Eddies connect the tropical Atlantic Ocean and the Gulf of Mexico

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Abstract

Numerical circulation modeling and observational studies have been conducted to understand the Loop Current (LC) system behaviors in the Gulf of Mexico (GoM). One of the factors that may influence the LC are upstream eddies from within the Caribbean Sea. By combining satellite altimetry, sea surface salinity and ocean color data, we demonstrate that mesoscale eddies from the western tropical Atlantic Ocean can eventually make their way to the Gulf of Mexico and affect the LC. In addition, our study shows that freshwater of Amazon and Orinoco River origin trapped within mesoscale eddies can also enter the GoM affecting the GoM stratification. This study provides insights into understanding variations of the LC system and showcases the roles of mesoscale eddies in connecting the open ocean and regional seas.

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12	Key Points
13	• Some eddies from the Atlantic Ocean can ultimately reach the Gulf of Mexico and affect
14	the Loop Current.
15	• Freshwater of Amazon and Orinoco River origin and other materials trapped in eddies
16	could reach the Gulf of Mexico.
17	• Weakening and strengthening of the long-propagating eddies are mostly related to the
18	variation of bathymetry.
19	

20 Abstract

21 Numerical circulation modeling and observational studies have been conducted to understand the 22 Loop Current (LC) system behaviors in the Gulf of Mexico (GoM). One of the factors that may 23 influence the LC are upstream eddies from within the Caribbean Sea. By combining satellite 24 altimetry, sea surface salinity and ocean color data, we demonstrate that mesoscale eddies from 25 the western tropical Atlantic Ocean can eventually make their way to the Gulf of Mexico and 26 affect the LC. In addition, our study shows that freshwater of Amazon and Orinoco River origin 27 trapped within mesoscale eddies can also enter the GoM affecting the GoM stratification. This 28 study provides insights into understanding variations of the LC system and showcases the roles 29 of mesoscale eddies in connecting the open ocean and regional seas.

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32 Plain Language Summary

33 The Loop Current (LC) is the dominant large-scale oceanic process in the Gulf of Mexico 34 (GoM). However, the mechanism for variations of the LC system is still unsolved. Here, we 35 show that some mesoscale eddies originated in the tropical Atlantic Ocean can pass through the Caribbean Sea and eventually enter the GoM. These remotely generated eddies could be an 36 37 important upstream factor affecting the behavior of the LC. Also, freshwater and other materials 38 (chlorophyll) trapped in the eddies could reach the GoM as well. In addition to advancing the 39 understanding of the LC system, this study provides an explicit example showing eddies can 40 serve as a route connecting regional seas and the open ocean.

42 **1. Introduction**

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Azcárate et al., 2009).

44 Ocean through the Yucatan Channel and the Straits of Florida, respectively. The Loop Current 45 (LC) is the most prominent physical feature in the GoM. It has a significant influence on various 46 processes in the GoM, such as dispersal of spilled oil (e.g., Crone & Tolstoy, 2010; Liu et al., 47 2011; Hazen et al., 2016; Weisberg et al., 2016; Weisberg et al., 2017), sediment transport, fish 48 production (e.g., Hazen et al., 2016), distribution of nutrients (e.g., Hu et al., 2005). In addition, 49 it plays an essential role in the atmosphere-ocean coupling, which influence the prediction of 50 hurricanes and their impacts (e.g., Shay & Jacob, 2006; Sheng et al., 2010; Chen & Curcic, 2016; 51 Curcic & Chen, 2016). 52 The past few decades have provided a large number of observational and numerical circulation 53 modeling studies on the LC system (e.g., Sturges & Leben, 2000; L.-Y. Oey et al., 2005; Xu et 54 al., 2013; Chang & Oey, 2010, 2013; Liu et al., 2016; Weisberg & Liu, 2017; J. Candela et al., 55 2019; Hirschi et al., 2019). Despite these and others, a fundamental question remains: what 56 controls the trajectory of the LC (Committee on Advancing Understanding of Gulf of Mexico 57 Loop Current Dynamics, 2018)? Many factors affecting this complex, dynamical system have 58 been proposed, such as the Yucatan channel transport, bottom topography, and atmospheric 59 forcing. In particular, several modelling studies suggest that upstream factors outside of the GoM 60 could be important (Murphy et al., 1999; Lie-Yauw Oey, 2004; Jouanno et al., 2008; Alvera-

The Gulf of Mexico (GoM) is a semi-enclosed sea connecting the Caribbean Sea and the Atlantic

Previous studies suggest that mesoscale eddies that may impact the GoM could originate as far
upstream as the North Brazil Current (NBC). Rings that are shed from the NBC as it retroflects
into the North Equatorial Countercurrent (NECC) can propagate northwestward and interact with

65 the Lesser Antilles. Such NBC rings may be deflected or defracted by the island chain, with the 66 result that some of these may enter the Caribbean Sea (Fratantoni & Richardson, 2006). 67 Numerical modeling studies (e.g., Murphy et al., 1999) show that potential vorticity from NBC 68 rings reforming west of the Lesser Antilles may then grow in the Caribbean Sea gaining energy 69 via mixed barotropic and baroclinic instabilities. Some of those eddies can then enter the GoM 70 through the Yucatan Channel, perhaps impacting the trajectory of the LC and the related eddy-71 shedding process. Besides the modeling studies, drifter track, altimetry observations and Amazon 72 river plume studies also show the advection of these rings and its filaments cross Lesser Antilles 73 (e.g., Carton & Chao, 1999; Fratantoni & Richardson, 2006; Richardson, 2005; Goni & Johns, 74 2001; Chérubin & Richardson, 2007; Avera-Azcarate et al., 2009). However, more definitive 75 studies on such long-distance mesoscale eddy connections between the GoM and the tropical 76 Atlantic Ocean remain to be accomplished.

In this study, using various satellite products, including altimetry, sea surface salinity and chlorophyll, we explore roles of mesoscale eddies in connecting the tropical Atlantic and the GoM and their impacts on the LC. The paper is organized as follows. A brief description of the data is provided in section 2. Section 3 presents the propagations of eddies from the tropical Atlantic Ocean to the GoM. At last, the results are summarized and discussed in section 4.

82 2. Data and Methods

The daily satellite altimetry dataset from the Copernicus Marine Environment Monitoring Service (CMEMS, <u>https://marine.copernicus.eu/</u>) was used to tack the propagation of eddies. The dataset covers the period from January 1993 to December 2018 and has a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$. This dataset includes a number of variables, including sea level anomalies (SLA),

absolute dynamic topography (ADT) and geostrophic currents. Note that the SLA is referenced
to a 20-year (1993-2012) mean (Pujol et al., 2016).

89 Mesoscale eddy trajectory from January 1993 to January 2018 produced by CMEMS was also 90 used. This product provides eddy trajectory information, including type, position, amplitude (i.e., 91 magnitude of the height difference between the extremum of SLA within the eddy and the SLA 92 around the contour defining the eddy perimeter) and speed. Note that the eddy trajectory in this 93 dataset will be stopped if there is land between two consecutive eddies, likely resulting in 94 discontinuities for long-propagating eddies when they encounter topography like island chains. 95 To avoid the discontinuities related to the eddy detection methods mentioned above, we also 96 examined the propagation of mesoscale eddies along a 60-cm sea surface height (SSH) isoline, 97 which is roughly the mean of the eddy trajectories in the study region (Figure 1a). In order to 98 examine the evolution of the eddies as they propagate, we also calculated amplitude of the 99 mesoscale eddies along the same isoline using a $3^{\circ} \times 0.5^{\circ}$ moving box (green boxes in Fig. 1). 100 The sea surface salinity (SSS) from European Space Agency Earth Explorer mission (SMOS) 101 was used to explore the impacts of mesoscale eddies on the freshwater transport. The SSS data 102 cover a period from January 2010 to December 2017 (Boutin et al., 2018). The SSS data have a 103 temporal interval of four days and a spatial resolution of about 25 km. In addition, we examined 104 the chlorophyll data from GlobColour, which merges several products from SeaWiFS, MERIS, 105 MODIS, VIIRS NPP, OLCI-A, VIIRS JPSS-1 and OLCI-B to achieve better spatial and 106 temporal coverage (Maritorena et al., 2010). The dataset is from 1997 to 2019 with a spatial 107 resolution of 4 km and a temporal resolution of 8 days. Also, we used ETOPO5 bathymetry data 108 examine the impacts of bathymetry on the propagating mesoscale eddies.

109

110 **3. Results**

111 The trajectories of mesoscale eddies that last more than 60 days in the study region are shown in 112 Figure 1a-b. From the western tropical Atlantic Ocean to the GoM, the eddy trajectories are 113 continuous except for three regions: Lesser Antilles, Chibcha Channel and Yucatan Channel. The 114 main pattern of the anticyclonic and cyclonic eddy track is similar, and the numbers of the 115 anticyclonic and cyclonic eddies are roughly the same. Note that since we consider the long-116 distance propagation of mesoscale eddies, only eddies lasting more than 60 days are presented. 117 Since the eddy detection method used to generate the trajectory data arbitrarily stopped the 118 trajectory if land was found between consecutive eddies, the discontinuity shown in Figure 1a-b 119 could be misleading. We then drew a line from the tropical Atlantic to the GoM (Fig 1) to track 120 the propagations of mesoscale eddies and examine if the eddies on the two sides of the 121 discontinuous locations are actually connected. Following the line, the Hovmöller diagram of sea 122 level anomalies (SLA) (as in Alvera-Azcarate et al., 2009) is derived and shown in Figure 1c. 123 Here, for better visualization we only present a few years of the data and the other years show 124 similar patterns. It is clear that the eddy connection shown in Figure 1a-b is also revealed in the 125 Hovmöller plot (Fig. 1c). In addition, many SLA signals now appear propagating continuously 126 from the western tropical Atlantic Ocean to the GoM even in the discontinuity regions shown in 127 Figure 1a-b. Along the line, SLA signals on the two sides of the Lesser Antilles are closely 128 related, displaying a significant correlation of 0.69 with a time lag of 1 month, indicating some 129 eddies inside the Caribbean Sea, particularly those originate near the Lesser Antilles are likely 130 related to eddies in the tropical Atlantic Ocean.

We also explored the propagation of individual eddies. Three cases of long-distance eddypropagation from the western tropical Atlantic Ocean to the GoM are presented in Figure 2. For

133 case 1 (Figure 2a-b), we firstly see a clearly defined eddies in the middle of the tropical Atlantic 134 Ocean in July 2014. The eddy then propagated westward until encountered the continent of the 135 South America around October 2014. Then, the eddy propagated northwestward following the 136 corridor along the north Brazil coastline and eventually encounter the Lesser Antilles (Figure 137 2a), where the intensity of the eddy was significantly reduced. However, after part of the eddy 138 was diffracted into the Caribbean Sea in March 2014, the eddy eventually grew into a much 139 stronger eddy as it propagated into the eastern Caribbean Sea in October 2015. At last, the eddy 140 entered the GoM and became part of the LC in January 2016 (Figure 2b). The long-distance 141 propagation from the middle of the tropical Atlantic Ocean to the GoM takes about 17 months. 142 Similar to case 1, the eddy shown in case 2 (Figure 2c) was first identified in the western tropical 143 Atlantic Ocean in March 2014, and after about 14 months it eventually entered the GoM. It 144 should be noted that eddies originated in the western tropical Atlantic can also enter the 145 Caribbean Sea but fail to reach the GoM. Case 3 (Figure 2d) is such an example. Therefore, the 146 evolution of the eddies along their trajectory, which involves a number of complex dynamics 147 (e.g., Murphy et al., 1999; Jouanno et al., 2008), deserves some further analysis. We further examined the evolution of the eddy along their propagation trajectory (Figure 3a). 148 149 When crossing the Lesser Antilles, the eddies are relatively weak with an amplitude of ~ 5 cm. 150 When the eddies reach the eastern Caribbean Sea, the amplitude sharply increased to 20-25 cm. 151 After that, the eddies intensity decreased again around the Chibcha Channel. To confirm if this 152 evolution of eddy intensity is robust or not, we calculated the statistical results of all the detected 153 cyclonic and anticyclonic eddies along the line shown in Figure 1. The results reveal similar but 154 more detailed features to the three individual eddies (Figure 3b). Note that the magnitude of the

amplitude is different since it is derived from the SLA trajectory dataset which is the same from

the previous individual cases. In general, the amplitude of the eddies decreases sharply when reaching the Lesser Antilles, the Chibcha Channel and the Yucatan Channel and increases when moving away from these large topographic features.

159 The eddy cases and the SLA propagation indicate that in contrast to the previous studies,

160 mesoscale eddies from the tropical Atlantic Ocean, at least some of them, can cross the

161 discontinuity regions and can finally reach the GoM. These eddies served as vorticity flux

162 passing the Yucatan Channel could trigger the Loop Current retraction, extension and eddy-

163 shedding. Previous studies suggest that the negative (anticyclonic) vorticity flux is related to the

164 Loop Current extension while the positive (cyclonic) vorticity flux causes retraction and

sometimes shedding (Candela et al., 2002; Lie-Yauw Oey, 2004; Athie et al., 2012). Our case
eddies shown in Figure 2a-c are examples of the anticyclonic eddies inducing LC extension

167 events.

168 The eddies under consideration carried other material properties along with energy and 169 momentum. Figure 4 shows the Hovmöller diagram of the SSS anomalies and the accompanied 170 SLA anomalies. Similar to the SLA anomalies, the SSS anomalies can translate from the NBC 171 region, across the Lesser Antilles and into the Caribbean Sea. This is important because the 172 barrier layers created by the fresh Amazon-Orinoco River plume, by raising SST, can contribute 173 to Atlantic hurricane intensification (K. Balaguru et al., 2012, 2020; Ffield, 2007), and the eddies 174 play an important role on the freshwater transport (Fournier et al., 2017). One can see the 175 transport across Lesser Antilles even there are some data missing in the Lesser Antilles. In some 176 years, such as 2013-2016, these SSS features can also translate cross the Chibcha and the 177 Yucatan channels to enter the GoM. The green box marked in Fig. 4 show several such cases, 178 which also includes two specific eddy cases in Figure 2a-c. The phases of SSS and SLA agree

179 well with each other, confirming that individual eddies can carry freshwater from western

180 tropical Atlantic Ocean to not only the Caribbean Sea as suggested by previous studies

181 (Hellweger & Gordon, 2002) but also further into the GoM.

182 In addition, chlorophyll and colored dissolved organic matter (CDOM) also show the

183 propagation of the mesoscale eddies (Hu et al., 2004; Fratantoni & Glickson, 2002). The contrast 184 between the high nutrient Amazon-influenced water and the surrounding relatively low nutrient 185 midocean water mark the NBC retroflection and the rings. The low-chlorophyll rings core and 186 high-chlorophyll boundaries show the evolution and propagation of the NBC rings. Here, the 187 propagation of chlorophyll is shown in Fig. 5. For example, from 2005 to 2006, the chlorophyll 188 anomalies propagate from the NBC retroflection regions, cross the Lesser Antilles into the 189 Caribbean Sea, and then finally into GoM. It should be noted that the mechanisms for the 190 chlorophyll anomaly are complex and are at least from two parts: horizontal advection and 191 vertical upwelling of nutrient or chlorophyll itself (Killworth et al., 2004; O'Brien et al., 2013). 192 Variability in river discharge and the numbers of the rings will also impact the chlorophyll. 193 Nevertheless, our results at least show the mesoscale eddies can affect the bio-productivity along their long-propagation trajectory that connects the tropical Atlantic Ocean and the GoM. 194

4. Conclusions and Discussion

By combining the SSHA, eddy track, SSS, chlorophyll data, we show that some of the mesoscaleeddies originating in the tropical Atlantic Ocean can eventually enter the GoM and affect the LC.

198 In other words, mesoscale eddies can connect the tropical Atlantic Ocean and the GoM.

199 Although such a long-distance connection by way of mesoscale eddies has been suggested in

200 previous numerical studies (Murphy et al., 1999; van Westen et al., 2018), here we provide direct

201 observational evidence. In addition, earlier studies have suggested that the potential vorticity flux

202	through the Yucatan Channel may influence the LC trajectory and the eddy shedding process in
203	the GoM (Murphy et al., 1999; Candela et al., 2002; Lie-Yauw Oey, 2004; Athie et al., 2012),
204	these long distance translating eddies from the tropical Atlantic Ocean may play a role in LC
205	evolution and LCE shedding. Besides the eddies shown along the line in Figure 1a, eddy
206	translation along a zonal line in the Atlantic Ocean was also examined (not shown). Consistent
207	feature translation from the Atlantic Ocean to the Caribbean Sea is seen, suggesting that such
208	eddy connections between the Atlantic Ocean and the GoM are quite common.
209	A more specific impact of those long-propagating eddies is related to the freshwater transport.
210	As the largest oceanic rings, the NBC rings transport freshwater and other materials particularly
211	considering that the NBC flows past the Amazon River (Fratantoni & Glickson, 2002; Hellweger
212	& Gordon, 2002; Chérubin & Richardson, 2007; Grodsky et al., 2015; Fournier et al., 2017).
213	Early studies show that the Amazon river plume can influence the Caribbean Sea salinity
214	variation through salt advection (Muller-Karger et al., 1988; Hellweger and Gordon, 2002). In
215	this study, we show that Amazon and Orinoco river freshwater trapped by the mesoscale eddies
216	can not only get into the Caribbean Sea but can finally enter the GoM in many cases (Figure 4).
217	There is similarity between the evolution and propagation of individual ocean eddy and of the
218	atmosphere hurricane and storm, which also show weakening and strengthening along their
219	trajectories. But the number of studies on the ocean counterpart of hurricanes and storms are
220	much less. In this study, we show a close relationship between topography and variations of eddy
221	intensity between the Lesser Antlilles and the Yucatan Channel. However, inside the GoM and in
222	the Tropical Atlantic Ocean, no such clear relations appear. These observations suggest that
223	various factors and mechanisms involved in any successful eddy connection events between the

tropical Atlantic and the GoM, and more carefully designed studies are needed in the future tofurther explore this complex dynamical process.

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- the data used in this study are publicly available. The altimetry and mesoscale eddy trajectory
- 230 datasets can be obtained from the Copernicus Marine Environment Monitoring Service
- 231 (CMEMS, <u>https://marine.copernicus.eu/</u>). The sea surface salinity dataset is from the European
- 232 Space Agency Earth Explorer mission (SMOS, <u>https://earth.esa.int/web/guest/missions/esa-</u>
- 233 <u>operational-eo-missions/smos</u>). And the chlorophyll dataset is available at GlobColour
- 234 (<u>https://hermes.acri.fr/</u>).

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Fig. 1 Eddy tracks of (a) Anticyclonic eddies, (b) Cyclonic eddies in the study region. Only the eddies last more than 60 days are shown. The black line stands for the mean eddy trajectory, which is used to further examine the eddy propagation. The 1000m isobath is marked in the North Brazil and the bathymetry is superimposed. (c) Time-longitude plot of SLA following the mean eddy trajectory marked above from 2011 to 2018. The circle and the box from 2014 to 2016 mark the two eddy propagation cases. The dash lines mark the Lesser Antilles, Chibcha Channel, Yucatan Channel and, NBC retroflection.



Fig. 2 Cases of long-distance propagation of individual eddy: (a-b) from July 2014 to January
2016, (c) from March 2014 to May 2015, and (d) from January 1995 to December 1995. The
dates are shown on the top of each snapshot. The absolute dynamic topography (ADT) is
superimposed by the geostrophic current and the outmost contour of ADT marks its boundary.
The 1000m isobath is marked.



396 Fig. 3 (a) Eddy amplitude evolution (magnitude of the height difference between the extremum 397 of ADT within the eddy and the ADT around the contour shown in figure 2) for the three cases. 398 (b) Black solid line: eddy amplitude (magnitude of the height difference between the extremum 399 of SLA within the eddy and the SLA around the contour defining the eddy perimeter) evolution 400 for all the anticyclonic eddy cases following the line in Fig. 1a. Black dashed line: same as black 401 solid line, but for cyclonic eddies. The blue patch marks the eddy-shedding position. The 402 position of the Lesser Antilles, the Chibcha Channel, the Yucatan Channel and the Beata Ridge 403 is marked in dash lines. Orange line: the topography evolution following the line in Fig. 1a.



406 Fig. 4 Longitude-time plot of (a) sea surface salinity (SSS) anomalies and (b) sea level anomalies

407 (SLA) band-pass filtered between 40 and 200 days. The green boxes represent relatively





411 Fig. 5 Longitude-time plot of (a) chlorophyll anomalies and (b) sea level anomalies (SLA) band-

412 pass filtered between 40 and 200 days from 2003 to 2007. For clear, the chlorophyll data on the

413 left side of Lesser Antilles is doubled.