to the difference in the background flow and relative vorticity. Both mooring observations and model results showed that strong inertial oscillation signals were present at the Loop Current mooring locations and inertial energy propagates downward after the passage of hurricane. In contrast, at the Campeche Bank, inertial oscillations were only weakly present and the high frequency oscillations were dominated by the internal diurnal tides.
Through the analysis of transport connectivity in response to signals at lower (seasonal to inter-annual) to higher frequencies (synoptic to near-inertial), an improved understanding of the circulation dynamics and possible biological implications were achieved. The study provides an important benchmark for the future coupling of circulation dynamics with biological behavior (growth, mortality, sinking and diel migrations) to yield a thorough understanding of physical-biological interaction dynamics.
Ocean Circulation Dynamics and Transport Connectivity in the Intra-Americas Sea on Inter-annual, Seasonal, Synoptic and Inertial Time Scales

by

Hui Qian

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APPROVED BY:

____________________  ____________________
Dr. Daniel. L. Kamykowski  Dr. David B. Eggleston

____________________  ____________________
Dr. Ping-Tung Shaw  Dr. Peter Hamilton

____________________
Dr. Ruoying He
Chair of Advisory Committee
BIOGRAPHY

Hui Qian was born in Suzhou, a beautiful city in southeast China. She received her bachelor’s degree in marine science in 2004 and a Master’s degree in physical oceanography in 2007 at Ocean University of China. She spent one year at Johns Hopkins University for graduate study in Oceanography, and then joined the Department of Marine, Earth, and Atmospheric Sciences at North Carolina State University in summer 2008 to continue her graduate education. She received a M.S. in Marine Science in 2010, passed the Ph.D. preliminary examinations in fall 2012, and is expected to complete her Ph.D. degree in December, 2013.
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Chapter 1: Introduction

The Intra-Americas Sea (IAS, Fig.1.1) is a semi-closed sea in the western Atlantic Ocean. It is composed of the Caribbean Sea, the Gulf of Mexico (GOM), and the South Atlantic Bight (SAB). The circulation system in IAS includes the Caribbean Current flowing westward from the Lesser Antilles, passing through the Yucatan Channel as the Yucatan Current, and then becoming the Loop Current in the Gulf of Mexico. The Loop Current subsequently forms the Florida Current and Gulf Stream as it exits the gulf. The IAS circulation system is an integral part of the western boundary current in the North Atlantic Subtropical Gyre and also an important conduit of the upper part of the meridional overturning circulation (e.g., Schmitz and Richardson, 1991; Schmitz and McCartney, 1993). Thus it plays an important role in transporting and dispersing mass, heat, salt and other material properties. As IAS covers a large geographic domain, detailed circulation features in the Caribbean Sea and Gulf of Mexico are illustrated below.

1.1 Circulation in the Caribbean Sea

The Caribbean Sea is the largest marginal sea of the Atlantic Ocean. It is connected to the North Atlantic Ocean via the Lesser and Greater Antilles on the east, and to the Gulf of Mexico through the Yucatan Channel on the north. Five major basins in the Caribbean Sea
from east to west are the Grenada, Venezuelan, Columbian, Cayman and Yucatan Basins. The Grenada Basin, which is located around the Lesser Antilles in the east of the Caribbean Sea, is the smallest and shallowest with water depth less than 3300 m. Separated by the Beata Ridge, the Venezuelan and Columbia Basins have water depths greater than 4000 m in the east and central Caribbean Sea, respectively. Further west and north is the Cayman Basin, with water depth more than 5000 m. It is located between the Nicaragua Rise and Cayman Ridge with a sill depth of 1200 and 1600 m, respectively. The Yucatan Basin lies between the Cayman Ridge and Yucatan Channel with water depth greater than 5000 m. The complex bottom topography of the Caribbean Sea plays an important role in its circulation, eddy activities, water mass formation, as well as other physical and biological processes (Molinari et al., 1981; Morrison and Nowlin, 1982).

The Caribbean Sea water is highly stratified in the upper 1200 m. It becomes weakly stratified between 1200 and 2000 m, and nearly homogeneous 2000 m downward (Wust, 1964). This water column structure is closely related to the sill depths of the passages (Antilles island arch) through which the Caribbean Sea is connected to the open ocean and the deep and bottom water within the Caribbean Sea is renewed. The Caribbean Sea surface water properties have moderate seasonal variations. Three major rivers: the Amazon, Orinoco and Magdalena rivers discharge a large amount of freshwater into the Caribbean Sea, influencing its surface salinity distributions (Mooers and Maul, 1998).
The main circulation feature of the Caribbean Sea is the westward throughflow known as the Caribbean Current. It flows from the Lesser Antilles westward into the Caribbean Sea, and bifurcates into two flows near the Nicaragua Rise with the main branch flowing northward and the smaller branch veering south to form the cyclonic Panama-Columbia Gyre. The main branch subsequently becomes Yucatan Current as it flows through the Yucatan Channel, and then Loop Current as it enters the GOM (Wust, 1964; Mooers and Maul, 1998).

The general circulation of the Caribbean Sea has been studied for decades based on observational data and numerical simulations. Early ship-drift observations showed that the basin scale mean circulation of the Caribbean Sea has a persistent westward current ranging from 50-100 cm/s (Wust, 1964; Gordon, 1967; Roemmich, 1981). As more observational data became available, the mean circulation conditions and their variability associated with meanders and mesoscale eddies were both explored (Febres-Ortega, 1970; Morrison, 1977; Kinder et al., 1980; Centurioni and Niiler, 2003; Richardson, 2005). Eddies associated with the westward Caribbean Current were found to be largely advected by the background flow and were affected by the varying topography in the Caribbean Sea (Molinari, 1981, Andrade and Barton, 2000). Results from numerical model simulations showed that nonlinear dynamics and freshwater flux from large rivers were also responsible for the enhanced eddy activities (Sheng et al., 2003; Cherubin et al., 2007; Lin et al., 2012).
1.2 General circulation in the Gulf of Mexico

The GOM is a semi-enclosed sea in the southwestern tropical/subtropical Atlantic Ocean. It is connected to the open ocean through two narrow openings. One is the Yucatan Channel in the south connecting the Caribbean Sea to the Gulf with a sill depth of approximately 2040 m. The other is the Straits of Florida between Florida and Cuba with a shallower sill depth of around 800 m, connecting the Gulf with Atlantic Ocean in the east.

A distinctive feature of circulation in the GOM is the Loop Current, which is a northward extension of the Yucatan Current into the Gulf, forming a clockwise rotating loop, and leaving the Gulf through the Straits of Florida. The Loop Current is mainly confined to the upper 1000 m, with a maximum speed of 2 m/s (Oey et al., 2003). Typically, the Loop Current extends northwestward within a 3-4 degrees latitude range (Maul and Vukovich, 1993; Romanou et al., 2004), but occasionally, it can extend further north to the Mississippi River delta and west Florida continental shelf (Huh et al., 1981; Wiseman and Dinnel, 1988).

The Loop Current episodically sheds anti-cyclonic eddies. Nof (2005) showed that the Loop Current grows with mass influx from the Yucatan Channel to a certain size. When the westward Rossby wave speed (-βR^2, where R is the Rossby radius of deformation based on the matured deep Loop, and β is the Coriolis parameter) is larger than the growth rate, the Loop Current sheds an eddy, and retreats southward. These anticyclonic eddies have
diameters of 200~300 km, vertical extent of 1000 m with swirl speeds around 1.8~2 m/s. These eddies then translate westward as warm core rings with average translational speed of 2-3 km d⁻¹ (Cochrane, 1969; Nowlin, 1972; Elliott, 1982; Vukovich and Crissman, 1986; Cooper et al., 1990; Forristal et al., 1992; Hamilton, 1999), consistent with long Rossby wave speed in the GOM. Theses eddies can largely retain their shape and most of their surface hydrographic features as they move westward. Sturges and Leben (2000) showed that periods of eddy shedding events in the GOM range from 3 to 17 months, having an average period of 10-11 months with considerable hydrodynamic variability.

The mechanisms of eddy shedding and its variability have not been identified adequately. Analytically, the dominant dynamics controlling the eddy shedding is the β-effect (Hurlburt and Thompson, 1980; Pichevin and Nof, 1997; Nof, 2005), while the great variability of Loop Current eddy shedding periods implies that the β-effect is not the sole dynamical factor. The upstream conditions, including the Caribbean eddies that squeeze through the Yucatan Channel, as well as wind-induced transport fluctuations through the Greater Antilles can also affect the time of eddy shedding (Murphy et al., 1999; Oey and Lee, 2003). In addition, transport variations in the Loop Current (Maul and Vukovich, 1993), including variations in the deep outflow (Bunge et al., 2002), has also been proposed as the potential mechanisms of eddy shedding. Baroclinic energy transfer (Romanou et al., 2004), the interaction between the Loop Current and its peripheral cyclones (Schmitz et al., 2005),
as well as the local wind conditions (Chang and Oey, 2010) can all potentially affect the eddy shedding. A triggering mechanism for the Loop Current eddy shedding is pulses of increased transport of the Florida current accompanied by the corresponding increase in the offshore sea level (Sturges et al., 2010). Though the exact mechanisms for Loop Current eddy shedding are still not fully understood, it is likely a complex process due to a combination of drivers.

In addition to the dominant flows of the anti-cyclonic Loop Current in the eastern GOM and the detached warm core rings in the western GOM, there are some other features in the upper layer circulation of GOM. For example, a mean elongated anti-cyclonic flow appears in the west-central gulf, centered around 24~25°N, 92.5°W (Nowlin and McLellan, 1967; Nowlin, 1972; Sturges and Blaha, 1975; Sturges, 1993; DiMarco et al., 2005). The mean anticyclonic flow is mainly influenced by the periodic shedding of Loop Current eddies, their westward migrations and their interaction with topography and other eddies (Lee and Mellor, 2003; DiMarco et al., 2005). Additionally, a cyclonic circulation is found in the Campeche Bay (Vazquez, 1993; Vazquez de la Cerda et al., 2005; DiMarco et al., 2005), attributed primarily to the wind stress curl over that region. Overall, the mean circulation of the upper layer GOM is anti-cyclonic and driven by the combined effects of the Loop Current system and the basin and regional scale wind patterns.
In contrast to the upper layer circulation, the deep circulation in the GOM is dominated by cyclonic flows in both the eastern and western gulf with speeds on the order of 1-2 cm/s at 2000 m. Early studies (using both observations and numerical models) indicated the existence of a deep cyclone associated with the upper layer anticyclone (Hurlburt and Thompson, 1982; Hamilton, 1990; Sturges et al., 1993; Indest, 1992). The analysis of historical hydrographic, current meter data (DeHaan, 2003) and intermediate-depth floats (Weatherly et al., 2005) also indicated a deep cyclonic flow. Results from subsequent numerical studies confirmed these early findings (Welsh and Inoue, 2000; Lee and Mellor, 2003; Romanou et al., 2004). An anticyclone-cyclone pair develops in the deep layer beneath the Loop Current when eddies are shed in the surface. During its westward movement, the deep anticyclone decays more quickly than the cyclone in the gulf; thus the cyclone dominates the deep circulation. When the deep cyclone accompanies the Loop Current anticyclones to the western gulf coast, the surface anticyclone moves north and the deep cyclone moves into the Campeche Bay area and dissipates. The cyclonic eddy variability is consistent with topographic Rossby waves, and bottom intensification of the flow was found close to steep topography (Hamilton, 1990; Hamilton, 2009). The work by DeHaan and Sturges (2005) put forth the possible mechanisms of deep cyclonic flow, including the topographic rectification and the renewal of cold and dense water from the Caribbean Sea. They found the average temperature around the southern edge of the GOM at 2000 m increased with the distance from the Yucatan channel in
a counter-clockwise manner, indicating the cyclonic boundary flow.

1.3 Connectivity in IAS

Although each sub-region in the IAS has its own physical and biological features and processes, on a broader scope all these regional processes are dynamically linked through the strong western boundary current system. One of the major research interests in regard to the IAS connectivity has been the understanding of the transport of biological species. Previous studies based on passive larvae dispersal had shown that the Barbados exhibited a local retention pattern and depends on local larval production to replenish larval populations, thereby potentially rendering these populations vulnerable to recruitment overfishing (i.e., overharvest of spawning animals leading to reductions on their progeny; Roberts, 1997; Young et al., 2012). Conversely, animal populations in the Bahamas and Florida Keys could draw larvae from very large upstream areas. Thus local depletion of larval population can be offset by the larvae inputs spawned elsewhere (Roberts, 1997), although within a short spatial coverage local current features can also play a critical role (Lipius et al., 2001). The dispersal of larvae can also be modified by biological factors, such as the pelagic larval duration, vertical and horizontal swimming capabilities and adult spawning strategies. With these parameters being considered, the Bahamas and the Turks and Caicos Islands generally exhibited high connectivity in the northern Caribbean region. The Nicaraguan Archipelagos
were strongly intra-connected. The Panama-Columbia Gyre region was isolated from the rest of the Caribbean. The west and east Caribbean are moderately isolated from each other (Cowen et al., 2006).

Some other studies in the GOM also reveal the effects of physical environment on modulating the transport of biological species. The tidal oscillations along the west Florida coast and the upwelling-downwelling cycles developed in response to the passage of cold fronts could cause the local retention of bay scallop larvae along west Florida (Arnold et al., 1998). The recirculation and gyre circulation formed in the Tortugas area potentially enhanced larval retention and recruitment into the Florida Keys (Lee and Williams, 1999). Red Snapper (scientific name) larval transport in the Northern GOM was found to be dependent on the wind stress and the coastal flow (Johnson et al., 2009). Information on potential larval dispersal and population connectivity over the entire IAS is limited. Although limited previous work showed the many reef fish species are limited due to larval movement (Cowen et al., 2006), the background flow taken into account in the study indeed needs to include of flow variability at time scales from seasonal to interannual.

One of the somewhat unique processes in the IAS is that it is a prime location for hurricane generation and intensification due to its stratified and warm water column that can fuel tropical cyclones fairly quickly (Palmen, 1948). The major upper ocean response to a
moving hurricane is characterized by sea surface cooling and inertial oscillations. During the passage of a hurricane, the Sea Surface Temperature (SST) decreases due to processes such as hurricane-induced entrainment, vertical mixing and upwelling, as well as air-sea heat exchange (Leipper, 1967; Fedorov et al., 1979; Pudovet et al., 1979; Greatbatch, 1985). The relative importance of these processes depends on storms (Price, 1981; Morey et al., 2006; Prasad and Hogan, 2007; Gierach et al., 2009). In addition to the physical response, the biological impact brought by hurricane is also of great interest. Upwelling associated with strong wind stress curl brings up the nutrient-rich water from the deep layer to the upper euphotic zone (Lin et al., 2003; Walker et al., 2005; Shi and Wang, 2007). Together with entrainment of subsurface phytoplankton maximum (Gierach and Subrahmanyam, 2008), these events may trigger phytoplankton blooms several days after hurricane passage. However, it is not the case for all the hurricanes because hurricane-induced vertical mixing may not reach the nutricline and therefore no significant increase of nutrient content is available to support phytoplankton blooms in the euphotic zone (Hu and Muller-Karger, 2007).

Indeed, hurricane-induced physical and biological responses are functions of hurricane characteristics (e.g., intensity and translational speed), pre-storm ocean conditions, as well as the presence of warm and cold core ocean eddies. A fast moving hurricane could induce strong rightward bias, while a slow moving hurricane could introduce stronger upwelling and
entrainment in the ocean with reduced rightward bias (Price, 1981). The pre-storm ocean environmental condition also matters. In a water column with shallow thermocline and nutricline, it is more likely for pronounced upper-ocean cooling and nutrient influx to happen. In contrast, if the upper ocean water column is well-mixed, the temperature and nutrient responses may be much more limited. The presence of cold-core and warm-core eddies in the ocean can complicate the hurricane-induced responses as well. The cold-core (warm-core) eddies are typically associated with shallower (deeper) thermocline and nutricline (e.g. McGillicuddy et al., 1999); thus the colder and nutrient-rich subsurface water properties are relatively easier (more difficult) to be pumped into the surface water under these eddy scenarios.

Finally, inertial oscillation is another important ocean process that can play an important role in redistribution of physical and biological properties, and energy for ocean mixing, especially near extreme events such as hurricanes (e.g. Leipper, 1967; Brink, 1989; Dickey et al., 1998; Price, 1981; Greatbatch,1983). Yet research on this topic is also relatively limited, and dynamics pertinent to the wake of the inertial oscillation is still not clear (Joyce et al., 2013). Both observations data and numerical modeling are needed in this regards.

To sum up, a more comprehensive understanding of transport connectivity and particle dispersal over the entire IAS, as well as their associated variability at different time scales
(inertial synoptic, seasonal and interannual) is needed, and thus the focus of this dissertation work.

1.4 Research objectives

The overall objective of this dissertation research is to seek a deeper understanding of the IAS circulation dynamics and transport connectivity, and their associated variability in different time scales, from inter-annual, seasonal, synoptic to inertial time periods. Both observational data analysis and modeling approaches will be used. Specific goals include:

(i) Conducting realistic IAS circulation hindcast computer simulations illustrating circulation dynamics.

(ii) Performing offline particle tracking calculations based on IAS circulation hindcasts generated in (i) and quantifying IAS transport connectivity and analyzing the seasonal and inter-annual variability in transport patterns; diagnosing effects of various physical processes on the distribution of particle dispersal.

(iii) Investigating the IAS circulation dynamics and transport/dispersal patterns in extreme weather conditions like hurricane.

(iv) Investigating the circulation dynamics and particle dispersal in the inertial time period after the passage of a hurricane.
Chapter 2 documents (i) and (ii), focusing on circulation and connectivity during mean, seasonal, and inter-annual time scales. Chapter 3 focuses on the results of (iii), illustrating circulation and transport connectivity during synoptic hurricane events. It is followed by discussion of item pertinent to (iv) in Chapter 4, which is centered on physical process on the inertial time period. Chapter 5 provides a summary of this dissertation.
References


Hamilton, P., G. S. Fargion, and D. C. Biggs, Loop Current eddy paths in the western Gulf of


Vazquez De la Cerda, A. M., Bay of Campeche Cyclonic, Ph.D. Dissertation, College Station, Texas, Texas A & M University, 91 pp, 1993.


Chapter 2: Numerical Investigation of Transport Connectivity in the Intra Americas Sea

Hui Qian, Yizhen Li, Ruoying He, and David Eggleston
Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC, 27695
To be submitted to Coral Reefs

Abstract

A high-resolution, eddy-resolving circulation model was used to investigate variations in ocean circulation and its role in shaping larval dispersal patterns and coral-reef fish larvae connectivity in the Intra-Americas Sea. Coral reef fish larval hotspots were chosen to synthesize how circulation transport modulates the particle dispersal on mean, seasonal and inter-annual timescales. Reasonable agreement was found between model solutions and in situ observations. While the model produced an overall consistent geographic dispersal pattern as reported in previous findings, further statistical analyses showed that dispersal patterns driven only by only mean circulation can significantly underestimate particle connectivity envelopes. Instead, seasonal and inter-annual variability in circulation were crucial in modulating both dispersal distance and directional anisotropy over most coral reef sites. Updated transport envelopes provided more accurate probability estimate that may help to guide coastal management and design of marine protected areas across state and country borders.
2.1 Introduction

The Intra-Americas Sea (IAS) is a semi-closed sea in the western Atlantic Ocean (Fig.2.1a). It is composed of the Caribbean Sea, the Gulf of Mexico (GOM), and the South Atlantic Bight (SAB). The circulation system in IAS includes the Caribbean Current flowing westward from the Lesser Antilles, which passes through the Yucatan Channel as the Yucatan Current to become the Loop Current in the GOM, and subsequently forms the Florida Current and Gulf Stream after it exits the Gulf. The IAS circulation system is an integral part of the western boundary current in the North Atlantic Subtropical Gyre and the meridional overturning circulation (Schmitz and Richardson, 1991; Schmitz and McCartney, 1993), and it plays an important role in transporting and dispersing mass, heat, salt and other material properties. Understanding the transport connectivity within the IAS is therefore a critical step forward before any coupling with biology can be comprehended.

One of the focus research interests in regard of the IAS connectivity has been the understanding of the delivery of deep-sea biological species by ocean circulation (e.g., Roberts, 1997; Young et al., 2012; Lipcius et al., 2001). One important contribution was made by Roberts (1997), who mapped the routes of passive pelagic larvae from coral reef fish larval hotspots in the Caribbean Sea for dispersal periods of 1 and 2 months based on the mean surface current patterns (Fig.2.1). The mapped connectivity pattern (‘transport
envelope’) showed oceanic regions can exhibit either local retention or more widespread dispersal pattern. Systemlike Barbados depended on local larval production of larvae to replenish benthic populations, and thus was more vulnerable to recruitment of overfishing. In contrast, systems like the Bahamas and Florida Keys might draw larvae from large upstream areas, although certain estuarine near Bahamas can be self-retentive as a result local gyre feature (Lipcius et al., 2001). In these open systems, local depletion of larval populations may be offset by the larval inputs spawned elsewhere. Young et al. (2012) studied the dispersal of deep-sea larvae in IAS using an off-line Lagrangian larval transport model driven by simulated ocean circulation. The results showed most of the larvae from Barbados were retained in the Southern Caribbean. A small portion of virtual larvae could be exported out of the area and drift as far north as the GOM and North Atlantic.

Coral reef larvae dispersals are also subject to biological behavior and activity in response to local hydrography and climate change (Taylor and Hellberg, 2003; Cowen et al., 2000, 2006; Munday et al., 2009; Jones, 1999). Although still subject to debate in reality, the inclusion of a linear mortality function in a simple 2-D biological model may reduce the dispersal envelopes (Cowen et al., 2000). Further study used a three dimensional, individual based model instead of 2-D model. Instead of passive larvae, biological parameters (such as the pelagic larval duration, vertical and horizontal swimming capabilities and adult spawning strategies) were considered. Their results showed that the Bahamas and the Turks & Caicos
Islands exhibited high connectivity in the northern Caribbean region that is largely isolated from the remaining expanse of the region; that the Nicaraguan Archipelagos were strongly inter-connected; the Panama-Colombia Gyre region were isolated from the rest of the Caribbean; and that the west and east Caribbean were moderately isolated from each other.

Other studies in the GOM in specific revealed the potential effects of physical environment on modulating transport of biological species. For instance, Arnold et al. (1998) analyzed the local retention of bay scallop larvae along west Florida coast and proposed that tidal oscillations along the west Florida coast and the upwelling-downwelling cycles developed in response to the passage of cold fronts could be the cause. Through the analysis of the mean and seasonal variability of coastal currents and temperature in the Florida key, Lee and Williams (1999) concluded the recirculation formed in the Tortugas area enhanced the larval retention and recruitment into the Keys. Johnson et al. (2009) analyzed Red Snapper larvae transport in the Northern GOM and found the transport pathways were mainly dependent on the wind driven coastal flow. The transport pathways were westward during September, October and May when the averaged wind stress was westward. In June, July and August, the transport pathways became eastward under the influence of shoreward wind stress and eastward coastal flow. Rooker et al. (2012) examined the distribution of Billfish and Swordfish larvae across the mesoscale features in the GOM. They showed the fish larvae aggregated on or close to the frontal features near the periphery of the Loop Current, which
was attributed to the hydrodynamic convergence effect there.

All these earlier studies provide an excellent research foundation to seek a systematic quantification of connectivity among different oceanic regions in the IAS. However, both observations and modeling studies were limited to a certain region (Lipcius et al., 2001; Johnson et al., 2009), or were restricted by highly liberalized/ simplified model (Cowen et al., 2000; 2006). At this moment, limited study has been conducted to quantify the connectivity at seasonal to interannual timescale. As a first step forward, in an abiotic sense we seek to quantify the IAS circulation transport connectivity at seasonal and inter-annual time scales based on realistic eddy-resolving circulation hindcast solutions during 2007-2010. Furthermore, we elucidate the connectivity at various oceanic domains in the IAS, and diagnose the effects of various physical processes on the distribution of particle dispersions, and possible implications for coral reef connectivity based on a more statistically comprehensive Lagrangian Probability Density Function (LPDF) method (Mitarai et al., 2009). The LPDFs describe the probability density function of particle displacement for a given advection time that can be used to quantify the source and destinations of the larvae (see further details in Section 2.2.2). Specifically, we sought to compare the larval envelope (Fig.2.1) proposed by Roberts (1997) with our simulation solutions, and thus to test their proposed hypothesis that upper-bound of the coral reef connectivity can be defined using a mean circulation. The remaining of the paper is as follows. We first introduced the
hydrodynamic model, particle tracking method, and a brief introduction to statistical approaches in quantifying connectivity in Section 2.2. Section 2.3 provided detailed model-data comparisons. The connectivity matrix and the mechanisms interpretations are presented in Section 2.4, followed by a discussion and summary in Section 2.5.

2.2 Model and Methodology

2.2.1 Model setup

The IAS circulation model was constructed based on the Regional Ocean Modeling System (Haidvogel et al., 2008; Shchepetkin and McWilliams, 2005). ROMS is a free-surface, hydrostatic, primitive-equation model that employs split-explicit separation of fast barotropic and slow baroclinic modes and vertically stretched terrain-following coordinates.

The IAS ROMS covers the entire Caribbean Sea, GOM and the South Atlantic Bight with a horizontal resolution of ~6km, sufficient for resolving mesoscale eddies in the IAS (Fig.2.2). Vertically, there are 30 terrain-following levels with increased resolution near the surface and bottom to better resolve boundary layer dynamics. The initial and open boundary conditions were provided by the global data assimilative Hybrid Coordinate Ocean Model (HYCOM). The global HYCOM assimilates satellite observed sea surface temperature and height, and ARGO measured temperature and salinity profiling data, providing daily data
assimilative global circulation at about 10 km resolution (http://hycom.rsmas.miami.edu/dataserver). At the land boundary, climatological monthly mean runoff of 144 rivers inside the IAS was applied. The Mellor-Yamada (1982) closure scheme was applied to compute the vertical turbulent mixing, as well as the quadratic drag formulation for the bottom friction specification.

Surface atmospheric forcing used to drive the IAS ROMS was obtained from the National Center for Environmental Prediction (NCEP) reanalysis, which has a spatial and temporal resolution of 1.875° and 6 hourly, respectively. Total cloud cover, precipitation, surface pressure, relative humidity, air temperature, surface wind, net shortwave and longwave radiations were used in the standard bulk formula to derive wind stress and net surface heat flux used to drive the ocean circulation. A 4-year circulation hindcast from 2007 to 2010 was carried out.

2.2.2 Particle tracking model and LPDFs

In order to study the connection among different oceanic domains in the broad IAS, the numerical surface particle trajectories were calculated using the offline particle tracking model, with a 4th order Runge-Kutta tracking scheme, which has been widely used by numerous other studies (Mitarai et al., 2009; Li et al., 2013; Xue et al., 2009; Incze et al., 2010). No diffusivity was taken into account in this experiment. We selected a set of particle
release centers that cover the IAS model domain at 120-km sampling interval (every 20 points in the model grid, Fig.2.3). Following the same approach of Mitarai et al. (2009), we chose each release site to be a 60-km radius circular area around the release center defined above. In this way, 650 release sites were defined that encompassed most regions in the IAS. At each site, a group of 45 particles was released every 10 days from 2007 to 2010, and subsequently tracked for up to 60 days. Thus, for each release site, there were 135 group releases (6075 particles) in total for the experiment. This is sufficient for quantifying the large-scale connectivity, as experiments with increased particle density showed similar dispersal pattern, a finding also stated by Mitarai et al. (2009).

The particle trajectories were further quantified using the Lagrangian Probability Functions (LPDFs). Following Mitarai et al. (2009), we define the LPDFs as the probability density of particle displacement. For a given set of advection time scales \( \tau \), sampling space variable \( \varepsilon \), initial position \( a \), and the position of n-th particle \( X_n(\tau, a) \), the discrete representation of LPDFs \( f'_X(\varepsilon; \tau, a) \) were defined as:

\[
f'_X(\varepsilon; \tau, a) = \frac{1}{N} \sum_{n=1}^{N} \delta(X_n(\tau, a) - \varepsilon)
\]

Where \( N \) is the total number of Lagrangian particles, and \( \delta \) is the Dirac delta function. The Dirac function is defined as the Heaviside function \( H \) in a unit area (i.e., \( \delta = \frac{dH}{dxdy} \), where the Heaviside function \( H \) is typically known as the unit step function, such that
\[ H(x) = \begin{cases} 
0 & \text{if } n < x \\
1 & \text{if } n \geq x 
\end{cases} \]

, where \( n \) is the integer (grid number) along the directional axis \( x \). As such, \( f'_{x} \) is also in the unit of reciprocal area.

The discrete LPDF \( f'_{x} \) can be expressed as spatially-averaged LPDFs over the surrounding area of each release site, that is:

\[
f'_{x}(\varepsilon; \tau, a) \approx \frac{1}{\pi R^2} \int_{|r| \leq R} f'_{x}(\varepsilon; \tau, a+r)rdr
\]

(2)

where \( R \) is the radius of each release site (taken as 6-km in this study). A smooth operator (Gaussian filter with radius of 6 km) was then applied to remove sub grid-scale noises to get the LPDF \( f_{x} \).

Based on the probability density (LPDF), the coastal connectivity \( C_{j,i} \) is then defined as the probability of a water parcel that moves from source location \( j \) to destination location \( i \) over a time interval \( \tau \). For a given set of source location \( x_j \) and a destination location \( x_i \), the value of \( C_{j,i} \) is evaluated from the LPDF as:

\[
C_{j,i}(\tau) = f_{x}(\varepsilon = x_i; \tau, a = x_j)(\pi R^2)
\]

(3)

The connectivity matrix can be normalized by the surrounding area \( \pi R^2 \) of each release site to convert probability densities into probabilities.

Once we have the connectivity matrix, the destination strength \( D_{i}(\tau) \), representing the
relative ‘attractiveness’ of site $i$ for all Lagrangian particles released in the study domain over a release time $\tau$, can be calculated by summing the connectivity matrix over all source sites in the domain, i.e.,

$$D_i(\tau) = \sum_{j \in J} C_{i,j}(\tau), J = j_1, j_2, \ldots, j_N$$

(4)

In other words, this quantity represents where the particles from different source sites are traveling to.

Similarly, the source strength $S_j(\tau)$ measuring the relative success of particles moving from site $j$ to other places in the domain within an advection time scale $\tau$, can be calculated by summing the connectivity matrix over all selected destination sites in the domain as:

$$S_j(\tau) = \sum_{i \in I} C_{i,j}(\tau), I = i_1, i_2, \ldots, i_N$$

(5)

In other words, this quantity represents where the particles arriving at a certain destination travel to.

2.3 Model Skill Assessment

The model simulation provides eddy-resolving, spatial and temporal continuous circulation solutions. As an example, Fig.2.4 presents 4-year temporal averaged SSH overlain with mean surface current, and a snapshot of the circulation field on June 7, 2010. In the
model, Caribbean Current flew westward from the Lesser Antilles with amplitude of \( \sim 1 \) m/s. It separated into two flows near the Nicaraguan Rise with the major current flowing north and westward toward Yucatan Channel, and the smaller branch veering south to form the cyclonic Panama-Colombia Gyre (PCG). The Yucatan Current, Loop Current, major circulation feature in the GOM, as well as the Gulf Stream are all readily present.

To further evaluate the performance the circulation model, we compared the model solutions with multiple satellite-based and in-situ observations. A suite of observational data including Florida Current (FC) Transport cable data, AVISO sea surface height anomaly, blended Sea Surface Temperature (SST), sea level height and ship CTD casts were all used to assess the model performance. Fig.2.5 showed the time series comparisons of Florida current (FC) transport between model, cable data and HYCOM counterparts. The FC transport is monitored by a cable between the U.S. east coast and the Bahamas (pink line in Fig.2.2), and the data is made available online at: http://www.aoml.noaa.gov/phod/floridacurrent/data_access.php. It suggests that the model was able to capture the variability of FC transport reasonably well. One caveat we note is the simulated 4-year mean FC transport was 28.4Sv (1Sv=\( 10^6 \) m\(^3\)-s\(^{-1}\)), as compared to observed average of 31.3Sv. This bias is likely from the global HYCOM that are used to drive the boundary inflows, which also underestimated the Florida transport with a mean transport value of 26.5Sv.
We also compared between model simulated and satellite (AVISO) observed mean Eddy Kinetic Energy (EKE) fields over 4-year study period (Fig.2.6). The EKE was calculated based on the geostrophic velocity anomaly $U'_g$ and $V'_g$ expressed below:

$$EKE = \frac{1}{2} \left( U'_g^2 + V'_g^2 \right)$$

Both AVISO and model presented stronger EKE in the Loop Current and Gulf Stream areas and weaker EKE along the coast and in the open ocean of Sargasso Sea. We do note that model shows a bit weaker EKE than that of the AVISOnear coastal GOM. This discrepancy can be attributed to the fact that AVISO has a spatial resolution of 1/3º and its ability to resolve the coastal dynamics is limited. Nonetheless, the model is able to resolve the kinetic structure of the circulation reasonable well.

To further assess the model performance in reproducing surface thermal structure, modelsimulated 4-year mean SST was gauged against NOAA Blended SST product with a 0.1°x0.1° spatial resolution (http://thredds1.pfeg.noaa.gov:8080/thredds/dodsC/satellite/BA/ssta/8day%Revised). The model reproduced the mean SST distribution in the IAS pretty well (Fig.2.7), including warmer water in the Caribbean Sea, Loop Current and Gulf Stream, cooler water along the northern coast of GOM, and relatively colder water along the South Atlantic Bight coast. In addition to the spatial distribution of temporal mean SST, the time series of spatial mean SST
showed favorable comparison between modeled and observed monthly mean SST (Fig.2.8).

In addition, NOAA National Ocean Service (NOS) sea level data were also used to assess the model performance in coastal areas. We compared 26 sea level stations along IAS coast from GOM, Florida coast to SAB to compare with model observations. For demonstration purpose only six stations are shown (Fig.2.9). Model clearly captured major feature of sea level variability. Correlation coefficient between model and observation were all statistically significant (>0.6), and is in good agreement with observations at both seasonal to interannual time scales.

Model hindcast solutions were further gauged against ship CTD casts in the GOM collected in 2010. A total of 1643 temperature and salinity profiles collected during April, 22, 2010 to October, 18, 2010 were utilized (Fig.2.10). The linear regression (T-S diagram) comparison showed the model reasonably reproduced observed temperature (water mass) Fig.2.11). The model slightly overestimates salinity near the Mississippi rivers mouth.

A more statistically robust temperature and salinity comparison is given in a Taylor diagram form (Fig.2.12), on which the standard deviation (STD), correlation coefficient and root mean square errors (RMSD) were all presented. The temperature comparison (left panel) showed the model was able to reproduce most of observations (1531 out of 1643 profiles) with RMSD being much less than 1, STD being close to 1 and correlation coefficient being
larger than 0.95. Compared to temperature, the salinity comparison had more scattered distribution in the Taylor diagram. Nevertheless, all modeled solutions were still in a region with STD less than 2 and RMSD less than 1. Therefore, these statistical comparisons further confirmed that the model was in good agreement with observations.

In summary, all the above mentioned model validations suggest the IAS ROMS has intrinsic skills in resolving regional circulation and water mass properties, providing us confidence to further carry out transport connectivity analyses, and thus the remainder of the paper.

2.4 Results

2.4.1 Particle trajectories and mean connectivity matrix in IAS

The 4-year circulation hindcast solutions drove the particle tracking calculations, thereby allowing us to characterize particle transport and connectivity in the IAS. As an example, Fig. 2.13 presented 60-day spaghetti plots of particles released at 4 different locations inside the IAS. Particles released in the western GOM (Fig. 2.13a, release site 10) spread over most of the northwest and central GOM. A small portion of particles traveled into the Gulf Stream, and dispersed as far as SAB. Particles released in the central northern GOM (Fig. 2.13b, release site 39) were dispersed both westward and eastward. The eastward moving particles reached the west Florida Shelf, some of which also entered the Florida
Current and Gulf Stream and moved northward along the southeast seaboard. For particles released on the west Florida Shelf (Fig.2.13c, release site 103), they either remained near the local area or entered into the Florida Current and the Gulf Stream, moving into the open ocean. Only a small portion of the particles moved northwestward to the central GOM. Particles released near Barbados (Fig.2.13d, release site 482) generally demonstrated two major transport pathways. The first path entered the Caribbean Sea and moved northwestward, and the other path moved northwestward along the U.S. Virgin Islands and into the Sargasso Sea.

Fig.2.14 shows the mean connectivity matrix with destination on the x-axis and source on the y-axis for all the 650 release sites in the IAS, and with an advection time of 10, 20, 40 and 60 days, respectively. Initially, with 10 days advection time, particles released at source locations still remained in their vicinity. As the advection time increased, particle distribution patterns became more diffusive. After 40- or 60-days of advection, particle distributions became more dispersive, but reached quasi-stable states. The resulting particle connectivity matrix shows how transport links one location to another. For instance, particles released in the western Caribbean Sea moved into the southeast GOM. We can also see that particles reaching to the eastern GOM originated mainly from releases in the central and eastern GOM, as well as the western Caribbean Sea.
2.4.2 LPDF, destination and source strengths focusing on coral reef connectivity

To better illustrate the possible biological implications of such transport, we compared the upper-limit of the coral reef connectivity defined by Roberts (1997) to that based on circulation with both seasonal and interannual variations taken into account. Following Roberts (1997), we focused on coral reef habitats and selected 18 coral reef fish larvae hotspots according to Roberts (1997) (pink dots in Fig. 2.2). These coral reef sites were distributed along the coastline in the IAS. For illustration of LPDFs, 6 of the 18 coral reef sites were chosen to quantitatively present the mean particle dispersal paths (Fig. 2.15). LPDFs illustrate the probability of particles reaching certain destinations. For example, particles released in Cayman Island and dispersing for 60 days (Fig. 2.15a) have high probabilities of moving downstream into the Loop Current, as well as being locally retained. There’s also limited probabilities for particles to go through the Florida Strait and continue northward. Particles initially released in the Panama and Nicaragua sites have similarities in their LPDFs particle distributions (Fig. 2.15b, c). Particles at these two sites have large probabilities to stay in their local areas due to the presence of permanent Panama-Colombia Gyre (PCG). Apart from the PCG area, particles released at Panama also exhibit high probabilities to move northwestward and enter into the Loop Current on a 60-day advection time scale. Compared to the Panama release site, particles released at the Nicaragua site had relatively small probabilities of moving northwestward and entering the
GOM at the same advection time scale. Particles released at the Flower Gardens (Fig.2.15d) showed high probabilities of dispersing both eastward and westward though with limited travel distance. The LPDF distribution for particles released at Barbados (Fig.2.15e) showed similar results as in the spaghetti plot in Fig.2.13. Particles have high probabilities moving both into the Caribbean Sea, along the Virgin Island, and stay in the nearby regions by the end of the 60 day advection time. In comparison with other release locations, particles released at Banco de Serranilla (Fig.2.15f) show much more dispersive pattern. Particles have higher probabilities leaving their local area, moving across the Yucatan Channel and reaching to the south and central GOM. Its distribution of particles covers almost the entire GOM, and part of the SAB.

Another way of illustrating the particle dispersal pattern is given in terms of mean dispersal distance and angular direction for the coral reef sites (Fig.2.16). Large variability clearly exists among various locations. For instance, in the western GOM region (Fig.2.16a, b), the majority of particles (over 65%) travelled at a distance of 100~200 km with angles mainly at 0, 120 and 150 degrees, suggesting particles are dispersing east- and northwestward near release site. Particles in the Sargasso Sea region (Fig.2.16c, d, e, f, g) generally dispersed over larger distances. Over 50% of the particles released from the Florida Keys travelled distances of 1700 km at a mean angle of 45 degree to the east. They are traveling with the Florida Current/Gulf Stream into the SAB. Particles released from Andros Is.,
Bahamas dispersed mainly at a distance of 100~300 km (over 50%) and 1600 km (over 12%) at an angle of 90 degrees to the east, showing the major northward movement of the particles. The distribution of particle dispersal distances for particles released from the Turks & Caicos, U.S. Virgin Island, and Saba demonstrate similar patterns, with the majority of the particles (~70%) dispersing at distances of 300~700 km in the direction of 150 degrees to the east, moving northwestward. Particles released from the northwest Caribbean region (Fig.2.16h, i, j) showed limited travel distances. Approximately 60% of the particles dispersed over distances of 100~300 km in the direction of northwestward. Particles from Banco de Serranilla and Belize southwest Caribbean region (Fig.2.16k, l) demonstrate different dispersal patterns with Banco de Serranilla showing a more dispersive pattern, while Belize exhibiting more retentive feature. At Banco de Serranilla site (Fig.2.16k), three major peaks exist at 100, 500 and over 2000 km, corresponding to the three hot spots in the particle exports at local area, southern and central GOM, eastern GOM, and SAB. However, particles at Belize are mainly restricted at distances of 100~200 km (~60%) to the north. The dispersal distances for the particles at Panama-Colombia region (Fig.2.16m, n, o) become increasingly dispersive from Nicaragua, Panama to Colombia. At Colombia, 90% of the particles disperse relatively uniform over a range of 100 to 1400 km in the direction of northwestward with maximum percentage of particles travel at a distance of 700 km, showing a distinctive dispersive pattern. Compared to Colombia, majority of particles at Nicaragua (60%) actually
move southward at a distance of 100~300 km. This feature can be attributed to the cyclonic PCG at this region, which delivers particles at Nicaragua southward and move the particles at Colombia northwestward. At southeast Caribbean Sea (Fig.2.16p), particles mainly move northwestward at any distances. At the Antilles region (Fig.2.16q, r), around 60% of the particles moves in the northwestward direction at distances of 300~700 km.

2.4.3 Seasonal and inter-annual variability focusing on coral reef connectivity

In addition to the mean particle dispersal, the seasonal and inter-annual variability of transport connectivity were also investigated for the 18 coral reef sites. For illustration purposes, we chose two release sites including the Florida Keys, and Andros Is., Bahamas to describe their inter-annual (Fig.2.17) and seasonal (Fig.2.18) variability in connectivity patterns. We do note some pronounced differences from year to year (Fig.2.17). For example, the dispersal distance in 2009 and 2010 in Andros, Is., Bahamas is more self-retentive compared to previous years. In 2009 and 2010, 70% of the particles travel within 400 km distance from their release site, which increased substantially from 48% in 2007 and 2008. Besides, only 10% (9%) of the particles could disperse over 1600 km in 2009 (2010), while in 2007 and 2008, over 20% of the particles could travel over 1600 km. The overall dispersal pattern changes from bimodal pattern in 2007 and 2008 to a single peak pattern in 2009 and 2010. The inter-annual variation in the angular direction is also noticeable in these years at
Andros, Is., Bahamas. In 2009 and 2010, though majority of the particles are still moving northward, more particles were moving westward compared to in 2007 and 2008. At the Florida Key site, 50% of the particles in 2007 moved over 1500 km with the Gulf Stream with a single peak distribution, however, in other years, the dispersal distribution was bimodal with peaks at both 1700 km and 1800 km.

The seasonal variability of particle dispersal was also significant for most of the coral reef sites (Fig.2.18). For instance, in winter time the dispersal distance for particles released at Andros, Is., Bahamas were within 200~300 km compared to in other seasons when particles could travel over 1500 km. In addition, the amount of particles moving westward in winter is comparable to those moving northward. In contrast, only a small portion of particles are moving westward in other seasons.

To quantify the contribution of circulation at seasonal and interannual time scale, A 1-way ANOVA test (e.g. Cuevas, 2003) was applied to each of the 18 coral reef sites to statistically examine particle dispersal distances and angles and how significant their inter-annual and seasonal variability. Table 2.1 & 2.2 showed that 16 (16) out of 18 sites show significant inter-annual differences in dispersal distance (direction). Likewise, dispersals at 16 (16) of 18 sites can vary significantly by seasons in their dispersal distance (direction). Thus, inter-annual and seasonal variability are important factors in modulating the particle
dispersal at most of the coral reef sites in the IAS, and therefore is crucial to be taken into consideration.

The importance of seasonal and inter-annual variability is also reflected in the mean export envelopes (Fig.2.19). Following Roberts (1997), we calculated the particle export envelopes after the advection of 30 and 60 days, respectively for six representative coral reef locations. There were some similarities in the basic envelop patterns between our analyses and Roberts (1997) results (Fig.2.1c). For instance, at the Florida Keys, the envelop ranges from the west of the Keys to the large areas downstream. However, one major discrepancy is that for all of the 6 locations, the export envelopes computed in our analyses cover much larger areas than Roberts (1997). Our study has taken all the high frequency variability associated with surface currents into consideration as compared to Roberts (1997) that only used mean surface currents. Indeed, the model simulated mean surface currents and their corresponding variance ellipses (Fig.2.20) indicated that the variability of surface currents is significant in most regions of IAS. The current variational ellipses were relatively larger compared to their mean flow in western GOM, northwest Caribbean Sea near Cuba, northeast Caribbean Sea and the open ocean. Particle dispersal from these areas therefore experiences more variability from the mean. In contrast, in regions such as the major flow system including the Caribbean Current, Loop Current and Gulf Stream, the mean flow overwhelms the major variations in general. However, the current variability is not negligible and can
modulate the particle trajectory. Therefore, relying solely on the mean surface currents to track the passive particles may be suitable to obtain general patterns, but may be biased in resolving details and variability in the transport envelope quantification.

2.5 Discussion and conclusions

Circulation transport connectivity in the IAS was investigated based on ocean circulation model hindcast and particle tracking computer simulations during 2007-2010. The model was able to reproduce the circulation, eddy kinetic energy, surface thermal structure, surface dynamic topography, and coastal sea level variations in a reasonable manner. The model also captured vertical structures of the temperature and salinity reasonably well as gauged against in-situ CTD data.

We applied particle tracking to study potential transport connectivity in the IAS and implications for the coral reef in the IAS. The mean, seasonal and inter-annual variability of connectivity were quantified for the 18 coral reef sites and compared with the export envelopes shown in Roberts (1997). Results are very similar in the general spatial distribution of larval dispersal of Roberts (1997). For example, mean particle dispersal varies among the 18 coral reef sites. Particles in the western GOM region were relatively retentive, whereas the majority of particles released from Florida Keys moved downstream and covered a large area of the SAB and Gulf Stream. Particles arriving at the Florida Keys came from a
large upstream area in the western Caribbean Sea. Most of the particles released from the northwestern Caribbean region tended to remain near their coastal areas, and only a small portion travelled into the Loop Current and Gulf Stream. Particles released from the southwestern Caribbean region had a large tendency of moving downstream into the GOM near Campeche area and depended heavily on local supply. Particles from the Panama-Columbia region were very much self-sustained, although a portion could disperse over larger areas to central and western Caribbean Sea. Although particles from the southeast Caribbean region show a dispersive pattern with a large portion of the particles move westward along with the Caribbean Current, it depended solely on local supply for replenishment. Particles from the Antilles region exhibited a retentive feature with particles moving both westward into the Caribbean Sea and northwestward along the island chain. Local supply of possible larvae is also the main contributor to this region.

In addition to mean dispersal discussed above, significant inter-annual and seasonal variability of particle dispersal distribution were demonstrated for 16 of the 18 coral reef sites. Our results also show that the upper-bound limit (i.e., far side that particle may reach) defined by Roberts (1997) is in a sense biased, supporting the conclusion that higher-frequency variations in hydrodynamics should be retained to yield accurate dispersal envelopes (Putman and He, 2013).
We note that our transport and connectivity analyses only considered ocean physics alone. The resulting transport envelopes we generated are therefore the upper bounds of real transport envelopes for the coral reef species (Jones et al., 1999). Species-oriented studies considering biological behaviors (i.e., swimming, growth, mortality, etc.) such as Cowen et al. (2000; 2006) and their coupling with ocean circulation are needed in the future to better assist coastal management and design of marine protected areas (MPAs) across state and country borders, and thus one of our ongoing research which will be report in the not far future (Young et al., in prep). Nevertheless, this study provide invaluable insight on how the circulation at seasonal to interannual timescale may change the larval dispersal potential, and is vital in any future physical or biotic simulation.
References


Young, C., He, R., Li, Y., and H. Qian, Effect of oxygen consumption on larval dispersal in the Gulf of Mexico, *Integrative and Comparative Biology*, in preparation.
Chapter 3: Circulation Dynamics and Particle Dispersal in the Gulf of Mexico during Hurricanes Gustav and Ike

Hui Qian, Ruoying He, and Yizhen Li
Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University,
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Abstract

The upper ocean circulation dynamics and passive particle dispersal during the passage of hurricane Gustav and Ike in 2008 in the Gulf of Mexico were investigated using numerical modeling and particle tracking methods. Model predictions were validated against buoy and sea level observations, and demonstrated that the model captured the major disturbances brought by hurricanes reasonably well. Based on the hindcast solutions, circulation dynamics including momentum, vorticity and energy budgets were analyzed and the results show that during hurricane periods, the wind plays a critical role in adjusting the ocean dynamics. The quantification of passive particle dispersal patterns along the hurricane tracks further indicates that hurricanes can induce strong vertical motions and change the fate of the particles over a time range of several days. Conversely, the horizontal dispersal brought by hurricanes are relatively limited especially to the particles at deeper depths.

3.1 Introduction

The Gulf of Mexico (GOM) is a semi-enclosed sea in the western Subtropical Atlantic
Ocean. It is connected to the open ocean through two narrow openings: one is the Yucatan Channel in the south connecting the Caribbean Sea to the Gulf with a sill depth of approximately 2040 m; the other is the Straits of Florida between Florida and Cuba with a shallower sill depth of around 800 m, connecting the Gulf with Atlantic Ocean in the east.

The GOM is known to be a prime location for hurricane intensification due to its stratified and warm water column that can fuel tropical cyclones fairly quickly. It is known that warm Sea Surface Temperature (SSTs) (>26°C) are favorable for hurricane genesis by providing the energy necessary for deep atmospheric convection (Palmen, 1948).

The interaction between hurricane and its underlying ocean has long been the major research focus in oceanography community (e.g. Leipper and Volgenau, 1972; Shay et al., 2000; Hong et al., 2000). Typically, during the passage of hurricane, the SST decreases due to processes including hurricane-induced entrainment, vertical mixing and upwelling, as well as air-sea heat exchange (Leipper, 1967; Fedorov et al., 1979; Pudov et al., 1979; Greatbatch, 1985). Many studies have been examined the relative importance of these processes and found them to be storm case dependent. Price (1981) examined the upper ocean response to a hurricane and concluded the entrainment is the primary mechanism for lowering the SST, and that air–sea heat exchange only plays a minor role. Morey et al. (2006) investigated the upper ocean response to the surface heat and moment fluxes associated with hurricane Dennis, and
demonstrated that the surface heat flux are primarily responsible for the widespread SST reduction, while the vertical thermal energy flux due to upwelling were responsible for the cooling in the center of the storm. Prasad and Hogan (2007) showed that the hurricane-induced seas surface cooling was mainly due to vertical mixing (~60%) and upwelling (~20%), and the air-sea exchange accounted for ~4% only during the passage of Hurricane Ivan in 2004. Based on numerical simulations from HYCOM, Gierach et al. (2009) examined the upper ocean heat budget as responding to hurricane Katrina. Their results showed that the surface heat flux accounted for pre-storm temperature changes, and wind-driven vertical mixing dominated net upper-ocean cooling. At deeper depths, temperature changes were largely due to vertical advection associated with upwelling and downwelling. In addition to these physical responses, the biological impact brought by hurricane is also of great interest. Strong wind associated with the processes of entrainment and upwelling brings up the nutrient-rich water from the deep layer to the upper euphotic zone and triggers phytoplankton blooms several days after hurricane passage. For instance, Lin et al. (2003) presented enhanced primary production triggered by hurricane using satellite data. Walker et al. (2005) showed that hurricane-induced upwelling led to a Chl-a enhancement within cold-core cyclones in the Gulf of Mexico. Likewise, Shi and Wang (2007) also showed that the elevated phytoplankton bloom occurred in the same region in the Gulf of Mexico where the significant sea surface cooling was induced by the passage of
hurricane *Katrina*. The work by Hu and Muller-Karger (2007) demonstrated that hurricanes do not necessarily induce chlorophyll bloom every time they pass the deep water because the hurricane-induced vertical mixing may not reach the nutricline and therefore no significant increase of nutrient content to support phytoplankton bloom in the euphotic zone. Gierach and Subrahmanyam (2008) further investigated the detailed mechanisms of surface Chl-a maximum associated with three major hurricanes in the GOM. They suggested that for hurricane Katrina and Rita, the increase of phytoplankton biomass was the result of both new production owing to nutrient influx and entrainment of subsurface phytoplankton maximum; while for hurricane Wilma, it was dominated by the entrainment mechanism.

The magnitude and orientation of hurricane-induced biophysical responses are functions of hurricane characteristics, including hurricane intensity and translational speed. Price (1981) suggested that a rightward SST bias was in response to fast moving hurricane ($\geq 6$ ms$^{-1}$), whereas under slower moving hurricanes the rightward bias was reduced due to significant upwelling and entrainment. In addition, the pre-storm ocean environmental conditions can also make a difference. In a water column with shallow thermocline and nutricline, it is more likely for pronounced upper-ocean cooling and nutrient influx to happen. In contrast, if the upper ocean water column is well-mixed at the first place, the temperature and nutrient responses may be much more limited. The presence of cold-core eddies and warm core eddies in the ocean can complicate the hurricane-induced responses as well. The cold-core
(warm-core) eddies are typically associated with shallower (deeper) thermocline and nutricline (e.g. McGillicuddy et al., 1999), thus cold and nutrient-rich subsurface waters are relatively easier (more difficult) to be pumped into the surface water.

One understudied question is the detailed 3-dimensional transport and distribution of water properties associated with strong advection and entrainment induced by hurricane. This is the focus of this study, and we will examine the upper ocean circulation dynamics and Lagrangian dispersal in response to two consecutive hurricanes in the Gulf of Mexico in 2008: Gustav and Ike. Both Gustav and Ike were category 2 hurricanes when they made landfall at the northern GOM coast. Gustav was a fast-moving hurricane with a mean translation speed of 7.5 m/s. It originated in east Caribbean on August 25, 2008, progressed into the GOM on August 30 and landed at southern Louisianan coast on September 1, 2008 (Fig. 3.1). Sequentially, Ike originated in the tropical Atlantic Ocean on September 01, 2008 and was having a relatively slower translation speed (4.8 m/s). It entered the GOM on September 9, 2008 and landed at Galveston, Texas four days later (Fig. 3.1). The two consecutive hurricanes brought great changes in the water properties and circulation structures in the GOM. In this study we used numerical model simulations and particle tracking methods to hindcast ocean circulation and quantify the corresponding Lagrangian dispersal patterns during these two storms.
3. 2 Model and method

3.2.1 Ocean circulation model

The ocean circulation hindcast was performed using the Regional Ocean Modeling System (Haidvogel et al., 2008; Shchepetkin and McWilliams, 2005). ROMS is a free-surface, hydrostatic, primitive-equation model that employs split-explicit separation of fast barotropic and slow baroclinic modes and vertically stretched terrain-following coordinates.

Our model domain covers the entire Intra America Sea (hereafter IAS) including the Caribbean Sea, the Gulf of Mexico and the South Atlantic Bight. The model has a horizontal resolution of ~6 km (Fig.3.2). Vertically there are 30 terrain-following levels in the water column with higher resolution near the surface and bottom to better resolve boundary layer dynamics. The initial and open boundary conditions for our IAS ROMS model were provided by the global data assimilative Hybrid Coordinate Ocean Model (HYCOM). HYCOM assimilates satellite observed SST, sea surface height, and drifter measured temperature and salinity profiles, providing daily global circulation (http://hycom.rsmas.miami.edu/dataserver) at roughly 10-km spatial resolution. At the land boundary, fresh water discharge from 144 rivers along the IAS coast was considered in the model simulation. We used USGS daily river gauge observations where they are available, otherwise long-term monthly mean values to define river freshwater fluxes.
For surface meteorological forcing, we blended the 6-hourly, 6-km resolution Hurricane Research Division wind (HRD wind, www.aoml.noaa.gov; Powell et al., 1998; Moon et al., 2008) with National Center for Environmental Prediction (NCEP) reanalysis wind. Other surface atmospheric variables including total cloud cover, precipitation, surface pressure, relative humidity, air temperature, net shortwave and longwave radiations were all provided by NCEP reanalysis and included in the standard bulk formula (Fairall et al., 1996a; Fairall et al., 1996b; Liu et al., 1979) to derive wind stress and net surface heat/salt flux needed by the simulation. The Mellor-Yamada (1982) closure scheme was applied to compute the vertical turbulent mixing, as well as the quadratic drag formulation for the bottom friction specification.

Using this model setup, we carried out circulation hindcast for a 2-month period (from August 1, 2008 to October 1, 2008) that encompasses the entire life span of Hurricane Gustav and Ike.

3.2.2 Analysis methods

Based on IAS model results, we can investigate the GOM circulation dynamics through term-by-term analyses of momentum, vorticity and energy budgets during the passage of hurricanes. These high-order diagnostics provide useful insights on detailed dynamical balances and vorticity and energy sources that reshape ocean conditions during the passage of
hurricanes Gustav and Ike.

### 3.2.2.1 Momentum balance

The vertically integrated momentum equations can be written as:

\[
\int_{-h}^{\xi} \frac{\partial u}{\partial t} dz + \int_{-h}^{\xi} u \frac{\partial u}{\partial x} dz + \int_{-h}^{\xi} v \frac{\partial u}{\partial y} dz + \int_{-h}^{\xi} w \frac{\partial u}{\partial z} dz - \int_{-h}^{\xi} f v dz = \int_{-h}^{\xi} \left( -\frac{1}{\rho_0} \frac{\partial p}{\partial x} \right) dz + \frac{\tau_{xx} - \tau_{bx}}{\rho_0} \\
\int_{-h}^{\xi} \frac{\partial v}{\partial t} dz + \int_{-h}^{\xi} u \frac{\partial v}{\partial x} dz + \int_{-h}^{\xi} v \frac{\partial v}{\partial y} dz + \int_{-h}^{\xi} w \frac{\partial v}{\partial z} dz + \int_{-h}^{\xi} f u dz = \int_{-h}^{\xi} \left( -\frac{1}{\rho_0} \frac{\partial p}{\partial y} \right) dz + \frac{\tau_{yy} - \tau_{by}}{\rho_0}
\]

where \( h(x, y) \) is bottom depth and \( \zeta(x, y, t) \) is the surface elevation, \( \tau_{xx} \) and \( \tau_{yy} \) are wind stress, \( \tau_{bx} \) are \( \tau_{by} \) are bottom stress. The left-hand-side of the equations \((1)\) includes the acceleration term, nonlinear advection, and the Coriolis term. The right-hand-side has the pressure gradient term, wind stress term and bottom stress term. Each term can be calculated based on model diagnostic output. Our analysis suggested that horizontal mixing term was negligibly small and thus were excluded in the analysis.

### 3.2.2.2 Vorticity balance

Based on \((1)\), we can derive the vertically-integrated vorticity equation by taking the curl of each momentum equation. If we define:

\[
P_x = \int_{-h}^{\xi} \left( -\frac{1}{\rho_0} \frac{\partial p}{\partial x} \right) dz, \quad P_y = \int_{-h}^{\xi} \left( -\frac{1}{\rho_0} \frac{\partial p}{\partial y} \right) dz, \quad A_x = \int_{-h(x,y)}^{\zeta(x,y,t)} \left( u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) dz.
\]
\[ A_y = \int_{h(x,y)}^{z(x,y)} (u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z}) dz, \quad A = A_x \hat{i} + A_y \hat{j}, \quad M = \left( \int_{-h}^{z} udz \right) \hat{i} + \left( \int_{-h}^{z} vdz \right) \hat{j} \]

then vertically integrated vorticity equation can be written as

\[
\frac{\partial}{\partial t} \text{curl}_z (M) + \text{curl}_z (A) + M \cdot \nabla (f) = \left( \frac{\partial (P_y)}{\partial x} - \frac{\partial (P_x)}{\partial y} \right) + \text{curl}_z \left( \frac{\tau_x - \tau_h}{\rho_o} \right)
\]

The terms on the left-hand-side stand for the time rate of change of vorticity, advection curl and Advection of Potential Vorticity (APV), respectively. The terms on the right-hand-side are pressure gradient force curl and stress curl. The pressure gradient force curl is equivalent to JEBAR (Joint Effect of Baroclinicity and bottom Relief) (Sakisyan, 2006) if zeta=0 is assumed in the derivation.

3.2.2.3 Kinetic Energy Budget

The Kinetic energy equation can be obtained by adding the u- momentum equation in (1) times u, and the v-momentum equation in (1) times v (e.g., MacCready et al., 2009). It can be expressed by

\[
d \left( \frac{1}{2} \rho_0 u^2 + \frac{1}{2} \rho_0 v^2 \right) = \left( -u \frac{\partial p}{\partial x} - v \frac{\partial p}{\partial y} \right) + \rho_0 u \frac{\partial}{\partial z} (K_m \frac{\partial u}{\partial z}) + \rho_0 v \frac{\partial}{\partial z} (K_m)
\]

where \( K_m \) is the vertical viscosity coefficient. If we define the horizontal Kinetic Energy (KE) and horizontal Pressure Work (PW) as
\[ KE = \frac{1}{2} (\rho_0 u^2 + \rho_0 v^2), \quad PW = (-u \frac{\partial p}{\partial x} - v \frac{\partial p}{\partial y}) \]

the vertically integrated energy equation can be written as

\[
\frac{\partial}{\partial t} \left( \int_{-h}^{\zeta} KE \, dz \right) + \int_{-h}^{\zeta} \left( u \frac{\partial KE}{\partial x} + v \frac{\partial KE}{\partial y} \right) \, dz \\
= \int_{-h}^{\zeta} PW \, dz + (u \tau_x + v \tau_y)_{z=\zeta} - (u \tau_x + v \tau_y)_{z=-h} \\
- \int_{-h}^{\zeta} \rho_0 K_m \left( \left( \frac{\partial u}{\partial z} \right)^2 + \left( \frac{\partial v}{\partial z} \right)^2 \right) \, dz
\]

This equation includes from left to right the rate of \( KE \) change, advection work, pressure work, wind stress work, bottom stress work and dissipation.

### 3.2.3 Particle tracking method

Passive particle trajectories during the passage of hurricanes were calculated using Lagrangian Larval TRANSport model (LTRANS, North et al., 2008, 2011). This is an off-line particle-tracking calculation that runs with stored 12-hourly predictions of a 3-D IAS ROMS hydrodynamic model. LTRANS includes a 4th order Runge-Kutta scheme for particle advection and a random displacement for vertical turbulent motion. To avoid possible beaching (hitting the land boundary of IAS ROMS model) of the particles, reflective horizontal boundary conditions were applied to keep the particles within the ocean domain.
 Specifically, when a particle hits the land boundary, it is reflected back using the same angle of its approaching to the boundary. Details on LTRANS are given in North et al. (2008; 2011).

3.3 Model validation

To assess the model performance, IAS ROMS model solutions were first validated against National Data Buoy Center (NDBC) observations at buoy 42001. Buoy 42001 is located right on the track of hurricane Ike (Fig. 3.1, pink triangle). The vector plot of surface wind (Fig. 3.3, upper two panels) from blended product of NCEP and Hwind shows good consistency with buoy observations as well. Stronger winds are detected both in model and observations when hurricane Gustav and Ike passed through on September 1 and 13, 2008, indicating the good performance of our blended surface wind product that was used to drive the model. Both Gustav and Ike were category 2 hurricanes when they made landfall at the northern GOM coast, and Gustav was a relatively faster-moving hurricane with a mean translation speed of 7.5 m/s compared the Ike which has a slower translation speed (4.8 m/s). In addition, a 24 hour low pass filter was applied to both buoy observed and model simulated SST to focus on the sub-tidal signals. Their comparison (Fig. 3.3, lowest panel) shows that the model is able to reproduce the SST temporal evolutions during the first 40 days and overestimated the SST after the passage of hurricane. Although the model successfully
captures the temperature decrease (by 2°C) when hurricane Ike passed by on September 13, the modeled SST is generally 0.5-1°C warmer than observations after hurricane passage. Such differences may due to a number of factors, including the spatial offsets between the buoy point and the model’s 6-km footprint, the difference between temperatures measured 1-m below the surface by the buoy and temperature simulated by the top vertical layer of the model, as well as possible forcing defects that need further refinement in the future.

The model solutions were further validated against National Ocean Service (NOS) sea level at 12 coastal stations along the GOM coast (Fig.3.4). We focused on sub-tidal circulation as they dominate material property transport, so both observed and simulated hourly sea level time series were 36-hour low-pass filtered before their comparisons (Fig.3.5). The results show the model successfully captured sea level variations. Both the model and data show that strong surge occurred during hurricane Ike than during Gustav. This is closely related to the fact that hurricane Ike is slow moving which has sufficient time to exert effects on its underlying ocean. The correlation coefficients between model and observations are all over 0.80 for all these stations, indicating reasonably well agreement between model and observations.

Overall, the model-data comparisons suggest that both wind forcing and the circulation model is in general capable of capturing the major ocean disturbances brought by hurricanes,
lending us confidence for further circulation dynamics and particle dispersal analysis.

3.4. Results

3.4.1 Ocean circulation dynamics

Snapshots of model simulated Sea Surface Height (SSH) with sea surface currents and hurricane tracks overlaid (Fig. 3.6) show the ocean surface conditions during the passage of the hurricanes. On September 1, 2008, strong currents and elevated sea level occurred in the northeastern GOM coast as hurricane Gustav was about to land. It also significantly affected its ambient regions along the track. Subsequently, on September 13, 2008, Hurricane Ike induced strong coastal currents and rising sea level on the Louisiana-Texas coast before its landing. In addition to the surface current and sea level, the SST response was characterized by large area of cooling as demonstrated by Tropical Microwave/Imager (TMI) data (Fig. 3.7). For hurricane Gustav (first row in Fig. 3.7 first row), the strongest cooling occurred on the right side of the track with maximum temperature decrease reaching around 2°C in northern GOM. Compared to hurricane Gustav, Hurricane Ike exerted a much larger impact (Fig. 3.7 second row). SST cooling occurred in the most of central to east GOM basin with a maximum temperature decrease around 3°C on the right of the track. It is noted that the reduced SST caused by hurricane Gustav (September 6-9, 2008) in the northern GOM did not have sufficient time to return back to its normal seasonal value before Hurricane Ike hit this
region again. So the combined effect of the two consecutive hurricanes on SST is clear (last row of Fig.3.7).

Hurricane induced changes at depth can be quantified by Ekman pumping using this formula

\[
w = \frac{\text{curl} (\tau)}{\rho f}
\]

where \( \tau \) is the wind stress, \( \rho \) is the water density and \( f \) is the Coriolis parameter. Fig.3.8 shows the distributions of Wind stress field and Ekman pumping velocity during the passage of hurricane Gustav (upper two panels) and Ike (lower two panels). The strongest upward Ekman pumping occurred at the center of the hurricane eyes. The strength of upwelling decreased away from the center and became downwelling at outer regions of the hurricane center. This feature moved along with hurricane eyes. Thus for a specific region in GOM, the detailed subsurface ocean response is complex due to the mixture of both upwelling and downwelling conditions depending on the timing and locations of hurricane.

To better illustrate the hurricane induced ocean dynamics changes, momentum, vorticity and energy budgets were further analyzed during the passage of hurricanes based on the numerical model solutions. To highlight the dynamic balance differences during hurricane periods, four snapshots were selected for each term: before hurricane on August 27, 2008,
hurricane Gustav on September 1, 2008, hurricane Ike on September 12, 2008 and after hurricane on September 16, 2008. Each term was vertically integrated from 50m to surface to reflect the direct impact of hurricane to ocean upper column. Fig.3.9 shows the distribution of vertically integrated momentum balance before, during Gustav, Ike and after hurricane passages in the GOM. Each period included both U- and V-momentum balances. As we can tell, before the hurricanes’ arrival (Fig.3.9a), the main momentum balance was geostrophic balance with the Coriolis term and pressure gradient term, both are several orders of magnitude larger than the rest of the terms. The ageostrophic balance (after summation of the Coriolis and pressure gradient terms) was mainly balanced by acceleration and advection terms in the majority of GOM, especially in the Loop Current region where advection is significantly important, while wind stress played a smaller role. However, during the passage of hurricane (Fig.3.9b and Fig.3.9c), each of the momentum term increased in the hurricane-affected regions. The main balance was still the geostrophic balance, but wind stress increased substantially and became an important contributor to balance the ageostrophic processes, meanwhile the advection and acceleration term continue to play important roles. After the passage of hurricanes (Fig.3.9d), with wind stress reduced significantly, the ageostrophic processes were mainly balanced by advection and acceleration terms and gradually going back to the pre-hurricane conditions. The acceleration term was larger compared to its pre-hurricane value, suggesting the ocean was still in a rapid
adjustment phase to disintegrate all the perturbations and energy injected by hurricanes.

The distributions of vertically integrated vorticity balance from 50 m to surface before hurricanes, during Gustav, Ike and after hurricanes were shown in Fig.3.10. Before and after hurricanes (Fig.3.10a, Fig.3.10d), the vorticity balance was mainly among APV, advection and acceleration terms. JEBAR term was significant along the shelf break region and negligibly small in the deep basin, and wind stress curl was important along coastal regions. When hurricanes came (Fig.3.10b and Fig.3.10c), the increased wind stress generated strong positive vorticity input along and in the vicinity of hurricane tracks, which was mainly dissipated through APV, advection and acceleration. In the hurricane affected regions, the wind stress curl became the dominant factor in the vorticity balance of APV. JEBAR term remained small throughout all these periods.

We also investigated distributions of vertical-integrated energy balance from 50 m to surface before, during Gustav, Ike and after hurricanes (Fig.3.11). Before and after hurricanes (Fig.3.11a&d), the pressure work was mainly balanced by advection work with stronger energy concentrated in the Loop Current area. In the rest of the GOM region, the energy was smaller. During the hurricane periods (Fig.3.11b and Fig.3.11c), wind stress work was over 20 times larger, especially in the hurricane attacked regions. In response, the dissipation increased accordingly, and the main energy budget was between wind stress work and

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dissipation.

### 3.4.2 Particle tracking

The circulation hindcast solutions provided a perfect opportunity to study the particle dispersal potential during a hurricane environment from a Lagrangian perspective. To do this, numerical passive particle trajectories were calculated using the particle tracking model LTRANS (North et al., 2008, 2011). Particles were released along the hurricane tracks at depths every 30 meters from 0 to 300 m (Fig.3.12). These particles were released every 6 hours when the hurricane entered the GOM, that is, particles along the Gustav (Ike) track were released every 6 hours from Aug31st (September 10th) to September 2nd (September 13th), 2008. In total, 2574 and 8008 particles were released along Gustav and Ike track respectively. All the released particles were tracked to the end of September, 2008. For comparison, the same release schemes were applied to the without hurricane conditions along both Gustav track and Ike track with arbitrary initial release time. In this study, the particles were released on Aug. 21, 2008 and tracked for 7 days. That is, the same number of particles were released along the Gustav track on Aug. 21, 2008 as they were during hurricane Gustav, and tracked for 7 days; the same number of particles were released along the Ike track on Aug. 21, 2008 as they were during hurricane Ike and tracked for 7 days. For consistency, particles dispersal after 3 days of hurricane passage was selected for further analyses.
As an example, Fig.3.13 shows the dispersal pattern of particles released at 60 m depth during the passage of hurricane Gustav. Initially, all the particles were lined up with the Gustav track (Fig.3.13a). As Gustav passed by, particles initially located at 60 m experienced strong vertical motions (Fig.3.13b). Some of the particles moved upward to 20~30 m depth, while some particles moved downward to deeper depths. Their horizontal dispersions are limited. The histogram in Fig.3.14 presented both vertical and horizontal dispersal of the particles in a quantitative way for both without and with hurricane conditions. Initially, 234 passive particles were released at 60 m (Fig.3.14a). Under no hurricane conditions, after 3 days, 80% of all the particles still remained within 5 m distance of their original positions (Fig.3.14b dark red bars). In contrast, after 3 days when hurricane Gustav went across the GOM, 49.2% of particles moved upward with around 13% even reaching 20 m; meanwhile, 84 particles (35.9%) dispersed into deeper depths with a few reaching 120 m (Fig.3.14b blue bars). In total, 85.1% of the released particles experienced strong vertical motions and the upward moving particles were quantitatively more than those moving downward. Compared to the significant change on vertical dispersal pattern brought by hurricane, the horizontal dispersion for the particles released at 60 m shows similar patterns for both no hurricane and Gustav conditions (Fig.3.14d) with the majority of particles move within a horizontal distance of 40 km, demonstrating limited horizontal dispersion after several days release.

Similar results were found in hurricane Ike case. Fig.3.15 showed the particle dispersal
during the passage of hurricane Ike in the same fashion as Fig. 3.13. During the passage of hurricane Ike (Fig. 3.15b), the majority of particles were displaced to 20~30 m, some even reaching to the surface. Fewer particles moved downward to deeper depths. Limited horizontal dispersion was present. Quantitatively, the histogram in Fig. 3.16 showed that initially 728 particles were released at 60 m along Ike track. By the end of the 3 days window when hurricane Ike passed over GOM, 391 particles (53.7%) were in the upper water column and 159 (21.8%) particles moved downward (Fig. 3.16b blue bars). Significantly more particles were in the upward motion than those moving downward. However, under no hurricane conditions, vertical displacements of the particles were quite limited with majority of the particles (93.5%) stay within 5 m of their original 60 m release depth after 3 days (Fig. 3.16b dark red bars). The horizontal dispersion pattern (Fig. 3.16d) after 3 days for both no hurricane and Ike condition shows that most of the particles disperse within 20 km of their original locations horizontally.

This vertical dispersal pattern under the effect of hurricane is not limited to the particles released at 60 m, but throughout the entire upper water column (0-300 m). Fig. 3.17 showed the vertical distribution of particles dispersal after release for 3 days at each release depth. Fig. 3.17a and b presented the comparison between no hurricane and Gustav condition. In the no hurricane condition, after 3 days of release, the majority of the particles throughout the upper 300 m stay near their release depth. At 30 m for instance, over 90% of particles stayed
essentially where they were released. Moving down to the deeper depths, we see more particles were entrained in the upward motion (up to 30% at 300-m depth). However, with the passage of hurricane Gustav, the particle’s vertical dispersal distributions changed dramatically. Both upward and downward motions increased significantly throughout the upper 300 m. At 3 days advection time, most of the particles could travel 30 m vertically, some even reaching to the surface. In addition, the percentages of particles moving upward and downward were comparable (more or less around 40%). In the upper 120 m, the upward moving particles were slightly more than those moving downward, while below 150 m, there were generally more particles moving downward than going upward. The comparison of vertical distribution between no hurricane and Ike demonstrated some interesting differences. The passage of hurricane Ike induced more particles moving upward. Over the upper 300 m, the percentage of particles moving upward was twice or more than those moving downward. In both Gustav and Ike cases, hurricane induced stronger vertical motion in the upper 120 m than that down below. For instance, at 90 m release level in Ike case, percent of particles moving upward increased from less than 3% under no hurricane condition to ~40% with Ike, while at 300 m, the percentage increased from 20% to around 50%, indicating the effect of hurricane was more significant in the upper 100 m compared to deeper depths.

In addition to the vertical displacement, the horizontal dispersion for particles released at all depths for advection time of 3 days were also quantified (Fig.3.18). The comparison of
horizontal dispersal distance between no hurricane and Gustav conditions (Fig. 3.18a, b) shows that in both conditions, the majority of particles disperse within 30 km and most of them travel at round 10 km. That is around 70~90% of particles are within 30 km of their release locations after 3 days advection, especially to the particles released below 120 m. Although Gustav does cause more particles to disperse over longer distances (over 40 km), its overall effect on the distribution of horizontal dispersal distance is quite limited. Similar conditions can be found in the comparison of no hurricane and hurricane Ike case (Fig. 3.18c, d). The distributions of horizontal dispersal distance under both conditions are quite similar throughout the upper 300 m where particles were released. Therefore, unlike the hurricane induced strong vertical displacements, the horizontal dispersal distance for the particles released along the hurricane tracks is not greatly influenced by the passage of hurricanes.

Thus, from the perspective of both horizontal and vertical displacement, it is clear that the effect of hurricane passage on the dispersal of particles released along the track is mainly vertical within several days. Under no hurricane conditions, passive particles at depth usually experience little vertical motions within several days of release. However, the passage of hurricanes can significantly change their vertical dispersal pattern by inducing strong vertical motions, and hence change the fate of the particles especially to those moving into the upper water column.
Fig. 3.19 showed the final dispersal pattern by the end of 20 days (Gustav) and 30 days (Ike) tracking for both Gustav track release (Fig. 3.19a) and Ike track release (Fig. 3.19b) at 60 m. In the Gustav case, the downward moving particles are more retentive (i.e., remain in the neighborhood of their initial horizontal locations), while the upward moving particles were more diffusive (Fig. 3.19a). Some of particles were able to travel northwestward to the Louisiana Texas shelf, some moved northeastward, some to the south and entering the Loop Current. The spatial discrepancy of the horizontal particle dispersal between upward and downward particles was mainly attributed to the larger currents at surface compared to the relatively smaller currents at depths. In the Ike case, particles in the northern part tended to move westward and particles released in the southern part tended to move into the Loop Current and even Florida Strait (Fig. 3.19b).

3.5. Discussions and conclusions

Two consecutive hurricanes Gustav and Ike in 2008 introduced dramatic perturbations in both physical and biological environments of the GOM. The SST analysis showed that during the passage of hurricanes, SST cooled 2~3°C in the vicinity of hurricane affected areas, with maximum cooling occurred to the right of the hurricane tracks. The wind stress field and its associated Ekman pumping suggested that hurricane induced both upwelling and downwelling, with strongest upwelling coinciding with hurricane eyes, decreasing further out
A regional domain IAS ROMS model was used to hindcast the ocean conditions associated with hurricane passages. Validations against sea level and buoy observations show the model performed well in capturing the major disturbances brought by hurricanes. Model hindcast solutions and particle tracking calculations are used to illustrate circulation dynamics and particle dispersal during the passage of hurricanes Gustav and Ike. The results showed: 1) during the hurricane period, although the major geostrophic balance still held, wind stress became a major contributor to the ageostrophic processes; 2) Vertically integrated vorticity balances changed from a balance among APV, advection and acceleration to a balance between APV, advection, acceleration and wind stress curl. The increased positive vorticity input from wind stress was mainly dissipated through APV, especially along and in the vicinity of hurricane tracks; 3) with regards to ocean energetics, the major upper ocean energy is primarily balanced by wind stress work and dissipation in the northeast GOM during hurricane periods. In contrast, the advection work and pressure work dominate the balance during pre-hurricane conditions. It is noted that most of the energy increases during hurricane period occurred to the right of hurricane tracks.

Corresponding to the physical environment change, the particle dispersals during the hurricane period were also very different. The motions of particles released along the two
hurricane tracks show that hurricane induced horizontal dispersal is quite limited and its main effect lies in the vertical displacement. Hurricanes served as an instant impulse triggering the movement of the particles. Under no hurricane conditions, the passive particles usually experience small vertical movements. However, as hurricane passed by, strong vertical motions were induced. The upward motion brought the majority of the particles at depth to the upper layer, or even surface, which subsequently result in a much more dispersed horizontal pattern compared to the relatively retentive feature in no hurricane conditions.

Several caveats of this study are noted here. We used passive particle tracking as an initial step to demonstrate the strong impact of hurricane on the transport of materials in a biological sense, a critical step forward for future study of biological species. This study is also a good approximation of larval dispersal with limited biological behavior (i.e., vertical aggregation, diel cycle, etc.). We do realize though, biological processes are perplexed by both physical transport and biological behavior (swimming, benthic-preference, etc.). A fully coupled bio-physical modeling study is necessary in the future to simulate the impact of hurricane on biogenetics and connectivity. We are in the process to report part of these efforts in modeling deep ocean larval species with biological behavior (Young et al., in prep.)
References


Leipper, D.F., Observed ocean conditions and Hurricane Hilda (1964), *J.Atmo., Sci.*,24,


Enterprise, 2011.


Young, C., He, R., Li, Y., and H. Qian. Effect of oxygen consumption on larval dispersal in the deep Gulf of Mexico, Integrative and Comparative Biology, in preparation.
Chapter 4: Inertial Oscillations Induced by the Passage of Hurricane

IDA in the Gulf of Mexico

Hui Qian¹, Peter Hamilton², and Ruoying He¹
¹Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University
²Science Applications International Corporation, Raleigh, North Carolina
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Abstract

Inertial oscillations in the Gulf of Mexico induced by hurricane Ida in November 2009 are investigated using current observations from the Loop Current (LC) ocean moorings and Campeche Bank moorings, as well as numerical model simulations. Results show that the hurricane induced inertial oscillations are present in most of the LC ocean moorings from 60 m (top of a mooring ADCP) all the way to the bottom (>3000 m), transmitting energy downward as near-inertial waves. In contrast, over the Campeche bank slope which is north of the Yucatan Channel, inertial oscillations are only weakly present, and high frequency oscillations are dominated by the internal diurnal tides. The discrepancy of ocean response to hurricane Ida in these two mooring groups is found to be closely related to the background relative vorticity as well as background geostrophic flow. The positive relative vorticity blocks the equatorward propagation of near-inertial waves and strong background Loop Current prohibits the propagation of near-inertial waves.
4.1 Introduction

The upper ocean response to a moving hurricane has been studied extensively (e.g. Leipper, 1967; Brink, 1989; Dickey et al., 1998; Price, 1981; Greatbatch, 1983). Sea surface cooling and inertial oscillations have been found to be most energetic to the right of the hurricane track. In this study, the inertial oscillations induced by hurricane Ida in November 2009 in the Gulf of Mexico (GOM) have been analyzed using both mooring observations and numerical models. Hurricane Ida is a category 2 storm that originated in the southwestern Caribbean Sea on November 4 and struck the Nicaragua coast within 24 hours. It entered the GOM on November 8, weakened and became extratropical cyclone in the northern GOM before landing. It was a fast moving storm, taking only 2 days to across the GOM (Fig.4.1 red line), and creating a good case to study inertial oscillation and underlying mechanisms on near-inertial energy distribution.

4.2 Data, model, and methods

Data from two groups of moorings in the GOM, one in the Loop Current area (A-B-C transects) and the other on Campeche Bank (E-transects) have been employed in this study (Fig.4.1). The LC moorings were deployed in the eastern GOM centered in 87°W, 26°N. Measurements were taken from April 2009 to November 2011 with ADCP sensor at around 450 m. There are 47 bins in the ADCP with bin length 8 m. Therefore the ADCP measured
current velocity covers the upper water column from around 60 m to 500 m with increment of 8 m. The LC moorings were also equipped with RCM7 and RCM8 current meter sensors at 900 m and 1300 m, respectively, and RCM11 current meters at 2000 m and 100 m above the bottom. The Campeche Bank moorings were deployed on the Campeche bank slope from June 2009 to June 2011. ADCPs were deployed at around 500 m for all the E-transect moorings except E1 where the water depth is around 100 m. Mooring E1 was excluded from the study as its ADCP sensor was not working during the hurricane Ida period. At E4 and E5, there were more ADCPs located at 1000 m. These ADCPs normally have 30 bins with 16 m bin length. These moorings were also equipped with RCM11 current meter sensors at various depths including 1000 m, 1300 m, 2000 m and 100 m above the bottom for E3, E4 and E5.

The Campeche Bank moorings were run directly through by hurricane Ida, while the LC moorings were close by on the right side of hurricane track (Fig.4.1). Hourly data from both mooring groups invaluable observational evidence on hurricane induced motions. We focus on velocity time series observed from November 1, 2009 to the end of December 2009. A 45-hour high-pass filter was applied to all time series to extract the near-inertial components. We also computed rotary spectrum for U- and V- component of velocity for one month period from November 6, to December 6. The relative vorticity fields normalized by local f (i.e., \( \xi/f \)) were also calculated using either triangle or least square interpolation for velocity data from moorings.
We also utilized a 4-year ocean circulation hindcast (2007-2010) that was performed using the Regional Ocean Modeling System (Haidvogel et al., 2008; Shchepetkin and McWilliams, 2005). ROMS is a free-surface, hydrostatic, primitive-equation model that employs split-explicit separation of fast barotropic and slow baroclinic modes and vertically stretched terrain-following coordinates. The model domain covers the entire Intra America Sea (hereafter IAS) including the Caribbean Sea, the GOM and the South Atlantic Bight. The model has a horizontal resolution of ~6 km (Fig. 4.2). Vertically there are 30 terrain-following levels in the water column with higher resolution near the surface and bottom to better resolve boundary layer dynamics. The model is forced by winds and atmospheric fluxes at ocean surface and by open boundary conditions given by data assimilated global HYCOM (http://hycom.rsmas.miami.edu/dataset). Detailed model configurations can be found in Chapter 2.

To construct hurricane resolving high-resolution winds during Ida, we blended the 6-hourly, 6-km resolution Hurricane Research Division wind (HRDwind, www.aoml.noaa.gov; Powell et al., 1998; Moon et al., 2008) with National Center for Environmental Prediction (NCEP) reanalysis wind. The comparison of wind vector between the merged wind and NDBC (National Data Buoy Center) buoy 42003 located adjacent to the LC moorings (indicated as black triangle in Fig. 4.1) shows excellent agreement (Fig. 4.3) throughout our study period.
Fig.4.4 clearly presents the time evolution of surface wind field and Loop Current conditions when hurricane Ida was passing through our study area. Sea surface height fields from satellite altimetry (Robert Leben, personal communication) show that a few weeks before the passage of hurricane Ida, the Loop Current had shed an anti-cyclonic eddy and had retreated southward with its northern front located south of 25°N. A very similar Loop Current condition is produced by ROMS simulation (Fig.4.5). We focus on model simulated ocean response from November 1, 2009 to December 7, 2009, a period encompassing the entire life span of hurricane Ida. Model simulated ocean states and diagnostics were both saved at hourly intervals to keep the high frequency signals. To compare with observations, simulated velocities at mooring locations were extracted and processed by the same 45-hour high pass filter to uncover hurricane induced inertial

4.3 Difference in inertial oscillation signal

The hurricane induced inertial oscillations are found in most of the LC moorings in the upper water column. Fig.4.6a for example shows the time series plot of 45 hour high pass filtered horizontal velocity at mooring A4 at various depth levels. Near-inertial oscillation signals are clearly present after the passage of hurricane Ida around November 10, 2009 and lasting for 2 weeks at 84 m. The wave packets gradually propagate downward over time. At around 412 m, the inertial oscillation signals are in the second half of November. Similar
downward propagation of near-inertial oscillation signal is also captured by model simulations (Fig.4.6b).

In contrast, observations from the Campeche Bank moorings show little inertial energy. Fig.4.7 for example shows time series of high pass filtered horizontal velocity at E5. No strong inertial oscillations and downward propagation were found.

We also performed clockwise rotary spectra analysis for the upper water column ADCP data at 9 selected moorings (Fig.4.8). The near-inertial power spectral peaks are found at LC mooring (A-B-C) around $f\sim1.07f$, and their near-inertial frequency increase with water depth, suggesting the near-inertial waves have both local and far-field (north) origins. At Campeche Bank mooring (E), the inertial oscillation signals were very weak and the power spectral peak near the frequency of local diurnal tides, with a range of $1.13f\sim1.25f$ throughout the depths. The high frequency signal at Campeche bank slope is dominated mainly by the local internal diurnal tide energy, which is much smaller than the near-inertial energy in the LC area (note the scale difference).

4.4 Discussion

The difference in the near-inertial ocean response to Ida in two adjacent mooring locations raise the question on what are the possible factors modulating the energy and propagation of near-inertial waves. We will explore this in terms of both the relative vorticity
effect and advection effect.

4.4.1 The effect of relative vorticity on the distribution of inertial oscillations

The hurricane induced inertial energy can propagate both horizontally and vertically (Gill, 1984). It is known that under the β-effect, the inertial oscillations can only propagate equatorward into regions of smaller $f$ as a result of beta-dispersion (Anderson and Gill, 1979; Garrett, 2001). Kunze (1985) showed that the presence of relative vorticity $\zeta$, can alter the propagation of near inertial waves through a change in the effective Coriolis parameter, $f_{\text{eff}}$, which is defined as $f_{\text{eff}} = f + \frac{\zeta}{2}$. When the near inertial wave approaches positive vorticity, the increase of $f_{\text{eff}}$ prohibits the further free propagation of near inertial waves; when it approaches to the negative vorticity, $f_{\text{eff}}$ becomes lower than $f$, allowing for a free propagation. Numerical simulation work (Zhai et al., 2005a; 2007) also showed that the distribution of near-inertial energy is strongly influenced by the background mesoscale eddy field and that the anti-cyclonic eddies are important in draining near-inertial energy from the surface to the deep ocean.

Following on the same idea, we examined the mean distribution of normalized relative vorticity $\zeta/f$ at 200 m from Nov. 6 to Dec. 6, 2009. The month-long mean relative vorticity at the LC mooring region (Fig.4.9a) shows $\zeta$ are all positive with a maximum of 0.11$f$ near the center. The maximum $f_{\text{eff}}$ then will be 1.05$f$, which is still in the near-inertial frequency
band. In that sense, this small positive relative vorticity in the region of the LC moorings would not prohibit the propagation of near-inertial waves. Similar conditions are found at other depths in this region.

However, the monthly mean relative vorticity along the Campeche Bank moorings (E-transect) shows larger positive relative vorticity in the upper 200 m with a maximum value of $0.4f$ (Fig.4.9b). This positive vorticity would increase the $f_{\text{eff}}$ to $1.2f$, which exceeds the near-inertial frequency band, leading to the suppression of the propagation of near-inertial waves at these stations. Therefore, the strong positive relative vorticity is shown to be an important factor at E-transect in prohibiting the propagation of near-inertial wave signals.

### 4.4.2 The effect of advection on the distribution of inertial oscillations

Other than the wave effect on the redistribution of hurricane induced near-inertial energy, background geostrophic advection may also play a role in carrying energy away from the hurricane track. Zhai et al. (2004) showed that the Gulf Stream can advect the hurricane induced near-inertial energy away based on numerical simulations. Using mooring observations, Park et al., (2010) showed that the strong advection of Kuroshio Extension dominates the near-inertial wave dispersion process, blocking the equatorward propagation of near-inertial energy.
We note from altimeter SSH maps (Fig.4.4) that the Campeche Bank moorings (E-transect) was located near the front of the Loop Current during the passage of hurricane Ida. The ratio between dispersion processes of near-inertial waves and background circulation advective processes near the Loop Current area can be estimated as

\[
R_1 = \frac{\text{dispersive process}}{\text{advective process}} = \frac{N^2 l}{m^2 (\omega - V l) V}
\]  

(1)

for the meridional component and

\[
R_2 = \frac{\text{dispersive process}}{\text{advective process}} = \frac{N^2 k}{m^2 (\omega - V k) U}
\]  

(2)

for the zonal component, where \( N \) is buoyancy frequency near thermocline, \( \omega \) is wave frequency, \( l \) is meridional wave number that is negative, \( k \) is zonal wave number, \( m \) is vertical wave number, \( V \) is meridional background flow and \( U \) is zonal background flow. Using typical values along the E-transect: \( N = 0.01 \text{ s}^{-1}, l = 2\pi/50 \text{ km}, k = 2\pi/50 \text{ km}, m = 2\pi/200 \text{ m}, \) and \( \omega = 7.3 \times 10^{-5} \text{ s}^{-1} \). For the true northward flow of Loop Current, \( V = 1.5 \text{ m/s}, U = 0 \), the estimated ratio from (1) is -0.0325 and the negative sign shows the equatorward propagation; for the true eastward flow of Loop Current, \( V = 0, U = 1.5 \text{ m/s} \), the estimated ratio from (2) is 0.1163. Therefore, at Campeche bank slope, strong advection from the background flow outweighs the wave dispersion process, and is sufficient to block or reflect the equatorward propagation of near-inertial energy.
On the contrary, at LC mooring (A-B-C transects), taking $\omega = 6.4 \times 10^{-5} \text{ s}^{-1}$, the monthly mean $V=0.15 \text{ m/s}$ and $U=0.013 \text{ m/s}$. We estimated ratios for meridional and zonal components are -1.02 and 21.7 respectively, indicating that wave dispersion processes overwhelms background advection, favoring the free propagation of near-inertial waves.

The ROMS model diagnostics provide another means of examination. Fig.4.10 shows the time evolution of model diagnosed momentum balance in November 2009 at mooring A4 and E5. On the left hand side of the momentum equation is local acceleration, while horizontal advection, Coriolis term, pressure gradient term and vertical viscosity are all on the right hand side. We applied the same 45-hour high pass filter on each of these momentum terms. At A4, the main momentum balance in the high frequency band is between two largest terms: local acceleration and Coriolis term, resulting in strong inertial oscillations as observed. At E5 however, the horizontal advection becomes comparable to the acceleration and Coriolis terms and acts as a major contributor in the momentum balance. As a result, the inertial oscillation signal is damped.

4.5. Summary and conclusion

Inertial oscillations in the Gulf of Mexico induced by hurricane Ida in November 2009 have been investigated using current observations from the LC moorings and Campeche Bank moorings, as well as numerical model simulations. Strong hurricane induced inertial
oscillations are found in most of the LC moorings throughout the depths and the inertial energy is transmitted downward as near-inertial waves. On the contrary, inertial oscillations are only weakly present in the region of Campeche bank moorings. Such a discrepancy of ocean inertial response to the moving hurricane Ida is found to be closely related to the background relative vorticity as well as background geostrophic advection. Both observational analysis and model diagnostics confirm that on the Campeche bank slope, strong Loop Current advection plays an important role in dampening the inertial oscillation signals and block propagation. In the deep-ocean, with the retreat of the Loop Current after shedding an anti-cyclonic eddy, weaker advection in the region in conjunction with effective Coriolis parameter allow the dispersive process to be dominant and near-inertial waves freely propagate.
References


Chapter 5: Summary

In this study, we investigated the ocean circulation dynamics and transport connectivity in the Intra Americas Seas (IAS) on inter-annual, seasonal, synoptic and inertial time scales. The long-term transport connectivity analysis shows significant seasonal and inter-annual variability of the particle dispersal pattern in most of the coral reef sites in IAS. It also indicates that particle dispersal pattern driven by mean circulation as suggested by previous studies may significantly underestimate the connectivity envelope. Therefore resolving seasonal and inter-annual variability of the circulation is crucial for accurate prediction of particle dispersal in the region.

Ocean circulation dynamics and particle dispersal were further examined during the passage of two consecutive hurricanes Gustav and Ike in the GOM. Upper ocean circulation dynamics changed dramatically during the hurricanes. Wind forcing becomes a crucial contributor in momentum, vorticity and energy budgets. Changes of physical environments influenced the particle dispersal pattern accordingly. Dispersals of particles released along hurricane tracks indicated that they experienced much stronger vertical motions during the passage of hurricanes than they did under normal weather conditions. Horizontally, some particles also traveled longer distances, whereas the horizontal dispersal pattern showed limited hurricane effect as compared to the case without hurricane.
Inertial oscillations and particle dispersal during the passage of hurricane Ida were further analyzed. Both numerical simulations and moored current observations show that strong inertial oscillations are present at deep-water sites where Loop Current moorings were located, and there were obvious downward propagation of inertial energy. At Campeche bank moorings sites, inertial oscillations are only weakly present and most of the high frequency signals are dominated by internal diurnal tides. The discrepancy of the ocean response to the hurricane Ida is found to be related to the background relative vorticity and background geostrophic advection. The presence of strong positive relative vorticity on the Campeche bank slope increases the lower bound of near-inertial wave propagation frequency, suppressing the free propagation of near-inertial waves. In addition, the Campeche bank moorings were located on the edge of the Loop Current, when Hurricane Ida passed through and the Loop Current had shed an anticyclonic eddy and retreated southward. Therefore, the strong Loop Current advection processes overwhelm the wave dispersive process, sufficiently blocking the southward propagation of inertial oscillation signals.

In summary, through a set of case studies, we systematically explored the complex nature of regional circulation, transport connection and their potential biological ramification on different time scales in the IAS. With baseline information established in this study, further research in incorporating refined ocean circulation and biological models (e.g., Young et al., in preparation), and advanced observation network will be advance coastal resource (e.g., coral
reef and fishery)monitoring and management among different states as well as across nation borders.
Fig. 1.1. Major circulation system and geography of IAS (adapted from T.L. Townsend, A.J. Wallcraft, and H.E. Hurlburt 8th HYCOM Mtg, 19 Aug 2003).
Fig. 2.1. (a) Mean circulation and eighteen coral reef hotspots (Andros Islands, Bahamas, Florida Keys, Belize, Turks & Caicos, Jamaica, Mexico, South Cuba, Colombia, U.S. Virgin Island, Bonaire, Saba, St. Lucia, Cayman Island, Panama, Nicaragua, Flower Gardens, Barbados, Banco de Serranilla) in the Intra-Americas Seas, (b) larval import (sources) and (c) export envelopes (destinations) for each of the six locations (Florida Keys, Jamaica, Panama, Bonaire, Barbados, and U.S. Virgin Island) of the coral reef as shown in the black dots. Both one and two month envelopes were shown. Figure adapted from Roberts (1997).
Fig. 2.2. Domain of 6-km resolution IAS circulation model overlaid with bathymetry. Red dots represent locations of sea level stations from NOS, pink line represents the transect location of Florida transport cable data.
Fig. 2.3. Particle release locations, red dots indicate the center of each release site, and small black dots represent particle release locations within 60 km radius of centers. Pink dots stand for the eighteen coral reef hotspots as in Roberts (1997).
Fig. 2.4. (a) 4-year mean surface currents; (b) a snapshot of sea surface height overlaid with surface velocity on June 01, 2010.
Fig. 2.5. Florida current transport comparisons among IAS ROMS, HYCOM solutions, and observations from cable measurement.
Fig. 2.6. 4-year mean Eddy Kinetic Energy (EKE) comparison between IAS model hindcast and 1/3°AVISO Altimeter observations. EKE values are scaled in log10 in the unit of \( \text{m}^2\text{s}^{-2} \).
Fig. 2.7. Comparisons of 4-year mean modeled sea surface temperature and satellite SST.
Fig. 2.8. Comparison between IAS ROMS simulated and satellite-based monthly mean time series of spatial averaged sea surface temperature. Error bar stands for the standard deviation of observational SST during that month.
Fig. 2.9. Sea level comparison between model and tidal stations; x-axis is time in the format of month/year; A 36-hour low-pass filter was applied to yield sub-tidal signals. In each panel, correlation coefficient between model and observations is shown.
Fig. 2.10. Locations of ship CTD observations in the GOM during April 22–October 18, 2010.
Fig. 2.11. Comparisons between simulated and observed (a) temperature (°C) and (b) TS-diagram.

(a)

(b)

total obs points = 1826475

y = 1.03x

total model points = 1839627
Fig. 2. Taylor diagram for temperature (left panel) and salinity (right panel) comparisons; the color coding responds to their locations in Fig 2.10. All points are normalized by their corresponding observation points denoted by asterisk. The radial distances from the origin are proportional to the ratio standard deviations; the azimuthal positions indicate the correlation coefficient; and the distance between the modeled and observed points indicates the centered RMS difference (RMSD).
Fig. 2.13. Examples of particle trajectories with advection time of 60 days for four of the initial release locations as seen in Fig. 2.3. Green dots stand for starting points for the initial release locations, and pink dots represent the ending points of the initial release locations.
Fig. 2.14 Mean connectivity matrix at advection time (a) 10, (b) 20, (c) 40 and (d) 60 days. X-axis (y-axis) is destination (source) for six locations from western GOM, eastern GOM, SAB, Sargasso Sea, eastern Caribbean Sea and western Caribbean Sea.
Fig. 2.15. Mean Lagrangian Probability Density Functions (LPDFs) for Cayman Island, Panama, Nicaragua, Flower Gardens, and Barbados, Banco de Serranilla at advection time 60 days. Black dots are the release locations.
Fig. 2.16. Dispersal distance and angular histograms for particles released from 18 coral reef sites from 2007 to 2010. The unit for x- (y-) axis is kilometer (percentage).
Fig. 2.17. Examples of inter-annual variability in dispersal distance and angular directional histograms for sites of Florida Keys, Andros Is., Bahamas from 2007 to 2010.
Fig. 2.18. Examples of seasonal variability in dispersal distance and angular directional histograms for sites of Florida Keys, Andros Is., Bahamas in spring, summer, fall, and winter seasons, respectively.
Table 2.1. P-value from one-way ANOVA test of inter-annual variations of dispersal distances (first two columns) and angular directions (last two columns) for 18 coral reef locations: AI (Andros Islands, Bahamas), FK (Florida Keys), BE (Belize), TC (Turks & Caicos), JA (Jamaica), ME (Mexico), SC (South Cuba), CO (Colombia), UVI (U.S. Virgin Island), BO (Bonaire), SA (Saba), SL (St. Lucia), CI (Cayman Island), PA (Panama), NI (Nicaragua), FG (Flower Gardens), BA (Barbados), BS (Banco de Serranilla).

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Table 2.2. P-value for one-way ANOVA test of seasonal variation of dispersal distance and angular directions for the 18 coral reef sites.

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Fig. 2.19. Mean particle export envelopes defined by the LPDFs for 6 coral reef locations (Florida Keys, Jamaica, Panama, Bonaire, Barbados, and U.S. Virgin Island), same as Roberts (1997). In each panel, both 30-day (solid line) and 60-day (dash line) envelopes are shown. Pink dots represent the initial release locations.
Fig. 2.20. Mean surface circulation and current variance ellipses for the IAS, a scale of 0.75 m s$^{-1}$ is labeled for reference purpose.
Fig. 3.1. Tracks for hurricanes Gustav and Ike, and pink triangle represents the location of buoy 42001 who's surface temperature were used to compare with model solution. Positions of two hurricanes centers are labeled in blue dots at daily time interval.
Fig. 3.2. The 6-km Intra-Americas Sea (IAS) circulation model domain. Both model boundaries and bathymetry (in meters) are shown.
Fig. 3.3. Comparisons of surface wind forcing (upper two panels) and sea surface temperature (lowest panel) at buoy 42001 between model and observations.
Fig. 3.4. Locations of NOAA NOS tidal stations in the Gulf of Mexico. Sea level observations at these sites were used to gauge against model solutions.
Fig. 3.5. Comparisons of model simulated and observed sea level in August and September. A 36-hour low-pass filter was applied to yield sub-tidal signals. In each panel, correlation coefficient (R) between model and observations is shown.
Fig. 3.6. Snapshot of sea surface height and surface current during the passage of hurricanes Gustav (upper panel) and Ike (low panel). Pink and Blue lines are tracks of hurricane Gustav and Ike respectively. Filled circles denote the current locations of the two hurricanes.
Fig. 3.7. Mean TMI sea surface temperature at the beginning (left column) and the end (middle column) of three different periods: Aug 27/30 – Sep 3/4 (during Gustav Passage), Sep 6/9 - Sep 14/15 (during Ike passage), and Aug 27/30-Sep 14/15 (during both Gustav and Ike passages). The right column shows the respective sea surface temperature change over each of three periods. Black lines show the tracks of the two hurricanes.
Fig. 3.8. The distributions of Wind stress field (unit: m/s) and Ekman pumping velocity (unit: 1e-4 m/s) during the passage of hurricane Gustav (upper two panels) and Ike (lower two panels). Black lines represent the hurricane tracks at daily time interval.
Fig. 3.9. The distribution of vertically integrated momentum budgets (a) before, during (b--Gustav, c--Ike) and (d) after hurricane passage. In each period, upper panel is U-momentum and lower panel is V-momentum.
Fig. 3.10. Spatial distributions of vertically integrated vorticity budgets (a) before, during (b--Gustav, c--Ike) and (d) after hurricane passage. (The terms are indicated on the title of the first panel and the units are at the end of the colorbar)
Fig. 3.11. The distribution of vertically integrated energy budgets (a) before, during (b--Gustav, c--Ike) and (d) after hurricane passage. Add information on what terms are they and their units (The terms are indicated on the title of the first panel and the units are at the end of the color bar).
Fig. 3.12. Particle release locations (crosses) along the two hurricane tracks. Red circles stand for the location of hurricane eyes with 6-hour interval, particles along the Gustav track were released every 6 hours from August 31 to September 2, and particles along Ike track were released every 6 hours from September 10 to September 13, 2008.
Fig. 3.13. 3-D view of particle dispersal during the passage of hurricane Gustav, (a) initial locations with dark blue line the hurricane track and light blue dots the particles released at 60m, pink dot shows the location of hurricane eye (b) Particles dispersal pattern at September 03, 2008. Colors indicate different depths of particles.
Fig. 3.14 histogram showing the vertical (upper panel) and horizontal (lower panel) distributions of particles at (a, c) initial stage and (b, d) 3 days later for those released at 60m along Gustav track.
Fig. 3.15. 3-D view of particle dispersal during the passage of hurricane Ike, (a) initial locations with dark blue line the hurricane track and light blue dots the particles released at 60m, pink dot shows the location of hurricane eye (b) Particles dispersal pattern at September 13, 2008.
Fig. 3.16 histogram showing the vertical (upper panel) and horizontal (lower panel) distributions of particles at (a, c) initial stage and (b, d) 3 days later for those released at 60m along Ike track.
Fig. 3.17. Vertical distributions of particle dispersal after release for 3 days at each release depth. Comparison was made for no hurricane and hurricane conditions for both Gustav (a, b) and Ike (c, d). Color and size of the circle represent the percentage of the particles.
Fig. 3.18. Distribution of horizontal dispersion distance for each release depth (x-axis) from surface to 300 m with 30 m interval at advection time of 3 days. Comparison was made for no hurricane and hurricane conditions for both Gustav (a, b) and Ike (c, d). Color and size of the circle represent the percentage of the particles.
Fig. 3.19. 3-D view of the particles dispersal by the end of the tracking for (a) Gustav track release and (b) Ike track release. Colors represent the depth.
Fig. 4.1. Locations for the mooring array in the Gulf of Mexico, the NDBC buoy and the track of hurricane Ida.
Fig. 4.2. Domain of 6-km Intra-Americas Sea (IAS) circulation model. Color shaded bathymetry field (in meters) is overlaid.
Fig. 4.3. Comparison of buoy observed (upper) and model blended (lower) wind time series in November-December, 2009. A daily low pass filter was applied to both time series. Shaded area represents the period during the passage of hurricane Ida.
Fig. 4.4. Time evolutions of merged surface wind field and Loop Current conditions during the passage of hurricane Ida. Also shown in Orange line is the Ida track, 17 cm SSH contour line in purple, and locations of moorings in red square.
Fig. 4.5. Model simulated Sea Surface Height in early November. Also shown in purple line is the 17 cm SSH contour.
Fig. 4.6. Time series of high pass filtered horizontal velocity at various depths (a) from 450 m ADCP measurements at mooring A4 and (b) from model simulations at the same location. Blue line is the V-velocity (positive northward) and black line is U-velocity (positive eastward). Red arrow line demonstrates the packet propagation. Units: cm/s.
Fig. 4.7. Time series of high pass filtered horizontal velocity at various depths from 500 m ADCP measurements at mooring E5. Blue line is the V-velocity (positive northward) and black line is U-velocity (positive eastward). Units: cm/s.
Fig. 4.8. Rotary power spectra analysis of high pass filtered horizontal velocity at various moorings for various depths in the upper 500m. Orange vertical line shows the local inertial frequency.
Fig. 4.9. (a) Mean normalized relative vorticity from Nov. 6 to Dec. 6, 2009 at 200 m for the LC moorings. (b) Vertical transect of mean normalized relative vorticity at Campeche Bank E-transect moorings for the same period as (a).
Fig. 4.10. Time evolution of momentum budget terms at mooring A4 and E5 during hurricane Ida period (November, 2009); black line is acceleration term, red line is the Coriolis term, purple line is horizontal advection, cyan line is pressure gradient term, brown line is the vertical viscosity unit: m/s$^2$. 