**We would like to thanks the reviewer for the positive criticism and recommendations. Below you will find a point-by-point response to all comments to the both reviews. We also include a version with tracking changes.**

**Here the list of all relevant changes made in the manuscript:**

- **We removed the discussion and figure of the monthly averages of the wind stress described in section 3.4 (including figure 6), but also we removed sections 3.5 (also figure 7) and section 3.7 (AMOC).**
- **We rewrote all section 3.2.**
- **We improve the introduction and discussion regarding previous studies, which referrer to the seasonal cycle of the LC. But also the conclusion regarding the decrease of Chl-a concentrations in the western Gulf of Mexico (GoM).**
- **We finally highlight the relevant contributions in the MS.**

## Answers to Reviewer No.1:

I would like to thanks the reviewer for taking the effort with this paper and for his/her helpful comments. Below you find a point-by-point response to all comments. Original reviewers' comments in regular typeface, response in bold-italic letter.

1. A minor point is to what extent some aliasing may have been introduced by standardizing the satellite data into the same spatial resolution.

***R: Our major conclusion about predictable seasonality with respect to Caribbean water intrusion into the Gulf and its extent in recent years comes from ADT satellite data but without standardization. Our major conclusion about seasonality comes from the ADT satellite data before it was standardized and potentially aliased by fitting it to a standard grid.***

***In our work satellite chlorophyll data were also used. We found minimum surface Chl-a concentrations during the summer-autumn period inside the region of maximum incursion of the CW. The satellite chlorophyll data were spatially standardized from 1/12 to 1/4 degrees to obtain clean and smoothed figures (Figures 8, 9 and 10; before Figures 10, 11, 12, see figures attached to this document) without noise introduced by submesoscale activity. However, to confirm that the results do not change with or without the standardization of the data, we computed Figures 8, 9 and 10 directly with the original chlorophyll data at 1/12 degree. We did not find differences.***

2. It is not clear that the authors are keeping in mind an inherent limitation of the data in that all the data sets they are analyzing are essentially surface or near surface (a small part of the overall circulation). This is germane to the comparisons made and between Eckman and geostrophic flow regime patterns as well as other issues raised.

***R: We were very conscious of the inherent limitation of all the data sets because they were obtained from the surface or near surface. We agree the data from surface just represent a small part of the overall circulation and may lead to errors in Ekman and geostrophic flow regime patterns.***

***The vertical extent of the Ekman effect depends on the degree of wind stress and its duration. Considering this, the Ekman current impacts a layer from the surface to 30 or, unusually, up to 100 m. Geostrophic currents computed by absolute dynamic topography represent the layer from 500 m to around 1500 m, which is the mean depth of the detached eddies of the Loop Current. When considering Ekman derived geostrophic currents, we need to consider only the first 100 m. But this does not affect the results of this paper. We have removed this section.***

3. While they properly conclude that their analysis "suggests" (see section 3.6) larger volumes from 2003 onward it is by no means conclusive (see comment above).

***R: As we did not make any direct current measurements, we agree with the referee that our analysis "suggests" an increased influx of Caribbean Water has entered the GoM. See our L49-L51 in abstract section.***

4. I have issues with section 3.7 AMOC both in that they proceed as if it were shown definitively that a greater volume of Caribbean water is entering the Gulf and their use of the Caesar paper. They also then elaborate upon AMOC and synoptic scales which is pure speculation and unrelated to their own analysis.

***R: Again, we agree about the speculation and that it is unrelated to our analysis. We have removed this section.***

5. With respect to the satellite chlorophyll data the authors do not appear to understand the limits of the data. It is not only that only surface (or near surface) pigment concentration is measurable by satellite, it is more fundamentally the case that changes in the measurement can be indicative of many things other than changes in plant biomass. There is particular sensitivity to changes in plankton community structure (therefore pigment type and concentration per unit biomass). Not only are some of the differences noted smaller than I for one would be comfortable as conclusive but in fact differences in community structure in many oceanic regions (including the GoM) have been widely reported and indeed are expected given warming, acidification and changes in nutrient loading. None of this is to say that over the deeper regions of the GoM plankton biomass has not decreased but it simply cannot be rigorously inferred from this analysis.

***R: We are grateful to the referee for pointing out potential problems in establishing the relationship between upwelled radiance and biomass, and indeed this could be a source of error in coastal waters. However, we have not revised the manuscript on this issue because today chlorophyll derived from ocean color is globally accepted as the index of chlorophyll in oceanic (case 1) waters, namely oligotrophic waters such as those in the central Gulf of Mexico (GoM). Additionally, our observations of chlorophyll are supported by our independent ADT-based analysis of the annual intrusion of very low productivity Caribbean Water (CW), which shows increasing intrusion into the GoM after 2002. Finally, we have looked at the chlorophyll issue from several points of view and are confident of our conclusion. In our work we can only say that according to these satellite "products", we find a time-dependent diminution of the chlorophyll signal. This diminution has been widely***

***observed by others (Behrenfeld et al., 2006, Polovina et al., 2008; Irwin and Oliver, 2009, Laffoley & Baxter., 2016).***

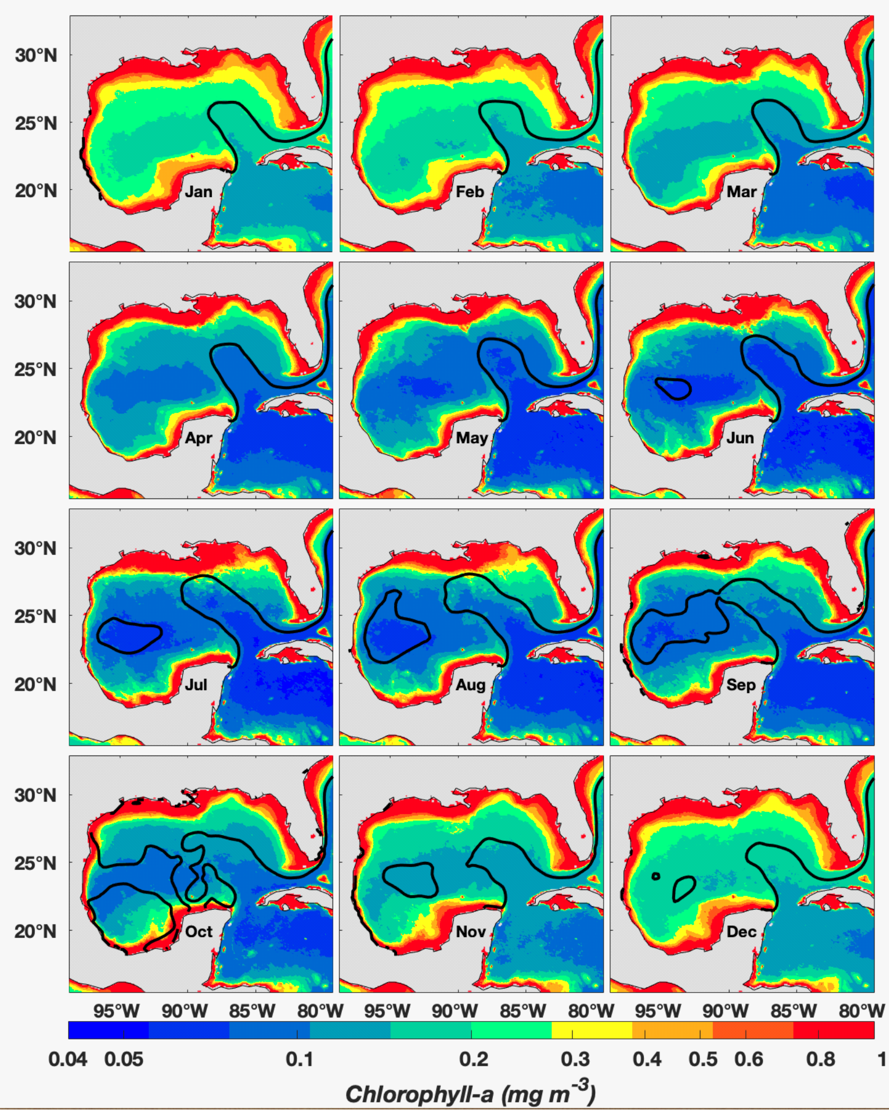
30°N
25°N
20°N
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
95°W
90°W
85°W
80°W
0.04
0.05
0.1
0.2
0.3
0.4
0.5
0.6
0.8
1
Chlorophyll-a (mg m-3)

Figure 8

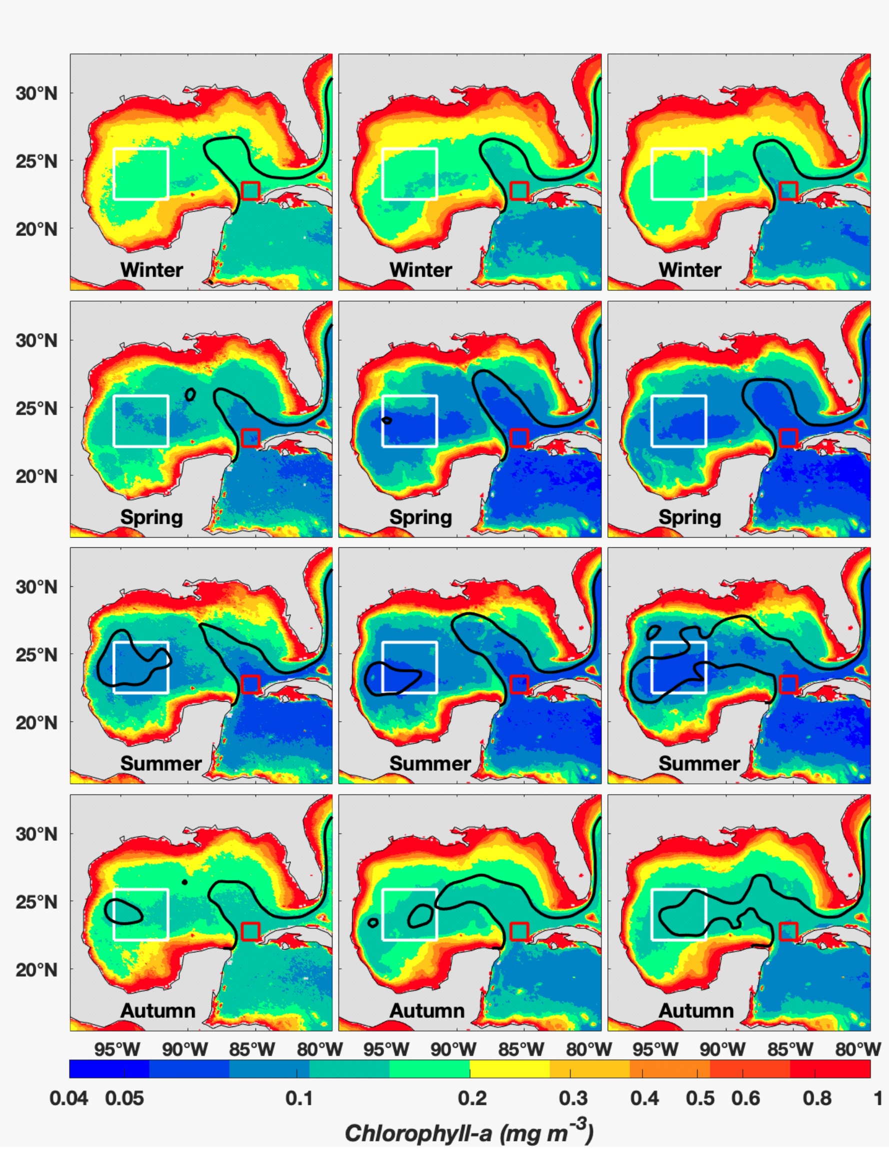
30°N
25°N
20°N
Winter
Winter
Winter
Spring
Spring
Spring
Summer
Summer
Summer
Autumn
Autumn
Autumn
95°W 90°W 85°W 80°W 95°W 90°W 85°W 80°W 95°W 90°W 85°W 80°W
0.04 0.05 0.1 0.2 0.3 0.4 0.5 0.6 0.8 1
Chlorophyll-a (mg m-3)

Figure 9

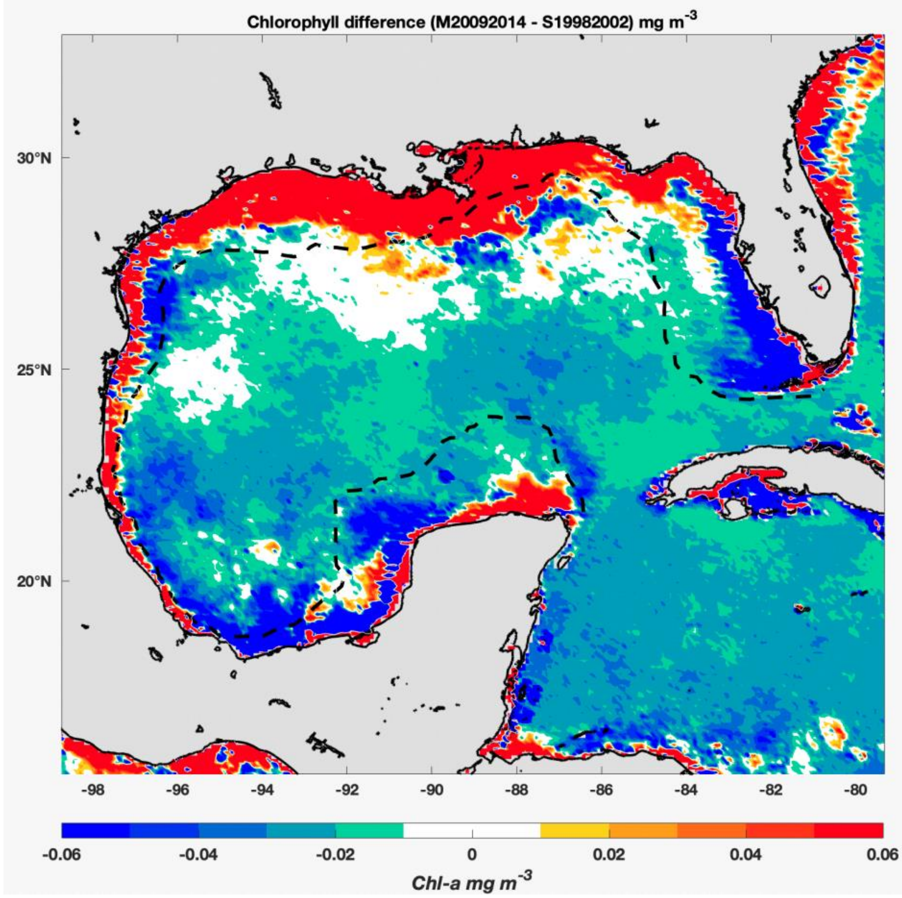
Chlorophyll difference (M20092014 - S19982002) mg m$^{-3}$
30°N
25°N
20°N
-98
-96
-94
-92
-90
-88
-86
-84
-82
-80
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
Chl-a mg m$^{-3}$

Figure 10

## Answers to Reviewer No.2:

- There is a lack of discussion regarding previous studies, which referrer to the seasonal cycle of the LC, like Chang & Oey (2012, 2013), which expose a bimodal cycle obtained with model outputs; Hall & Leben (2016), which show an annual cycle with altimetry data; or Candela et al. (2019), which estimate the amplitude of the seasonal cycles of the transport at Yucatan Channel and at the Strait of Florida using mooring observations. Those works, among others, must be at least mention in the introduction and their findings should be discussed with what was found in this MS.

**ANSWER: About the lack of discussion regarding previous studies that refer to the seasonal cycle we add in L97-105:**

***"LC extension and anticyclonic eddy separation are the result of the momentum imbalance (Pichevin and Nof, 1997) and form the shape of future LCEs. Chang and Oey (2010) using a numerical model, proposed that the wind stress could be the primary forcing that releases LCEs. In a second paper, supported by satellite observations, they proposed that the LC intrusion and the shedding of the LCEs followed a biannual cycle (Chang and Oey, 2013). A reanalysis of archived data also detected statistically significant LCEs separation seasonality (Hall and Leben, 2016). Recently, Candela et al. (2019) analyzed four years of water current data and reported a seasonal cycle in the transport through the Yucatan channel with the annual cycle as the main harmonic peak in July.***

- The conclusion regarding the decrease of Chl-a concentrations in the western Gulf of Mexico (GoM), where the authors state that there is a reduction due to a larger volume of waters coming from the Caribbean Sea toward the GoM, should be taken with caution and considers/discuss the limitations of the data series used for this conclusion. There are other sources that could contribute to a reduction in Chl-a in the western GoM. It is not obvious to me what the authors state with the footprint of the CW/LC path, in the Chl-a climatological patterns (Fig. 11).

**ANSWER: We agree with the reviewer about being cautious. However, without data on changes of time-dependent optical properties caused by population shifts ( ex. to picoplankton) we can only speculate. Therefore, we clarified our statement in L431 to L436.**

***"Our own results and conclusions are based on SeaWifs and AquaMODIS chlorophyll data, which in <u>Type One</u> water, correlate very well with chlorophyll measured with standard laboratory methods (Mati Kahru, personal communication). In our work we can only say that according to these satellite products, we find a time-dependent diminution of the Chl-a signal. This diminution has been widely observed by others although in other waters (Behrenfeld et al., 2006, Polovina et al., 2008; Irwin and Oliver, 2009, Laffoley and Baxter., 2016).***

**About the state with the footprint of the CW/LC path, in the Chl-a climatological patterns (Fig. 11) we agree and we improve the lines 324-326 as follow:**

***"During spring-summer, when the maximum CW penetration occurs, our data confirms that the footprint of the CWF water (delineated by the 40 cm isoline of ADT) is in general oligotrophic indicating that Caribbean water has indeed entered the GoM".***

- The MS need to focused to highlight the relevant contributions.

**ANSWER: We feel that the Summary and Conclusion section amply states our results and conclusions, starting with the summary of our observations on L 438-to L465:**

***"The availability of a large spatial extension of satellite observations of ADT, sea surface currents, wind stress over a quarter of century and Chl-a over 20 years has enabled us to confirm the LC and CW dynamics observed in the 60's and 70's with more recent in situ observations. The verification of the CWF climatologies developed in this work is important as a reference baseline for further numerical modeling, and it impacts assessments of the gulf's biogeochemistry, energy, heat transport, and Chl-a concentration. A recent committee of the National Academic of Sciences, (2018) suggested three main study topics to advance the knowledge of the processes that characterize the GoM: 1) the LC system active area, 2) the variation of the inflows of the LC system, and 3) the dynamic interactions of the LC system in***

***the west. Following these suggestions, we have confirmed that the maximum influence of the CW into the GoM (e,g., its maximum extension into the gulf or intrusion) has a temporal variability, being stronger in summer and weaker in the late fall and winter. This is supported by the fact that the generated monthly EKE maps have the maximum gradient at the periphery of the CWF and have a similar monthly pattern of extension and retraction as the CWF.***

***We noted that in the summer months the wind stress from the southeast is weak, thereby minimizing the flow of nutrients to the surface and causing Chl-a to be low, specifically for three reasons: 1) The increase in the surface temperature of the water column strengthens stratification 2) The intrusion of the CW to the western gulf´s surface thickens the surface layer, and 3) The eddy-driven anticyclonic circulation deepens the nutricline. This contrasts with the cold seasons, when the surface temperature of the water is lower and the northerly winds are stronger, favoring the flow of nutrients to the surface.***

***The three-year running averages of ADT 40 cm isoline reproduce qualitatively the climatological pattern of a quarter of a century showing that before 2002 the CWF was less intrusive and the LCEs sizes were smaller. In the 1993-2002 period, we calculated that the mean life cycle of the eddies was 6.8 months and that in the 2003-2015 period the mean life cycle was 11.7 months. This difference suggests that after 2003, larger volumes of oligotrophic waters from Caribbean Sea have invaded the western GoM and reduced mean surface Chl-a concentrations."***

**Additionally, we have summarized the above in three points L467 to L473.**

- Additionally, statistical relevance of the seasonal cycle needs to be deeply discussed; it is necessary to specify how representative are the climatological averages (Fig. 1), obtained from the monthly averages of the individual years (using information from Fig. 4).

**ANSWER: We improved section 3.1 by specifically naming the months and pointing out in the caption of Fig. 3 (old 4) that at the 95% confidence level, the geographical positions of the of the 40+/- 2.2 cm isolines are virtually identical.**

- Description of section 3.2 (lines 229 – 262 and lines 271 – 280) needs to be rewrite in order to guide the reader to the months of the year that the authors are talking about (maybe a Table will be useful); What is the main message given by all these numbers and description? Besides, there need to be an agreement between the months of the year with the LC extension/retraction throughout the MS.

**ANSWER: All section 3.2 was rewritten and throughout the MS we were careful to connect the months of the year to the LC extension/retraction. We have made it clear that maximum LC influx occurs in the summer months in synchrony with higher temperatures and low chlorophyll.**

## Specific comments

- The MS focus the discussion on the oligotrophic CW intruding the GoM owing to the Loop Current. Therefore, the description of the water masses that conform the GoM, must be introduced and supported by additional bibliography, aside from Nowlin & McLellan (1967), since the reference of Schmitz (2005) is not referred to water masses composition. Further Tanahara (2004), cannot be consulted.

**ANSWER: We introduce the description of the water masses that conform the GoM as follows in L75 to L80 (In addition, the reference Tanahara (2004) was deleted from the manuscript):**

> I do not understand why the Loop Current track is called Caribbean Water. Discernment must be used throughout the MS when the authors refer to the Caribbean Water and the Loop Current; CW could be used to name the water intrusion from the Caribbean with specific biological and physical characteristics (maybe when they talk about Chl-a characteristics) and the LC when you refer to dynamic characteristics, i.e. current that enters the Yucatan Channel, loops at the eastern GoM and through the Florida Strait.

**ANSWER: We agree with the comment. Following the suggestions from the referee, we**

**define the CW in L81-82:**

***CW enters the gulf via the LC with specific biological (i.e low Chl-a) and physical characteristics (warmer and saline waters).***

- Lines 66-67: I do not consider that the MS shows a detailed analysis of the Loop Current Eddies, maybe the approach could be focus to the analysis of the LC and the LCE path footprint.

**ANSWER: We rewrote L67-69…**

***"Unlike previous studies, this work entails the analysis of the Loop Current (LC) and the LC eddies (LCEs) path footprint, and of the dominant features of the surface circulation that transport Caribbean Water (CW) into the GoM** …**".***

- Line 77: Who is this acting as a primary forcing mechanism of the Loop Current? Yucatan Current? The term PFM is not clear and must be specified.

**ANSWER: We deleted PFM and rewrote in L81-82:** "***CW enters in the GoM via the LC.....***

- Line 100: "which move CW". . .. . ..where?

**ANSWER: We rephrased this in Line113 115.**
***Despite extensive research, after more than a half-century we are still struggling to completely understand LC variability, the processes controlling the loop current extension, and the mechanism of detachment of anticyclones from the loop.***

Lines 104-105: "In this work we reexamine the effect of . . .." Rephrase please.

**ANSWER:** ***We rephrase as (L118-122):***

***"In this work, 25-years (1993-2017) of daily ADT data combined with monthly radiance data from 1998-2017 are used to investigate the variability of the transport of Caribbean surface water into the gulf and its effect on Chl-a concentration. We examined temporal changes, mean differences, and regional concentration tendencies."***

- Line 121: "we considered eddies in any state of formation, detaching. . ..", then they are Loop Current Eddies (LCE), not only eddies.

**ANSWER: In line 139 rephrase (L121) "We considered LCEs in any stage of formation…"**

- Lines 146-154: The first three points of the paragraph referring to data description are repetitive with the first paragraph of section 2; the description of the datasets is disordered, since they are described in two different places. I suggest to add additional information, such as the years of the data that you are using at the beginning of the section, before methods description. The calculation description of the mesoscale instabilities, as well as the AR can be described in the methods section, where they have already been described (without paragraph mark).

**ANSWER: We deleted the three bullets of the paragraph:. These were incorporated in the first paragraph on section 2 . We also added the years in which the data were collected at the beginning of the section (L127-133), as follow:**

***"Three independent data sets were used to provide evidence of temporal variability in the extension of CW into the GoM. We used ADT and surface velocity fields (geostrophy and Ekman) from the GEKCO (Geostrophic Ekman Current Observatory, Sudre et al., 2013) product from 1993 - 2017 with a resolution of 0.25˚x0.25˚, in conjunction with Chl-a ocean color data derived from the reprocessing R2014.0 product suite from Aqua MODIS (Moderate Resolution Imaging Spectroradiometer) and from SeaWIFS (Sea-Viewing Wide Field of view Sensor), using the OCx Algorithm with a spatial resolution of 9X9 km (https://oceancolor.gsfc.nasa.gov/cgi/l3). The 2003-2017 monthly Chl-a ocean color product was derived from Aqua MODIS and the 1998-2002 monthly Chl-a ocean color product was derived from SeaWIFS."***

- For the comments "The calculation description of the mesoscale instabilities, as well as the AR can be described in the methods section, where they have already been described (without paragraph mark).

**ANSWER: We removed the bullet.**

- Line 164: Is repetitive with line 110.

**ANSWER: We removed the line.**

- Line 192: The contours from the ADT are not determined by the influence of the CW, please rephrase.

**ANSWER: We rephrase (L189-190) "*In this work, we used the ADT to track both the LC and the LCEs formed by the influence of the CW*"**.

- Please define which months of the year are described for each season (I guess winter (Jan, Feb, Mar), spring (Apr, May, Jun), etc.?).

**ANSWER: We define the months of the year described for each season as follows in L197 to 202:**

***"Fig. 1 shows that (mostly) in autumn (October, November and December) and winter (January, February and March), the CW retracts to its most southeasterly location. In contrast, in spring (April, May, June) and summer (July, August, September), CW penetration moves towards the northwest. In fact, the extension begins in May and reaches maximum penetration in August, showing an annual pattern."***

- It is not clear to me, at least from Fig. 1, that the LC extension is retracted in autumn and extended in spring (lines 200-203), or the fact that the maximum penetration occurs in September, instead of August (see also your statement in line 232). I think it could be useful for the authors to discuss their results with previous work referring about the seasonality of the LC (see comment above).

**ANSWER: We rewrite as follows (See L197-205):**

***"Fig. 1 shows that (predominately) from November to April, the CW retracts to its most southeasterly location. In contrast, from May to October, CW penetration moves towards the***

***northwest. In fact, this extension begins in May and reaches maximum penetration in August, resulting in an annual pattern. This movement is similar to that observed by Chang and Oey (2013). They found that in summer, the maximum LC intrusion was forced by the trade winds. Their and our observations are also consistent with the work of Candela et al. (2019) who reported that water transport into the GoM in July through the Yucatan channel was at a maximum."***

- Line 241 and Fig.3: Please specified if the ADT was spatially averaged.

**ANSWER: In Lines 230 to 232 we added:**

***The monthly intrusions of the CW were tracked by taking as a reference the northernmost latitudes and westernmost longitudes of the 40 cm ADT isoline representing 1993-2017 monthly average values of the ADT (not spatially averaged).***

- The steric signal included in the ADT data must be discussed, considering the high-energy observed in the annual period (see Hall & Leben, 2016).

**ANSWER: Lines 238 to 240 we wrote:**

***In this work, the ADT signal also includes the seasonal steric effect.. Based on Hall and Leben (2016), a steric signal appears as an annual sine wave with a 5.8 cm amplitude.***

- Section 3.2 (Fig. 4): Why the STD contour of 15 cm was chosen as a reference for the regions of maximum variability?

**ANSWER: In Lines 266 to 268 we add "*The STD contour of 15 cm was selected because this value was three times greater than the annual steric signal reported by Hall and Leben (2016)".***

- Lines 278-280: How this cycle of the monthly ratios compares with the results of Chang & Oey (2012, 2013)?

**ANSWER: In Lines 273 to 275 we compare the results as follow:**

***Chang and Oey (2012, 2013) proposed that the LC intrusion and the shedding of the LCEs***

***followed a biannual cycle. The biannual cycle can also be related to the annual lowest and highest ratio values .***

- It makes not sense to me the discussion of the monthly averages of the wind stress, shown in Fig. 6 and described in section 3.4, it is not relevant for the main objective of this section, further this discussion do not reinforce de main idea exposed here; I suggest to delete this part or move this description elsewhere in the MS.

**ANSWER: We agreed with the reviewer and we removed the section and Figure 6.**

- Lines 300-301: Please be more specific; Do you mean an upwelling? Is so where? Please use references.

**ANSWER: The lines 300 to 301 were part of section 3.4 and were removed).**

- The whole paragraph of section 3.5 is not linked with the rest of the MS, if you want to keep it, at least it go deeper in the implications and discussion of these calculations.

**ANSWER: We also removed those lines because we are agree with the reviewer.**

- Statement of line 327-329: The difference between the mean life of the LCEs (6.8 vs 11.7) needs to be discussed with previous studies.

**ANSWER: We complemented as follow in lines 304-308:**

***"These observations also agree with the results of Lindo-Atichati et al. (2013), confirming that, on average, the LC northward intrusion starts to increase in 2002. These authors also report an increase in number/year of LC rings over the same period that also coincided with a significant increase in sea height residuals (2.78 ± 0.26 cm/decade from 1993–2009)"***

- Lines 378-379: How these three periods were chosen? Why not using the same two periods of the ADT? Please explain.

**ANSWER: We decided to separate and evaluate the extreme period pattern from the transitional data.**

- Table 1 (lines 386-399), please specify what means the bold numbers in Table 1 and show the difference between Early and Contemporary periods at each row. Using the differences obtained here discuss the significance of the Chl-a averages between these two periods.

**ANSWER*: The bold numbers represent the average CHl-a concentrations. We add the meaning for bold numbers in Table 1 as follow: "Table 1. Bold numbers denote average Chl-a concentrations (mg $m^{-3}$)……." We also include the differences and percentages between Early and Contemporary periods at each row. For discussion see section 3.5.***

- Second point mark of the conclusions (line 515). I do not see that in Fig. 10, or in Fig. 11.

**ANSWER: We agree with the reviewer and we deleted that sentence from the conclusion.**

## Technical corrections:

Please avoid the double space throughout the manuscript (i.e., lines 58, 60, 144, 263, 267, 269, etc.).

**ANSWER: Done. Spacing was corrected.**

Caribbean water is mentioned for the first time in the MS in line 68 as the acronym CW and in the line 75 as Caribbean Water. The acronyms must be defined for the first time as they are mentioned in the text and then they should be used throughout the MS as an acronym (the same for Loop Current as LC, which is even lowercase in line 99).

**ANSWER: The acronyms were defined in the abstract and Introduction and used through the MS.**

Line 119: Specifiy the years used for the 25 years climatologies.

**ANSWER: this issue was corrected, and we specified (1993 to 2017).**

Line 140: ‘island’ instead of Island.

**ANSWER: This error was corrected.**

Line 216 and 230: CWF instead of Caribbean water front, it is already defined in line 151.

**ANSWER: Corrected.**

Lines 294-295: Please specify that this is a supposition.

**ANSWER: We have reworded the phrase to say " We suppose that the greater percentage area of the STD may be attributed to a greater influence of Caribbean Sea water.**

Line 314: Please use the accurate terms.

**ANSWER: The section 3.5 was removed and sections were renumbered.**

Line 324: ‘extended to the west’. . .in summer and autumn?

**ANSWER: Corrected in line 294-295.**

Line 337: Avoid the use of acronyms in the title sections (especially if it has not been previously defined).

**ANSWER: Corrected**

Line 360: Use CW.

**ANSWER: Done.**

Line 402: Add (see also Fig. 11).

**ANSWER: Added in line 356.**

Lines 413-415: Rephrase.

**ANSWER: Done (See L362-364) as follow:** ***This effect is also evident in the LC core, where Chl-a concentrations decreased with time and signals the entrance to the gulf of more oligotrophic water during the middle and contemporary epochs".***

Line 432: Check the point marks.

**ANSWER: Done.**

Lines 446-450: Rephrase the way you mention the M-K work please.

**ANSWER: We repharesed M-K for Müller-Karger *et al.* (2015).**

Please avoid the use of 'we', instead use something like 'in this work. . .'

**ANSWER: Because this is optional we prefer to use "We, it is more direct.**

- Line 470: R means correlation?

**ANSWER: Correlation Coefficient (R) in Line 417.**

- Line 480: Change 'begs' for a more appropriate word (needs, requires, etc.).

**ANSWER: "Begs" was changed for "requires"**

Lines 508 and 509: Please change the term 'lifespan'.

**ANSWER: changed to "lifetime" in line 297.**

- Line 513: Please rephrase the first point of the conclusions.

**ANSWER: This was done as follow (L467-468):** ***"The intrusion of the CW by LC-LCEs extends further into the western GoM than was previously known".***

Effect of Caribbean Water Incursion into the Gulf of Mexico derived from Absolute Dynamic Topography, Satellite Data, and Remotely - sensed Chlorophyll-*a*

***Authors:***

**Juan A. Delgado[1,2,5]; Joël Sudre [3], Sorayda Tanahara[1]; Ivonne Montes[4],**

**J. Martín Hernández-Ayón[5], Alberto Zirino[6]**

Author affiliations:
[1]*Facultad de Ciencias Marinas, Universidad Autónoma de Baja California, Transpeninsular Tijuana-Ensenada, no. 3917, Fraccionamiento Playitas, CP 22860. Ensenada, Baja California, México.*

[2]*Instituto Tecnológico de Guaymas/ Tec. Nacional de México, Guaymas, Sonora, México.*

[3]*LEGOS, CNRS/IRD/UPS/CNES UMR 5566, 18 av. Ed Belin, 31401 Toulouse Cedex 9, France*

[4]*Insitituto Geofísico del Perú. Lima, Perú.*

[5]*Instituto de Investigaciones Oceanológicas, Universidad Autónoma de Baja California, Transpeninsular Tijuana-Ensenada, no. 3917, Fraccionamiento Playitas, CP 22860. Ensenada, Baja California, México.*

[6]*Scripps Institution of Oceanography, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093, USA.*

Corresponding author: Sorayda Tanahara (stanahara@uabc.edu.mx)
*Facultad de Ciencias Marinas*
*Universidad Autónoma de Baja California.*

**Key points:**

Twenty-five years of satellite observations of absolute dynamic topography confirm the patterns of Caribbean water intrusion in the Gulf of Mexico.

Larger volumes of oligotrophic waters from Caribbean Sea are entering the western Gulf of Mexico and lowering the surface and near surface *Chl-a* concentration.

**Abstract**

The dynamics of the Loop Current (LC) and the detached Loop Current eddies (LCEs) dominate the ~~Gulf of Mexico's~~ surface circulation of the Gulf of Mexico (GoM) and transport Caribbean water (CW) into the gulf. In this work, 25-years (1993-2017) of daily satellite data are used to investigate the variability of these physical processes and their effect on chlorophyll-a (Chl-a) concentrations from 1998-2017 including temporal changes, mean differences, and regional concentration tendencies. Physical variables analyzed are absolute dynamic topography (ADT), oceanic currents, and wind stress. From the ~~absolute dynamic topography~~ADT and oceanic current monthly climatologies, it is shown that there is an annual intrusion of the ~~Caribbean water~~CW with an inward incursion that starts in spring, peaks in the summer, reaches to 28˚N and 90.45˚W, and then retreats in winter to 26.5 ˚N and 88.3 ˚W, ~~–~~approximately. Minimum surface ~~Chlorophyll-a~~Chl-a concentrations (<0.08 *mg* $m^{-3}$) are found during the summer-autumn period inside the region of maximum incursion of the ~~Caribbean water~~CW; the opposite is observed during the winter period when ~~the~~ ~~Chlorophyll-a~~Chl-a concentrations were at a maximum, e.g., >0.14 *mg* $m^{-3}$. The three-year running averages of the ~~absolute dynamical topography~~ADT 40-cm isoline reproduce qualitatively the climatological pattern of 25 years showing that before 2002 the ~~Caribbean water~~CW was less intrusive. This suggests that from 2003 onward, larger volumes of oligotrophic waters from Caribbean Sea have invaded the western ~~Gulf of Mexico~~GoM and reduced mean surface ~~Chlorophyll-a~~Chl-a concentrations. A direct comparison between the 1998-2002 and 2009-2014 periods indicates that~~,~~ in the latter time interval, Chl-a ~~*Chlorophyll-a*~~ concentration above waters deeper than 250 *m* has decreased significantly.

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## 1. Introduction

The effects of global warming on the circulation of the world's oceans and its concomitant consequences on the oceans' biological productivity are some of the most important scientific and economic issues of our times. Forecasting of the effects of global warming on the ocean~~'~~s' resources depends on having a clear understanding of the manner in which physical processes (e.g., solar radiation, winds, ~~ocean~~ circulation and vertical mixing) affect primary production. This understanding is aided by the availability of remote sensing observations, unparalleled in their spatial and temporal coverage of the earth's surface. Since 1990, satellite data of absolute dynamic heights (ADT), ~~chlorophyll-a~~Chlorophyll-a (Chl-a) concentration, and derived products (eddy kinetic energy (EKE), geostrophic and Ekman currents) have been available to study the Gulf of Mexico (GoM), an important socio-economic region for fisheries, petroleum, natural gas, and tourism. We have availed ourselves of a 25-year time series of satellite data to study the relationship between the physical dynamics of the GoM and its effect on primary production in the context of a global warming scenario. Unlike previous studies, this work entails the analysis of the Loop Current (LC) and the LC eddies (LCEs) path footprint, and of the dominant features of the surface circulation that transport Caribbean Water (CW) into the GoM (Nowlin and McLellan, 1967; Morrison et al., 1983). The LC in the eastern GoM is part of the North Atlantic Ocean Subtropical Gyre, an essential contributor to the inter-hemispheric Meridional Overturning Cell (Schmitz and McCartney, 1993; Candela et al., 2003; Schmitz et al., 2005). This current carries warm waters from the gulf to the North Atlantic through the Florida Straits via the Gulf Stream (Hurlburt and Thompson, 1980), thereby also being an important contributor to the upper ocean heat budget of GoM (Liu et al., 2012). Based on a detailed analysis in the central and western GoM by Portela et al.~~,~~ (2018), within the Gulf are seven water masses in order of increasing mean density: remnants of the Caribbean Surface

Water (CSWr: also referred to~~-~~ as CW), North Atlantic Subtropical Underwater (NASUW), Gulf Common Water (GCW), Tropical Atlantic Central Water (TACW), the nucleus of the (TACWn), Atlantic Intermediate Water (AAIW) and North Atlantic Depth Water (NADW). Here, we are principally concerned with surface effects.

Knowledge of how the thrust of the LC affects the intrusion of CW is based on hydrographic data (Leipper, 1970; Niiler 1976; Behringer et al., 1977; Molinari et al., 1977; Huh et al., 1981; Paluszkiewicz et al., 1983), remote sensing observations (Vukovich et al.1979; Vukovich, 1988; Leben and Born, 1993; Leben, 2005), and, in the last twenty years, by numerical modeling (Hurlburt and Thompson, 1980; Candela et al., 2003; Oey et al., 2005; Sturges and Lugo-Fernandez, 2005; Counillon and Bertino, 2009; Cardona and Bracco, 2016; Wei et al., 2016). More recently, novel developments based on artificial neural networks and empirical orthogonal function analysis have also been applied to predict LC variation (Zeng et al., 2015), effecting reliable forecasts for up to 5 to 6 weeks. Knowledge of how the primary forcing mechanism affects the loop current is important to the circulation of the GoM both as a direct and indirect generator of surface-layer eddies and as a source of lower-layer flows (Hamilton et al., 2016). Based on satellite altimetry observations and the dynamic height gradient from 1993 to 2009, Lindo~~-~~-Atichati et al. (2013) observed northward seasonal penetration of the LC, peaking in summer. ~~Loop current~~LC extension and anticyclonic eddy separation are the momentum imbalance (Pichevin and Nof, 1997) and form the shape of future LCEs. Chang and Oey (2010) using a numerical model, proposed that the wind stress could be the primary forcing that releases LCE~~'~~s. In a second paper, supported by satellite observations, they proposed that LC intrusion and the shedding of the LCE~~'~~s followed a biannual cycle (Chang and Oey, 2013).

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reanalysis of archived data also detected statistically significant LCEs eddy separation (Hall and Leben, 2016). Recently, Candela et al. (2019) analyzed four years of water current data -and –reported –a seasonal cycle in the transport through the Yucatan channel– with the annual as the main- harmonic peak in July.

Interacting seasonal and stochastic processes could trigger the separation of the LCEs (Fratantoni et al., 1998; Zavala-Hidalgo et al., 2003; Zavala-Hidalgo et al., 2006) as well as forming Caribbean eddies and other topographic features (Garcia-Jove et al., 2016). In this context, the LC system has some similarities with the North Brazil Current retroflection (Pichevin et al., 1999; Goni and Johns, 2001; Zharkov and Nof, 2010), the Agulhas retroflection (de Ruijter et al., 1999; Baker-Yeboah et al., 2010) and with the Gulf Stream, where large meanders pinch off as warm rings (Brown et al., 1983; Richardson, 1983; Savidge and Bane, 1999).

Despite extensive research, after more than a half-century we are still struggling to completely understand LC variability, the processes controlling the loop current extension, and the mechanism of detachment of anticyclones from the loop. Because positive time trends have been reported in temperature, winds, sea level and the greater number of detached eddies separated from the LC, it can be expected that these phenomena would affect primary productivity and, indirectly, surface Chl-achlorophyll concentration (Polovina, et al., 2008; Baxter., 2016). In this work, 25-years (1993-2017) of daily ADT data combined with monthly radiance data from 1998-2017 are used to investigate the variability of the transport of Caribbean surface water into the gulf and its effect on chlorophyll-aChl-a –concentration.– We examined mean differences, and regional concentration tendencies.

**2. Data and Methods**

Three independent data sets were used to provide evidence of temporal variability in the extension of CW into the GoM. We used ADT and surface velocity fields (geostrophy and Ekman) from the GEKCO (Geostrophic Ekman Current Observatory, Sudre et al., 2013) product from 1993 - 2017 with a resolution of 0.25˚x0.25˚, in conjunction with *Chl-a* ocean color data derived from the reprocessing R2014.0 product suite from Aqua MODIS (Moderate Resolution Imaging Spectroradiometer) and from SeaWIFS (Sea-Viewing Wide Field of view Sensor), using the OCx Algorithm with a spatial resolution of 9X9 km (https://oceancolor.gsfc.nasa.gov/cgi/l3). The 2003-2017 monthly *Chl-a* ocean color product was derived from Aqua MODIS and the 1998-2002 monthly *Chl-a* ocean color product was derived from SeaWIFS.

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Specifically, monthly CWF positions were obtained from short-term running averages of daily satellite observations in three-year periods. Each running average was moved rearward by one year, e.g. 1993-1995, 1994-1996 … 2014-2016, 2015-2017. For each three-year period, a set of 12 monthly maps was obtained resulting in a total of 23 sets of monthly CWF maps: 10 sets from 1993 to 2002 and 13 sets from 2003 to 2017. We used the 40 cm contour of each set of three-year averages because this was the contour with the highest EKE observed in the 25-year data set. To retrieve the CWF contours, we first determined the initial latitudinal position of the CWF to be at 80.7$^{o}$W with the respective corresponding longitudinal positions between Cuba and Florida. The CWF contour lines that run from east to west and finish close to the tip of the Yucatan peninsula were separated by 0.2 ±0.1 degrees. However, some ADT contour "islands" appeared next to the CWF with a typical distance of > 0.3 degrees from the CWF contour.

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Additionally, a spectral analysis was done using a daily time series of 25 years of ADT data to build a spatially averaged region influenced by the LC between 91.25°W, 23.125°N and 83.5°W, 28.12°N.

When ADT island distances were > 0.3 degrees from the front, we used a Matlab code procedure to eliminate them from the CWF contours. Once the CWF's contours were retrieved, the next step was to visually corroborate the quality and coherence of each CWF contour over the monthly field maps of ADT, sea surface currents, and *Chl-a* distribution. In this way, inconsistencies were detected and corrected. The Matlab code procedure satisfactorily corrected 91.3% of the contours. The remaining sets were corrected by hand via visual analysis.

Main mesoscale instabilities were obtained from calculations of the climatological monthly EKE maps of geostrophic and Ekman currents obtained from 25 years of daily satellite observations of GEKCO using following equation:

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$$u = u' + U; \qquad u' = u - U$$

$$v = v' + V; \qquad v' = v - V$$

$$EKE = \tfrac{1}{2}\,(u'^2 + v'^2)$$

Where ($u$, $v$) is the total current ($u = u_E + u_g$ and $v = v_E + v_g$; ($u_E$, $v_E$), is the Ekman and ($u_g$, $v_g$) is the geostrophic current, ($U$ and, $V$) are the means of the oceanic currents and ($u'$ and, $v'$) are the anomalies of the current. To find the relationship between ADT and EKE patterns, the 40 *cm* ADT isoline was overlaid on the monthly EKE maps. This made the EKE means representative of the energy of the mesoscale eddy field (Jouanno et al., 2012).

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For consistency between the different satellite datasets, all monthly climatological spatial fields were standardized at 0.25˚x0.25˚ spatial resolution by bilinear interpolation.

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## 3. Results and discussion

### 3.1. Tracking the Intrusion of Caribbean Water

The LC enters the gulf through the Yucatan Channel and exits through the Straits of Florida, penetrating northward into the GoM until instabilities form in the current and a ring-like LCEs pinches off. There are two ways of tracking the LC: 1) tracking the thermal signal (not possible in summer due to weak thermal contrast in the GoM), and 2) tracking the sea surface height trough the satellite altimetry. In 2005, Leben, using the 17 *cm* contour in the daily sea surface topography maps (this contour closely follows the edge of the high-velocity core of the LCEs and LC), tracked the LC thermal fronts in the sea surface temperature images during good thermal contrast. In a different way, Lindo-Atichati et al. (2013) calculated the maximum horizontal gradient of the sea surface height (SSH) to track only the contours of the LCF. In this work, we used the ADT to track both the LC and the LCE´s formed by the influence of the CW. Monthly mean surface oceanic currents from GEKCO overplotted on the ADT data are shown in Fig. 1. Maximum satellite surface current velocities in the Caribbean Sea and the GoM, as well as in the Yucatan current on the continental coast, were > 50 $cm\ s^{-1}$, coinciding with *in situ* estimates of ~ 60 $cm\ s^{-1}$ (Badan et al., 2005). The monthly GoM total current fields show the variability of the primary forcing that coincides with the mean ADT edge; the vectors of maximum velocity are tangent to the edge of the maximum slope change. To locate the CW, the 40 *cm* mean ADT's isoline was chosen. The ADT reference corresponds to regions of maximum gradients of ADT, and maximum EKE (*vide infra*). Fig. 1 shows that (mostly) in autumn

November and December) and winter (January, February and March), the CW retracts to its most southeasterly location. In contrast, in spring (April, May, June) and summer (July, August, September), CW penetration moves towards the northwest. In fact, the extension begins in May and reaches maximum penetration in August, showing an annual pattern. This movement is similar to that observed by Chang and Oey (2013). They found that in summer, the maximum LC intrusion was forced by the trade winds. Their and our observations are also consistent with the work of Candela et al. (2019) who reported that water transport into the GoM in July through the Yucatan channel was at a maximum.

It is accepted that the LCE's occur in a geographical control zone that is based on momentum imbalance (Pichevin and Nof, 1997; Nof, 2005) rather than instability. Also, we should not abandon the idea that the formation of instabilities such as meanders and cyclonic eddies are due to high EKE produced by upstream conditions that influence the circulation within the GoM (Oey et al., 2003) and produce changes in the fluxes in the Yucatan Channel (Candela et al., 2002), transport variations in the LC (Maul and Vukovich, 1993), variations in the deep outflow (Bunge et al., 2002), and cyclonic eddies in Campeche Bank and Tortugas (Fratantoni et al., 1998; Zavala-Hidalgo et al., 2003). The areas of large EKE are related to the intrusion and retreat of CW (Garcia-Jove et al., 2016) via baroclinic and barotropic instabilities (e.g. Jouanno et al., 2009).

Fig. 2 shows that the 40 *cm* isoline encloses the maximum EKE area of the LC-LCEs during each climatological month, demonstrating that its distribution is mainly centered in the LC region; consequently, the maximum EKE borders the CW front just where the abrupt horizontal gradients of ADT exist and changes of current speed occur. It is clear that the 40 *cm* isoline of ADT matches very well both the maximum EKE values and the maximum ADT

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gradient and is a good tracker of the contours of LC-LCEs. Lindo-Atichati et al. (2013) proposed a methodology using the SSH maximum horizontal gradient, which is the addition of sea height anomaly and mean dynamic topography, to obtain the contours of LCF and the LCE~~'~~s. In our analysis, we chose the 40 *cm* isoline as a general reference to track both LCF and LCE~~´~~s, and ~~transporting~~ CW transport.

The enhanced monthly EKE signals respond in the same way as the LCF, repeating the mean monthly pattern as well as the total currents; the CW intrusion starts in spring and peaks in summer to retract in autumn and winter, and there are no relevant mesoscale EKE's structures in the western GoM. These results confirm an annual pattern of CW intrusion in summer months and retraction in winter.

**3.2 West and Northward Caribbean water extension**

The monthly intrusions of the CWF were tracked by taking as a reference the northernmost latitudes ~~(hereafter CWF)~~ and westernmost longitudes of the 40 *cm* ADT isoline representing 1993-2017 monthly average values of the ADT (not spatially averaged). The climatological position of the CWF for each month of the year is shown in Figure 3. These results confirm the annual intrusion of the CW as follows: 1) Analysis of the maximum north and westward penetration of the front over 25 years shows that from January to February, it is retracted southeast to ~ 26.55˚N and ~ 88.32˚W (Fig. 3a and 3b, respectively), and intrudes to 28˚N, 90.45˚W in August; 2) an ADT spectral analysis derived from 25 years of daily data from the CWF region shows a strong annual signal that originates from the back and forth of the ADT signal (Fig. 3c). In this work, the ADT signal also includes the seasonal steric effect~~, and the spectral analysis reveals a high-energy peak in the annual frequency~~. Based on Hall and Leben amplitude~~ the details of which are described below.~~ When the estimated seasonal steric diminishes by 74%.

In winter, the "tongue" of the CWF moves slowly to the north without westward advance; in spring ~~the CWF tongue~~it lengthens and travels slightly towards the west. From January to March, the northward CWF position shifts slowly, tracing a gently sloping line, that starts at 26.5˚N, reaches its maximum northern position of 28˚N in August, and then decreases in December to 26.28˚N (maximum travel of the CWF was 1.72˚ or 191 *km)*. In summer, the CWF intrudes further into the interior of the GoM both in the north and west: its maximum northern and westward advance occurs in August to 28˚N and 90.45˚W, but then the CWF retracts in the last month of summer. Regarding CWF´s westerly movement (Fig. 3b), the CWF traveled little from January to April; in May however, it extended quickly and in July, August, and September reached approximately 90.2˚W, and peaked in October at 90.76 ˚W (maximum range was 2.56˚ or 253 *km*, calculated at 27.5˚N latitude). In December, the CWF retracted abruptly to 88.24˚W.

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Another aspect of the CWF is the rate of intrusion and retraction. From March to August, the CWF moves to the north with a penetration speed on the order of ~ 1.02 $km\ day^{-1}$, covering a distance of 153 *km or* 1.37˚. On the other hand, the rate of retraction from August to November is ~ 1.86 $km\ day^{-1}$, equivalent to *168 km (1.51˚)*. The entire process of northerly intrusion occurred in three stages: first, from January to April, the front moved slowly northward, increasing its speed while maintaining its westward position. Between May and July the front moved northwest; then was quasi-stationary in July and August, near 90.45˚W; finally, in September, it moved from 90.13˚W to 90.76˚W, equivalent to 63 *km* at a rate of 2.1 $km\ day^{-1}$. The retraction to the west occurred relatively quickly as the front retracted 193 *km* towards the east in a single month (October) at the rate of 6.3 *km day*$^{-1}$, and in November traveled 41 *km* at a rate of 1.4 *km day*$^{-1}$, also towards the east.~~-~~

Fig. 4 shows the calculated climatological ~~ratios between the~~ areas of standard deviation (STD) of the CWF contours > 15 cm (dotted line) and CWF contours > 40 cm (heavy black line). From these areas we calculated ratios between the two (15cm/40cm). The STD contour of 15 cm was selected because ~~considering~~ this value was three times greater than the annual steric signal reported by Hall and Leben (2016). Ratio values greater than 1 were found in February (1.62) and April (1.60). From May to August, the monthly ratio~~s~~ descended to 1.36~~were from 1.41~~, ~~descended to 1.36~~, and increased in September back to 1.60, peaking in October to 1.68, then decreasing in November to 1.60 and finally settling to 1.62 in December. The average w~~W~~inter months (Dec., Jan., and Feb.) had an ~~high~~ average ratio of 1.56. From March to July, ~~In the last two months of spring and the first two months of summer~~ T~~t~~he average ratio was 1.40. However, in August the ~~in the last summer month the~~ ratio increased abruptly to 1.60. Fall (Sept., Oct., and Nov.) had~~kept~~ high ratios, averaging 1.62. Chang and Oey (2012, 2013) proposed that the LC intrusion and the shedding of the LCEs followed a biannual cycle. The biannual cycle can also be related to the annual lowest and highest ratio values.

**3.3 Monthly Spatial Variability of the Caribbean Water Front**

It was found that where penetration-retraction of the CWF occurs, STD variability varies from 15 to 35 *cm*, extending west to 90.8°W in winter and 93.5°W in summer (Fig. 4). West of the CWF, in the deep zone of the GoM, the observed variability was close to 10 *cm* distributed in the band of latitude between 23˚N and 28.5˚N. The regions of maximum variability (STD > 15 *cm*) occur in the CWF zone and extend outside the irregular area of reference (isoline of the 40 *cm* ADT). The effect of CWF penetration and regions of anticyclonic circulation was determined

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from the area of the variability of ADT, with maximum values close to ~35 *cm* in the central region of the CWF, at 86.67˚W and 25.6˚N. The percentage of the area of influence of STD > 15 *cm* in relation to the area of the gulf (1.56x10$^6$ *km$^2$*) is presented in Fig. 5, where a gradual monthly increase is observed from January to October, followed by a decrease in November and December. In January, the direct influence of the CWF on the gulf by area was 12.4%, rising to 21.5% for October, to subsequently decrease in December to 15.4%.— We suppose that the greater percentage area of the STD may be attributed to a greater influence of Caribbean Sea water.

**3.4 Changes in the Caribbean Water Incursion from 2003 to the Present**

Using the 40 *cm* reference, a 3-year running average of the ADT data was calculated to extract the minimum number of years that would produce a similar pattern over a quarter century of the CWF. The results have shownindicate a difference in CWF path and westward penetration before and after 2002. It is observed that before 2002 the CWF was less intrusive in the west- (Fig. 6), after 2002 it extended towards -the west -in both summer and autumn (Fig. 7-). It is important to note that the intrusion of the CWF is due to the influence of LCE's that have a strong presence in the western GoM. This fact is supported by a statistical analysis of the lifetimes of the LCEs during two time periods (1993-2002 and 2003-2015) (http://www.horizonmarine.com/loop-current-eddies.html). The data shows that the LCE's in the 1993-2002 period had a mean life of 6.8 months while the average life in 2003-2015 was 11.7 months. To prove that there is significant difference between these periods, a student-*t* test was applied with the result that the difference between them is significant (t = -3.098, p = 0.005). The LCE mean life difference is clear evidence that the incoming volume of water from Caribbean Sea (with oligotrophic features, Aguirre –Gómez and Salmerón-García, 2015) has reached farther in the western GoM after 2002. These observations also agree with the results of Lindo-Atichati et al. (2013), confirming that, on average, the LC northward intrusion starts to increase in 2002. These authors also report an increase in number/year of LC rings over the same period that also coincided with a significant increase in sea height residuals (2.78 ± 0.26 cm/decade from 1993–2009). This supports the finding suggests that from 2003 onward, larger volumes of oligotrophic waters from Caribbean Sea have invaded the western GoM.

### 3.5 Chlorophyll-a Satellite Imagery, Climatology, and Changes in the Last Decade

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Another product that tracks the effect of CW inside the western GoM is the *Chl-a* satellite imagery, being an index of primary productivity (Boyer et al., 2009). Physical processes that affect the distribution and abundance of *Chl-a* include estuarine influxes, depth of the nutricline, wind stress, thermal stratification and eddy advection. However, over deep waters of the GoM, it is the wind stress and the thermal stratification that principally affect the *Chl-a* concentration (Martínez-López and Zavala-Hidalgo, 2009; Müller-Karger et al., 2015, Damien et al., 2018). It was found that the oligotrophic CW contrasts seasonally with the gulf waters and allows the observation of two levels of *Chl-a* –(high and low, Müller-Karger et al., 1989). Here, the temporal relationship between the CWF and *Chl-a* concentration was constructed from SeaWifs and MODIS monthly climatological images (Fig. 8). The highest concentrations of *Chl-a* in the interior of the GoM are observed during autumn and winter months when high concentrations are triggered by vertical mixing (Pasqueron de Fommervault et al., 2017; Damien et al., 2018) when values were > 0.14 $mg\ m^{-3}$ in agreement with Dandonneau et al. (2004), whereas in spring-summer they decreased to 0.08 - 0.09 $mg\ m^{-3}$. During spring-summer, when the maximum CW penetration occurs, our data confirms that the "footprint" of the CWF water (delineated by the 40 *cm* isoline of ADT) is in general oligotrophic indicating that Caribbean water has indeed entered the GoM. During this period, the *Chl-a* surface concentration remains low as the increase in surface temperature strengthens stratification. Additionally, the winds from the southeast are weak, thereby reducing the mixing of nutrients to the surface. In contrast, during the autumn-winter months, the northerly winds are stronger, increasing vertical mixing, deepening the mixed layer, and carrying cold, nutrient-rich subsurface water into the euphotic layer (Müller-Karger et al., 1991; Müller-Karger et al., 2015; Pasqueron de Fommervault et al., 2017).

In seeking relationships between the spatial-seasonal distribution of the *Chl-a* concentration and the incursion signaled by the ADT-generated data, three spatial-temporal periods were selected, each was averaged pixel by pixel, and the three were labeled: "early" (1998-2002), "middle" (2003-2008), and "contemporary" (2009-2014) epochs. The 5-year averages of the "early" and "contemporary' periods of two separate areas were compared: 1) an area located in the western GoM at 95.5˚W, 22.12˚N and 91.5˚W, 25.87˚N, and 2) a smaller area located in the center of the LC at 86˚W, 22.12˚N and 84.75˚W, 23.37˚N (Fig. 9). The differences in the means were tested for significance with a 2-tailed z test at the 95% confidence level (Fowler et al., 2013). The results are shown in Table 1 and may be summarized as follows:

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**A**. Temporal differences: 1) Western GoM differences between e"Early" and c"Contemporary" *Chl-a* concentrations are significantly different in all seasons; 2) Loop Current differences between "Early" and "Contemporary" *Chl-a* concentrations are significantly different during winter, spring, and autumn, but not in summer;

**B**. Spatial differences: 1) In winter, the Western GoM is significantly higher in *Chl-a* than the LC during both "early " and "contemporary" periods; 2) In the spring, the Western GoM is significantly higher than the LC during the "early" period, but not in "contemporary" period; 3) In summer, the LC is significantly higher than Western GoM during both "early" and "contemporary" periods; 4) In autumn, the Western GoM is significantly higher than LC during "early" period but not significantly different from the LC in the "contemporary" period.

**C**. Seasonal Differences. In the Western GoM and the LC in both the early and contemporary periods, *Chl-a* decreases from winter to spring and from spring to summer, and increases from autumn to winter, but autumn concentrations do not exceed winter (See also Fig.9). All differences are significant.

Examination of Table 1 indicates that at both areas, the winter season is most productive, followed by autumn, with the lowest *Chl-a* concentrations occurring in summer (see also Fig. 9). There is also a time-dependent trend, with contemporary values that are, in general, lower than the values in the early and middle epochs. Both areas exhibit identical climatic trends over time and during each season, indicating that these effects are applicable outside of the continental shelf. The "early" spring epoch is more eutrophic than the middle and contemporary epochs, indicating a decline in nutrient concentrations over time. This effect is also evident in the LC core, where *Chl-a* concentrations decreased with time and signals the entrance to the gulf of more oligotrophic water during the middle and contemporary epochs. Perhaps the most notable seasonal scenario occurs in the summer to early October period, when the CWF "tongue" extends in the interior of the GoM. Although the concentration of *Chl-a* in the Western GoM declines gradually with time to from ~ 0.09 to ~ 0.08 $mg\ m^{-3}$, the interesting fact is that the area of oligotrophic water expands and become larger in the contemporary period. On the other hand, in the LC core, the *Chl-a* concentrations in the three epochs do not significantly differ, suggesting that the water entering the GoM is from a single source, namely, the Caribbean Sea. In general, the extensive penetration of the LC within the GoM, as well as the increase in the life periods and sizes of LCEs~~eddies~~ coincide with the intrusion of nutrient-poor CW~~aribbean Sea water~~.

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Two points summarize the result of the seasonal analysis of the three epochs: First, the extent of the CW intrusion confirms the north-west migration of eddies during each epoch, second, the *Chl-a* concentration declines over time.

The second point was confirmed by calculating the average *Chl-a* concentrations outside the continental shelf over two time periods, considering only the concentrations above waters deeper than 250 *m*. Using data from 1998 to 2002 (SeaWIFS), and from 2009 to 2014 (MODIS) we conducted a student-t test for difference in the means (Fig. 10). The latter period was significantly lower with $t = 4.75$ and $p<0.001$ ($n_1 = 1,825$; $n_2 = 2,190$). This analysis confirms that the *Chl-a* concentration of the GoM decreases over time and appears to disagree with the results of Müller-Karger et al. (2015) who did not indicate a time trend in *Chl-a* concentration in the GoM. As the data were taken with different sensors and to eliminate the uncertainty that this difference is not caused by a systematic difference between the SeaWIFS and MODIS data sets used in our analysis, we calculated least square regressions to the SeaWIFS and MODIS time series at four stations corresponding to the northwest, northeast, southwest and southeast regions of Müller-Karger et al. (2015) (Fig. 11). For each data set, inner slopes as well as overall slopes were calculated. For all four stations, the SeaWIFS (1998-2002) and the MODIS (2003-2017) data series merged exactly and all stations show negative trends; equivalently, the combined time series (1998-2017) also show a negative tendency, supporting the conclusion that the *Chl-a* concentrations over the deep GoM has decreased over time.

The difference between our results and those obtained by Müller-Karger et al. (2015) may be attributed to the different way in which in this work and treated the data. Müller-Karger et al. (2015) divided the GoM into 4 quadrants with depths of over 1000 m: Region 1-North East (RO1), Region 2 (RO2 -Northwest), Region 3 (RO3-Southeast), and Region 4 (RO4 Southwest) and calculated the spatial average in each quadrant to build four-time series, from 1993 to 2012. In their words, "Time series of anomalies of wind speed, SST, SSHA and *Chl-a* concentration were obtained by subtracting the monthly mean (climatology) from the monthly field for that variable". Time series of wind speed"intensity", sea surface temperature (SST), sea-surface height (SSH), and *Chl-a* data obtained at these stations from satellite products was analyzed statistically, and plotted. Other variables plotted by- Müller-Karger et al. (2015) were mixed layer depth (MLD) as calculated from a hydrodynamic model, and net primary production (NPP) calculated from MODIS data using the vertically generalized productivity model (VGPM) of Behrenfeld and Falkowski (1997).

On the other hand, we calculated the average of the *Chl-a* concentration pixel by pixel in waters over 250 m depth, for two time periods (1998-2002 and 20098-20146), and subtracted the respective monthly (climatological) means to find the difference (Fig. 10). From 2009 onward, the difference indicated a small reduction of *Chl-a* in the first optical depth (1-20 or 40 meters of depth) that is increasing with time. A student-t test was used to conclude that the reduction was significant. We also treated the data exactly as- did and Müller-Karger et al. (2015) obtained slightly negative slopes Müller-Karger et al. (2015) over the entire 1998 to 2013 period.

We suggest that Müller-Karger et al. (2015) did not detect the small negative trend in their *Chl-a* plots because their calculated slopes indicated no time-dependent change. We surmise that they were also influenced by the lack of slope in the modeled MLD plot, despite clear, positive, trends for SST, SSHA, and wind force. Actually, although close to zero, the slopes, as indicated in Müller-Karger et al. (2015) were not zero, but -0.03 for RO1, -0.01 for RO2, and simply given in as -0.0 for RO3 and 0.0 for RO4 (see their Table 1). The Müller-Karger et al. (2015) also ignored the fact that the time-*Chl-a* correlation coefficients (R) for all four regions wasere negative.

To confirm our findings, we chose 4 stations, each one centrally located in each- quadrant (Müller-Karger et al., (22015), and conducted regression analyses of the logarithmic transform of the SeaWifs and MODIS *Chl-a* concentrations. All four regions showed a negative slope, a negative R, and the negative slopes in the southern gulf (RO3 and RO4) were significantly different from 0 (p<<0.05). This is shown in Fig. 11.

The observed small, but persistent decline in *Chl-a* from 1993 to 2017 may be attributed to the AMOC's over-all effect of warming the surface water and thereby promoting stratification. However, we wish to make clear that our conclusion about the recent time-dependent lowering of the *Chl-a* pertains only to the near surface, and may not indicate a decrease in the primary productivity integrated over the entire water column. In the GoM, the chlorophyll maximum as measured by fluorescence occurs at about 75 m, e.g., below one optical depth, and is greater in summer than in winter (Pasqueron de Fommervault et al., 2017), indicating that the relationship between water column productivity and near surface *Chl-a* concentration in the GoM requires further study. Our own results and conclusions are based on SeaWifs and AquaMODIS chlorophyll data, which in -Type One water**,** correlate very well with chlorophyll measured with standard laboratory methods (Mati Kahru, personal communication). –In our work we can only say that according to these satellite "products", we find a time-dependent diminution of the Chl-signal. —This diminution has been widely observed by others although in other waters ( et al., 2006, Polovina et al., 2008; Irwin and Oliver, 2009, Laffoley and Baxter., 2016).

**4. Summary and conclusions**

The availability of a large spatial extension of satellite observations of ADT, sea surface currents, wind stress over a quarter of century and Chl-a over 20 years has enabled us to confirm the LC and CW dynamics observed in the 60's and 70's with more recent *in situ* observations. The verification of the CWF climatologies developed in this work is important as a reference baseline for further numerical modeling, and it impacts assessments of the gulf's biogeochemistry, energy, heat transport, and Chl-a concentration. A recent committee of the National Academic of Sciences, (2018) suggested three main study topics to advance the knowledge of the processes that characterize the GoM: 1) the LC system active area, 2) the variation of the inflows of the LC system, and 3) the dynamic interactions of the LC system in the west. Following these suggestions, we have confirmed that the maximum influence of the CW into the GoM (e,g., its maximum extension into the gulf or intrusion) has a temporal variability, being stronger in summer and weaker in the late fall and winter. This is supported by the fact that the generated monthly EKE maps have the maximum gradient at the periphery of the CWF and have a similar monthly pattern of extension and retraction as the CWF.

We noted that in the summer months the wind stress from the southeast is weak, thereby minimizing the flow of nutrients to the surface and causing Chl-a to be low, specifically for three reasons: 1) The increase in the surface temperature of the water column strengthens stratification 2) The intrusion of the CW to the western gulf´s surface thickens the surface layer, and 3) The eddy-driven anticyclonic circulation deepens the nutricline. This contrasts with the cold seasons, when the surface temperature of the water is lower and the northerly winds are stronger, favoring the flow of nutrients to the surface.

The three-year running averages of ADT 40 cm isoline reproduce qualitatively the climatological pattern of a quarter of a century showing that before 2002 the CWF was less intrusive and the LCEs sizes were smaller. In the 1993-2002 period, we calculated that the mean

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life cycle of the eddies was 6.8 months and that in the 2003-2015 period the mean life cycle was 11.7 months. This difference suggests that after 2003, larger volumes of oligotrophic waters from Caribbean Sea have invaded the western GoM and reduced mean surface Chl-a concentrations. This work shows that

- The intrusion of the CW by LC-LCEs extends further into the western GoM than was previously known.

- *Chl-a* concentrations respond to the dynamics inside the GoM and are influenced by the CWF and the LC anticyclonic and cyclonic eddies.

- Since 2002, near surface *Chl-a* concentrations over bathymetry deeper than 250 m have decreased, and GoM surface waters may be turning more oligotrophic than in the previous decade.

This work, based on 25 years of remotely sensed data, emphasizes the role of climatology in determining GoM circulation and its productivity and suggests that further climatologically-induced changes are probably imminent.

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## 5. Acknowledgements

This study was carried out as part of the PhD thesis research conducted by the lead author at the Faculty of Marine Science and the Oceanographic Research Institute (FCM-IIO / UABC), Postgraduate Coastal Oceanography Program, and it was supported by the Graduate Professional Development Mexican Program grants (PRODEP: DSA/103.5/16/5801), the National Institute of Technology of Mexico (TecNM) and the Mexican Energy Bureau and Hydrocarbons Mexican

Trust, project 201441. This is a contribution of the Gulf of Mexico Research Consortium (CIGoM).

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Table 1. Average bold numbers for *Chl-a* concentrations (*mg* $m^{-3}$) and differences (*mg* $m^{-3}$; (%)) between Early and Contemporary averages with % of difference (reffered to the Early averages) at two geographical areas: 95.5˚W, 22.12˚N and 91.5˚W, 25.87˚N, (Western GoM) and 86˚W, 22.12˚N and 84.75˚W, 23.37˚N (LC-LCEs) during "**early**" (1998-2002), "**middle**" (2003-2008), and "**contemporary**" (2009-2014) epochs. Table 1 shows the compared averages in bold print. Standard deviations and number of pixels considered are shown in parenthesis.

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| Geographical Areas | Season | Early Averages (1998-2002) | Middle Averages (2003-2008) | Contemp. Averages (2009-2014) | Difference (Early-Contemp) |
|---|---|---|---|---|---|
| Western GoM | Winter | **0.180** (±0.047, n=4026) | **0.167** (±0.048, n=4866) | **0.173** (±0.0624, n=4828) | **0.007 (4%)** |
| Loop Current | | **0.149** (±0.052, n=536) | **0.129** (±0.064, n=647) | **0.117** (±0.062, n=645) | **0.032 (21%)** |
| Western GoM | Spring | **0.114** (±0.033, n=3693) | **0.087** (±0.049, n=4658) | **0.0834** (±0.036, n=4754) | **0.030 (27%)** |
| Loop Current | | **0.0948** (±0.074, n=526) | **0.085** (±0.1287, n=642) | **0.0835** (±0.116, n=648) | **0.011 (12%)** |
| Western GoM | Summer | **0.0887**(±0.024, n=3924) | **0.080** (±0.022, n=4794) | **0.0755** (±0.023, n=4837) | **0.013 (15%)** |
| Loop Current | | **0.109** (±0.217, n=535) | **0.091** (±0.171, n=647) | **0.0938** (±0.148, n=648) | **0.015 (14%)** |
| Western GoM | Autumn | **0.151** (±0.052, n=3894) | **0.137** (±0.044, n=4876) | **0.127** (±0.043, n=4846) | **0.024 (16%)** |
| Loop Current | | **0.138** (±0.128, n=525) | **0.1325** (±0.114, n=643) | **0.122** (±0.103, n=648) | **0.016 (12%)** |

**FIGURE CAPTIONS:**

Fig. 1. Monthly means of absolute dynamic topography (ADT) and surface currents averaged over a quarter of a century (1993-2017).

Fig. 2. Climatological monthly maps of eddy kinetic energy (EKE) in GoM: red color contours correspond to the areas of maxima EKE. The heavy~~thick~~ black line corresponds to the isoline of 40 *cm* 2.2 *cm* of the CWF (the contour of the CWF is significant at the 95% of level). The EKE was calculated using daily maps of satellite-derived currents from AVISO (GEKCO) for a quarter of a century (1993 – 2017).

Fig. 3. Geographical positions of the CWF tracked using the 40 *cm* ADT isoline representing 1993-2017 monthly average values: a) Northward and b) Westward, respectively; c) ADT spectral analysis in a region influenced by the CWF (91.25$^{o}$W, 23.125$^{o}$N and 83.5$^{o}$W, 28.12$^{o}$N).

Fig. 4. The ADT quarter-century CWF (1993-2017) monthly climatology and its standard deviation are shown in heavy~~solid~~ and dotted lines, respectively. The heavy~~solid~~ line corresponds to the 40 *cm* isoline of the CWF. The dotted line encloses values of the standard deviation >15 *cm*.

Fig. 5. Average monthly percentage surface areas of CW in the interior of the Gulf of Mexico determined from climatology of the STD contour > 15 *cm*; enclosed areas were calculated in relation to the GoM area (1.56x10$^{6}$ $km^2$).

Fig. 6. Monthly means of absolute dynamic topography (ADT) from 1993-2002 (color) and its respective CWF computed with the 40 *cm* isoline (heavy black~~thick~~ line).

Fig. 7. Monthly means of absolute dynamic topography (ADT) from 2003-2017 (color) and respective CWF computed with the 40 *cm* isoline (heavy black~~thick~~ line).

Fig. 8. Monthly climatologies of *Chl-a* (SeaWIFS, 1998-2002 and MODIS data source, 2003-2017). The heavy~~solid~~ black line represents the contour of the 40 *cm* ADT data that represents the CWF (1998-2017). *Chl-a* values larger than 1 $mg\ m^{-3}$ are plotted in red.

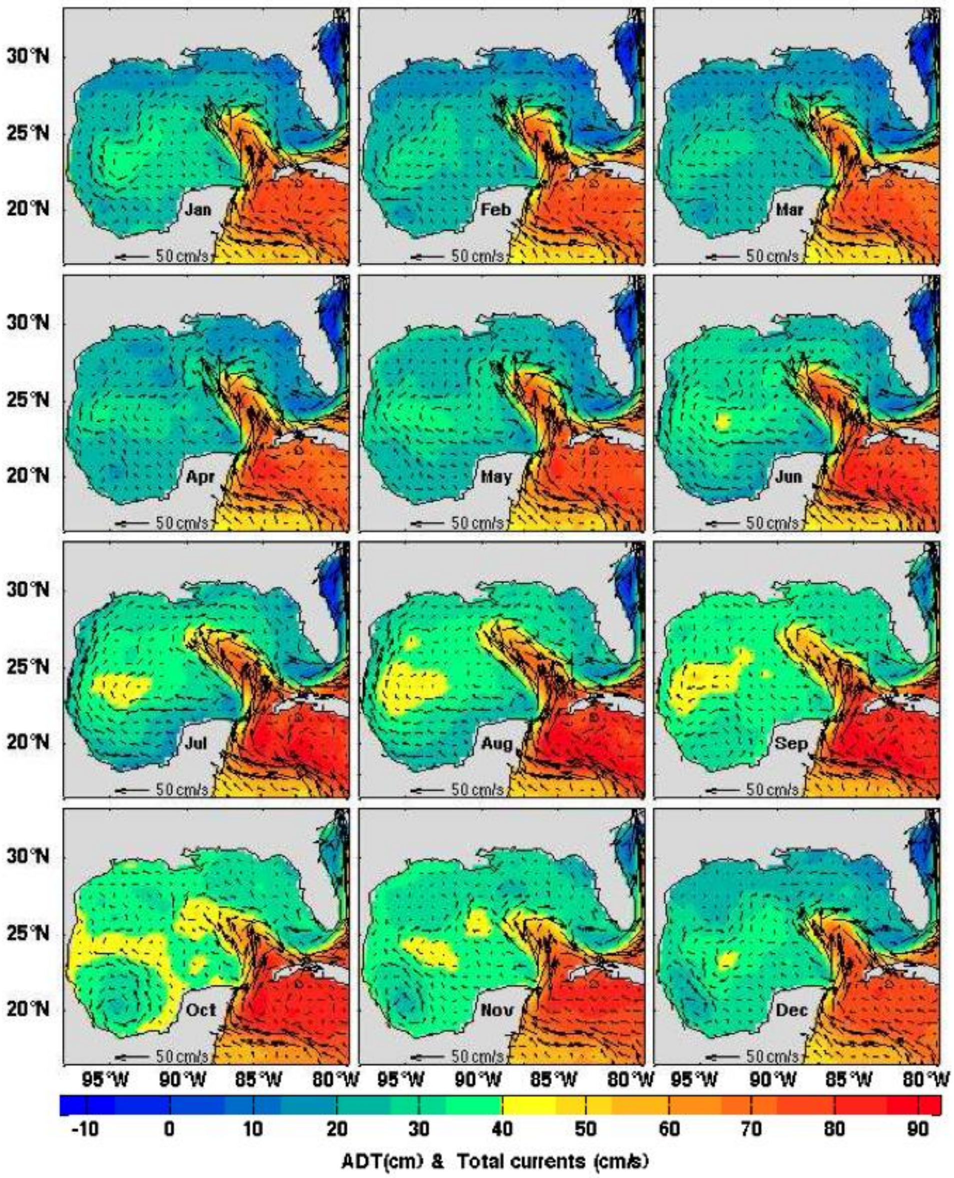
Fig. 9. From top left to bottom right, average *Chl-a* values according to period: column 1, SeaWIFS 1998-2002, column 2, MODIS 2003-2008, and column 3, MODIS 2009-2014. From top to bottom figures correspond to the mean seasons. Average *Chl-a* concentration is computed inside the white and red squares (white corresponds to the western GoM and red corresponds to the LC area). Average values for each time period and season are in Table 1.

Fig. 10. Differences of *Chl-a* concentration ($mg\ m^{-3}$) between 2009-2014 average values of MODIS data minus 1998-2002 average SeaWIFS values. The broken line represents the 250 *m* isobath. White contoured areas indicate no significant differences.

Fig. 11. *Chl-a* concentrations ($mg\ m^{-3}$) at four stations (a to d) in the GoM, daily time series derived from SeaWIFS from 1998 to 2002 (green) and MODIS from 2003 to 2017 (blue). Least square regressions for SeaWIFS (red line), MODIS (cyan line), and the overall linear regressions

for each station (dashed black line).

FIGURE 1



30°N
25°N
20°N
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
50 cm/s
95°W 90°W 85°W 80°W
-10 0 10 20 30 40 50 60 70 80 90
ADT(cm) & Total currents (cm/s)


FIGURE 2

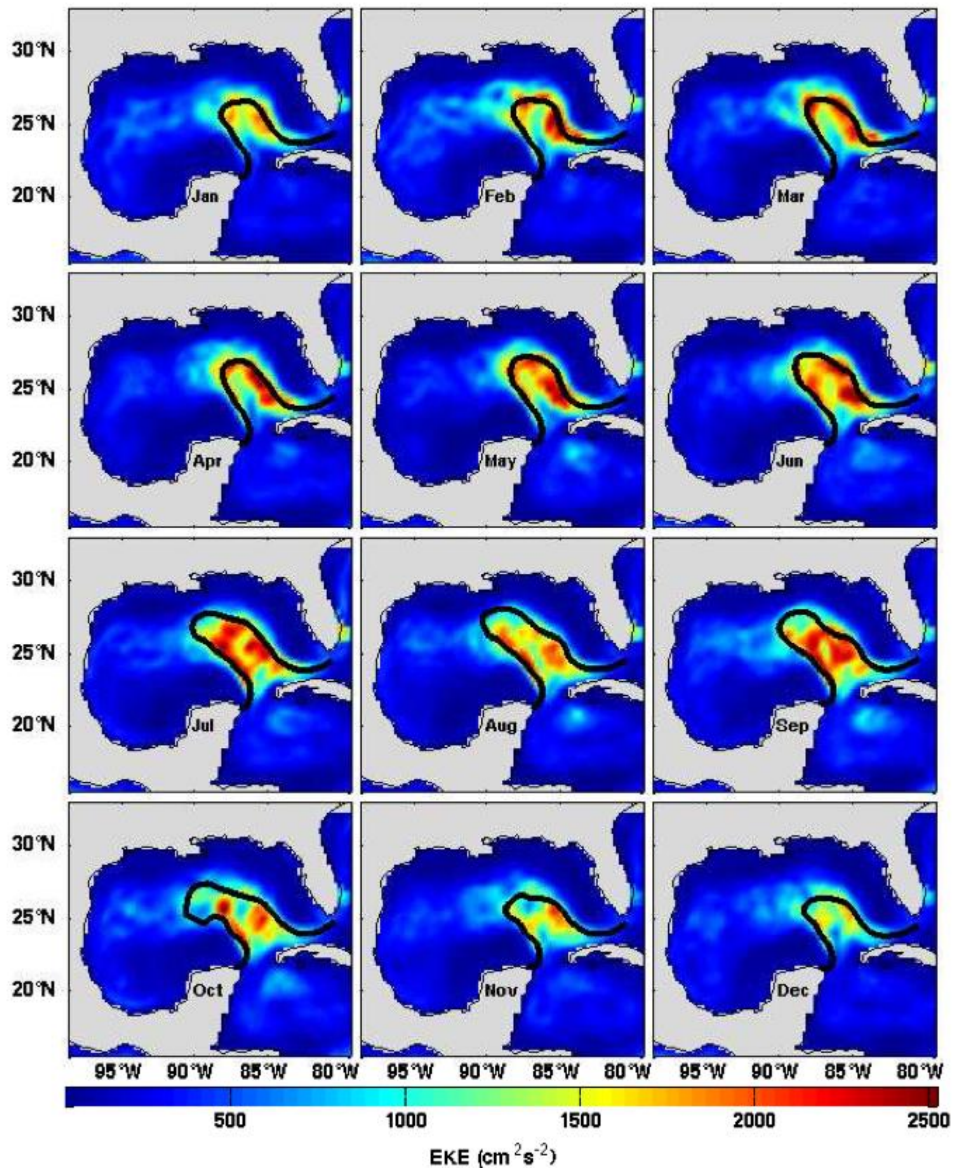

30°N
25°N
20°N
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
95°W
90°W
85°W
80°W
500
1000
1500
2000
2500
EKE (cm^2 s^-2)

FIGURE 3

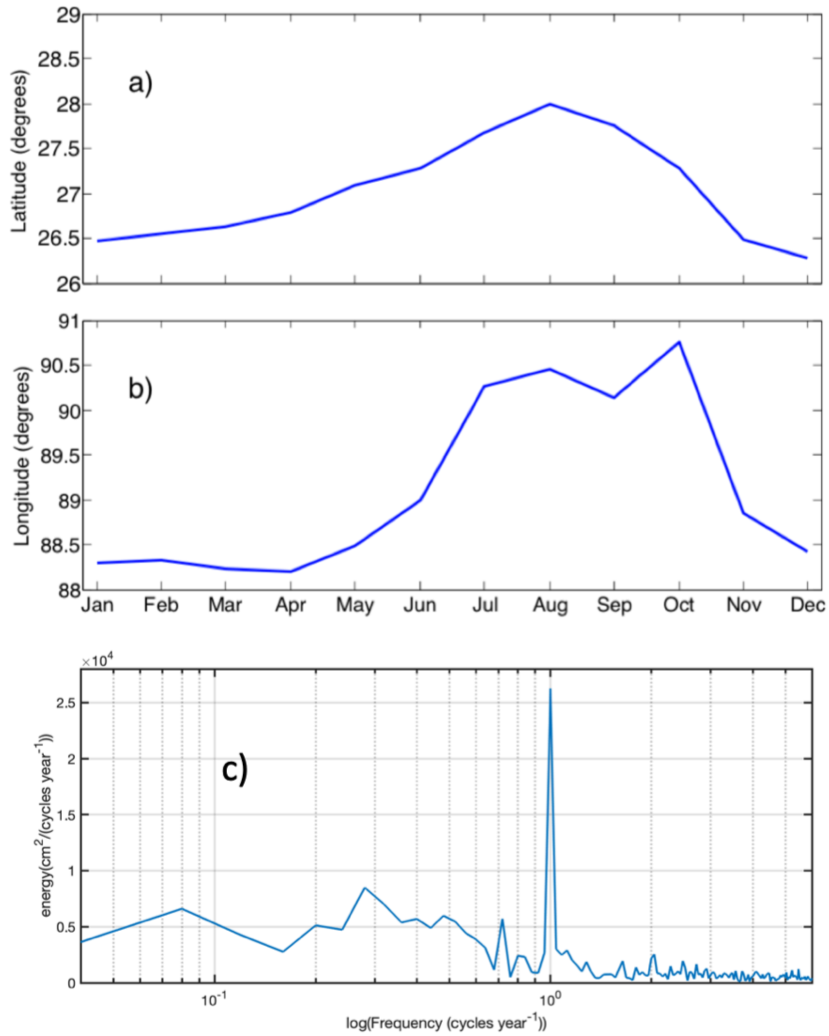



FIGURE 4

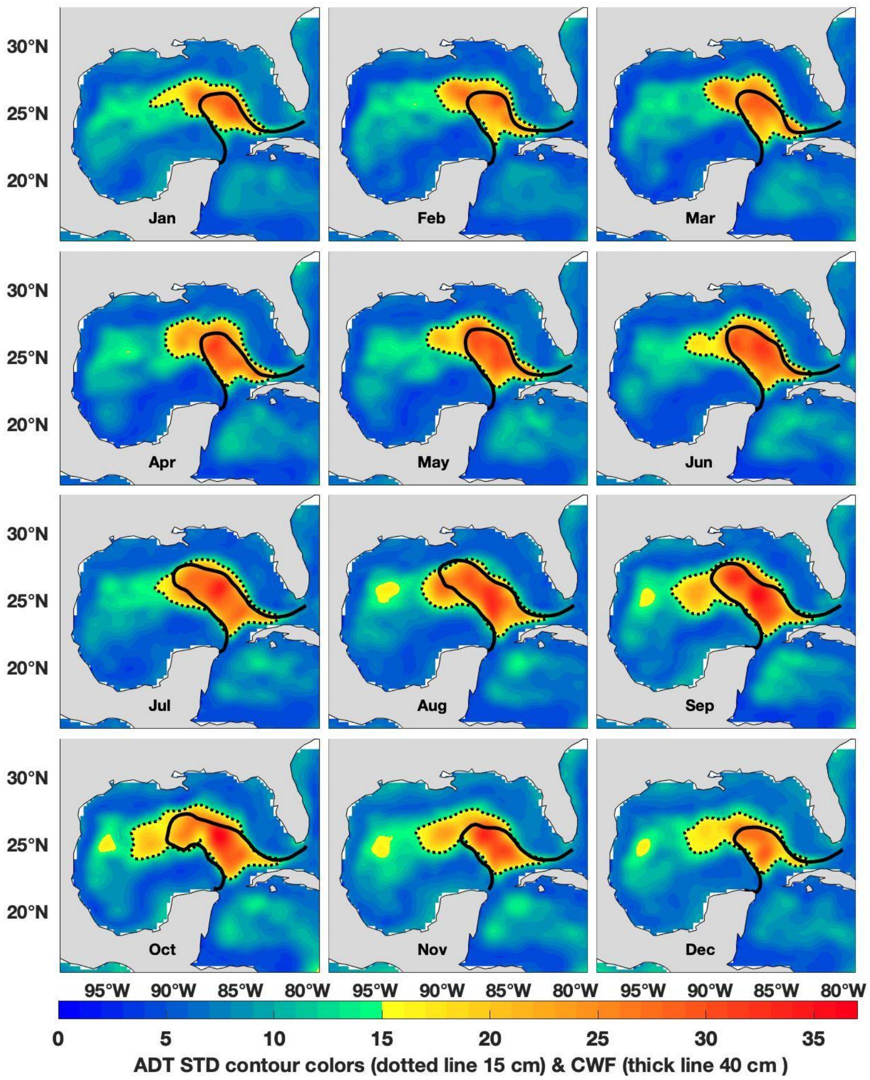

30°N
25°N
20°N
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
95°W 90°W 85°W 80°W 95°W 90°W 85°W 80°W 95°W 90°W 85°W 80°W
0 5 10 15 20 25 30 35
ADT STD contour colors (dotted line 15 cm) & CWF (thick line 40 cm )

FIGURE 5

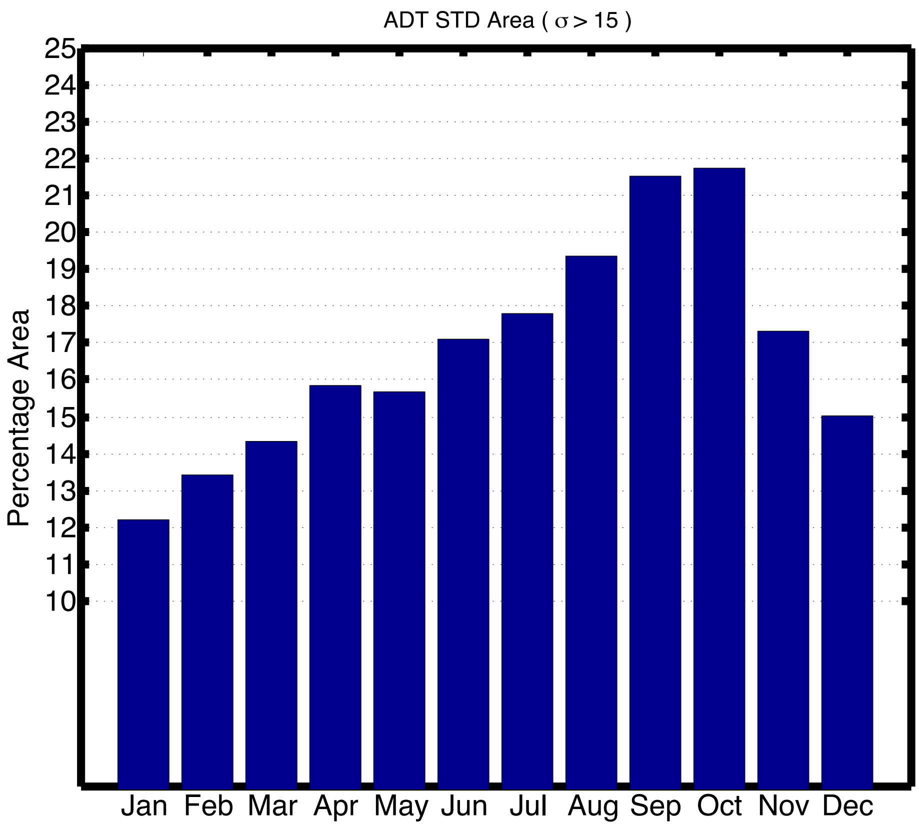
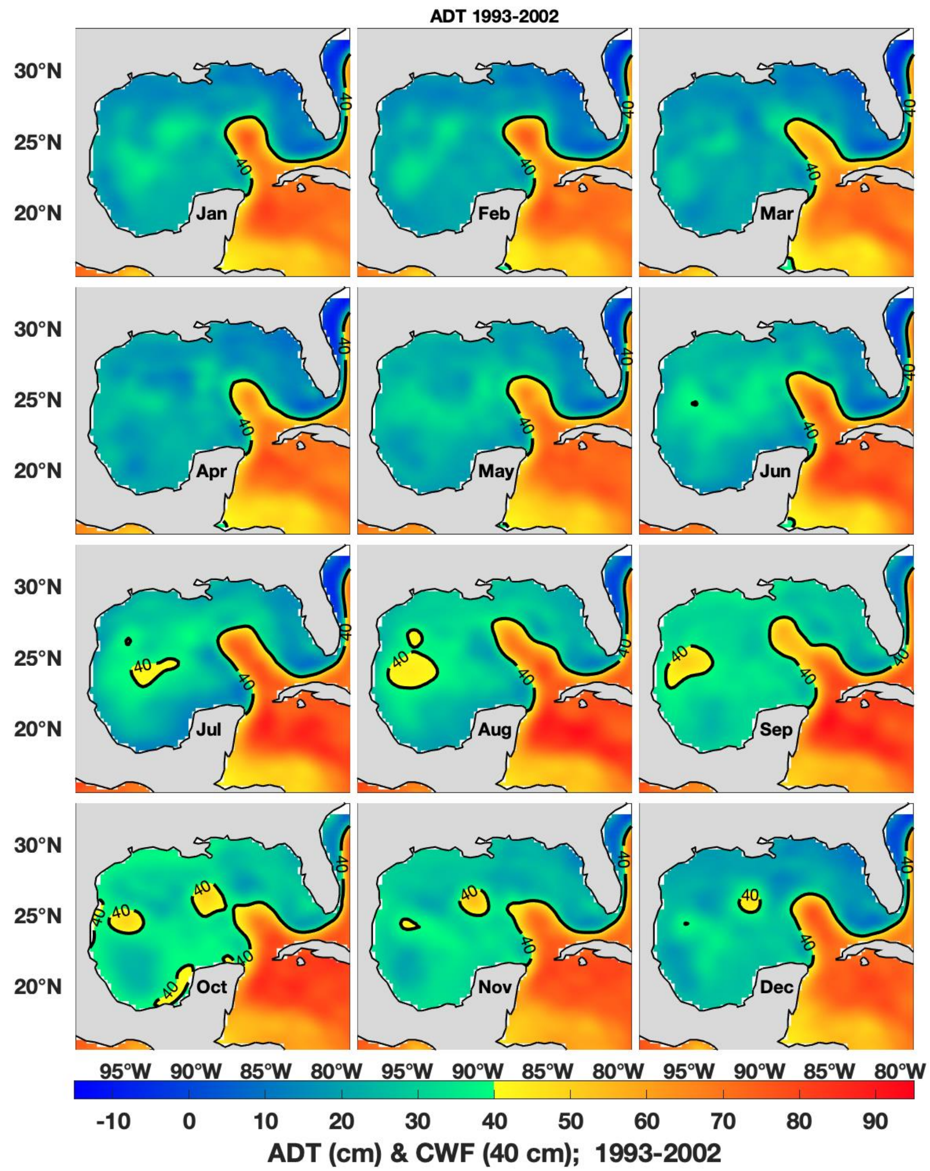

ADT STD Area ( σ > 15 )
Percentage Area
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

FIGURE 6



ADT 1993-2002
30°N
25°N
20°N
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
40
95°W 90°W 85°W 80°W 95°W 90°W 85°W 80°W 95°W 90°W 85°W 80°W
-10 0 10 20 30 40 50 60 70 80 90
ADT (cm) & CWF (40 cm); 1993-2002


FIGURE 7

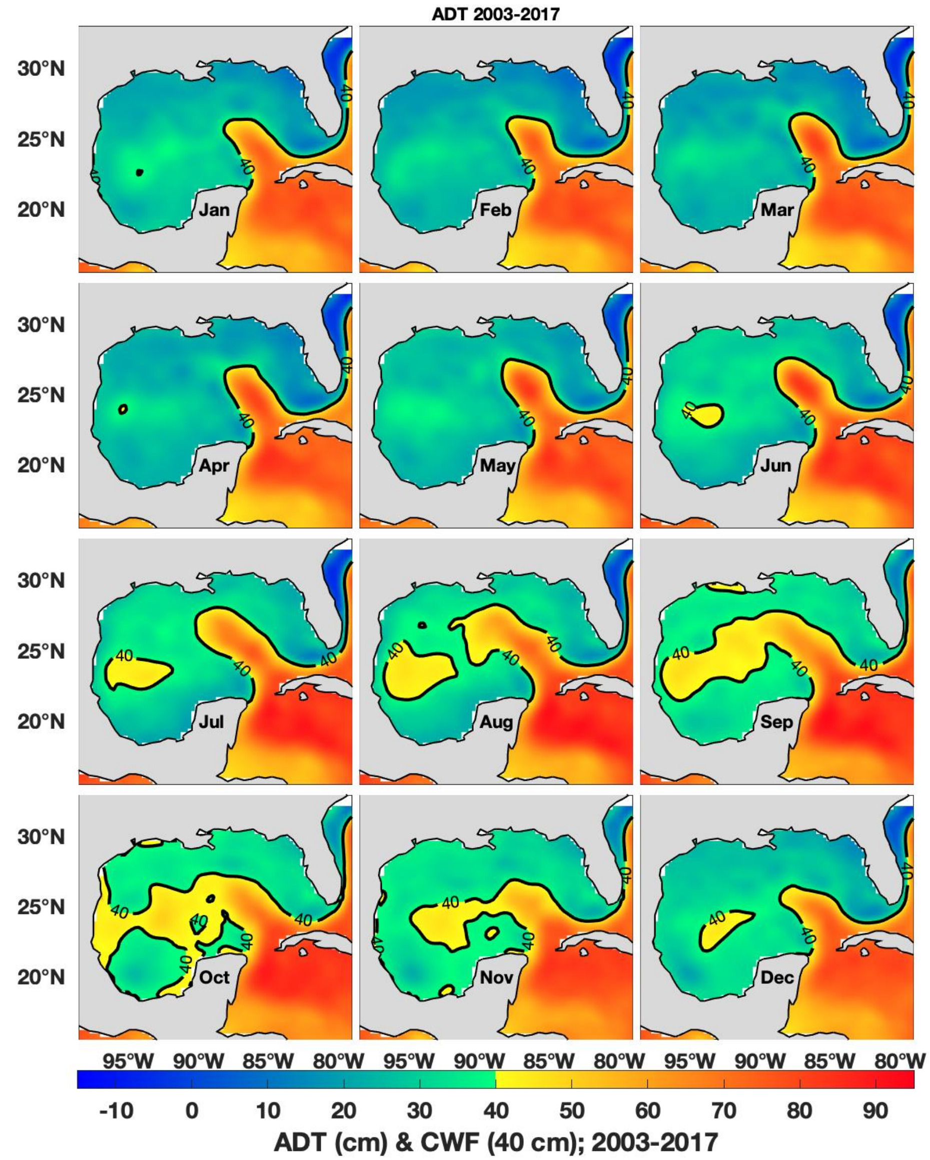

ADT 2003-2017
30°N
25°N
20°N
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
40
95°W 90°W 85°W 80°W
-10 0 10 20 30 40 50 60 70 80 90
ADT (cm) & CWF (40 cm); 2003-2017

FIGURE 8

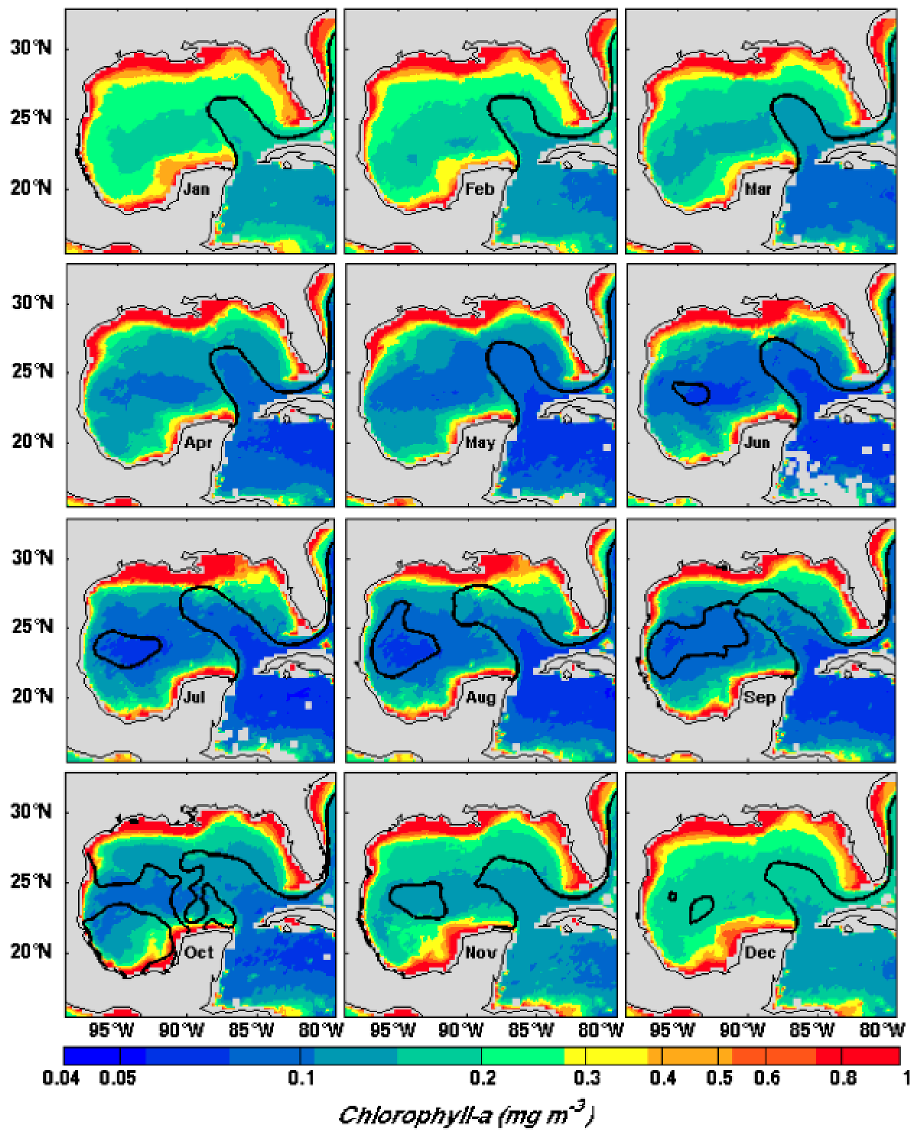

30°N
25°N
20°N
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
95°W
90°W
85°W
80°W
0.04
0.05
0.1
0.2
0.3
0.4
0.5
0.6
0.8
1
Chlorophyll-a (mg m-3)

FIGURE 9

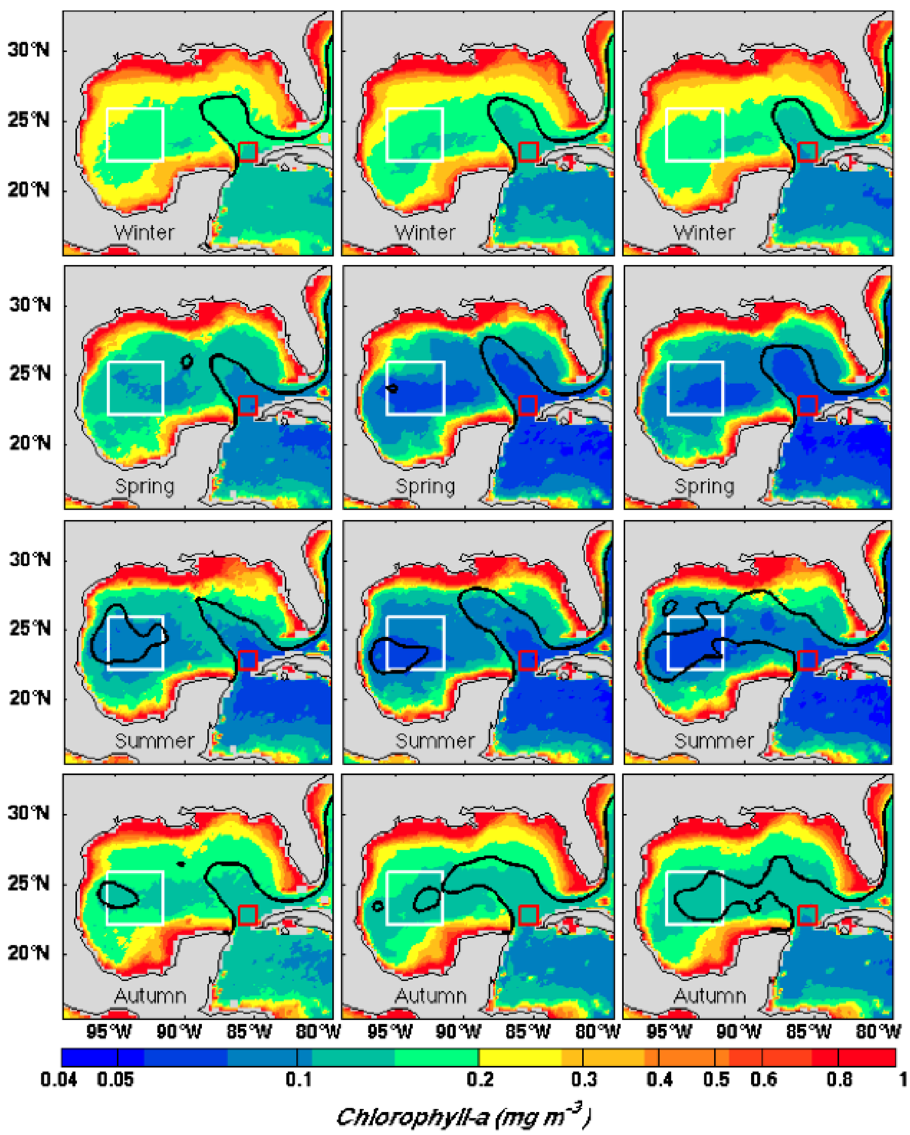
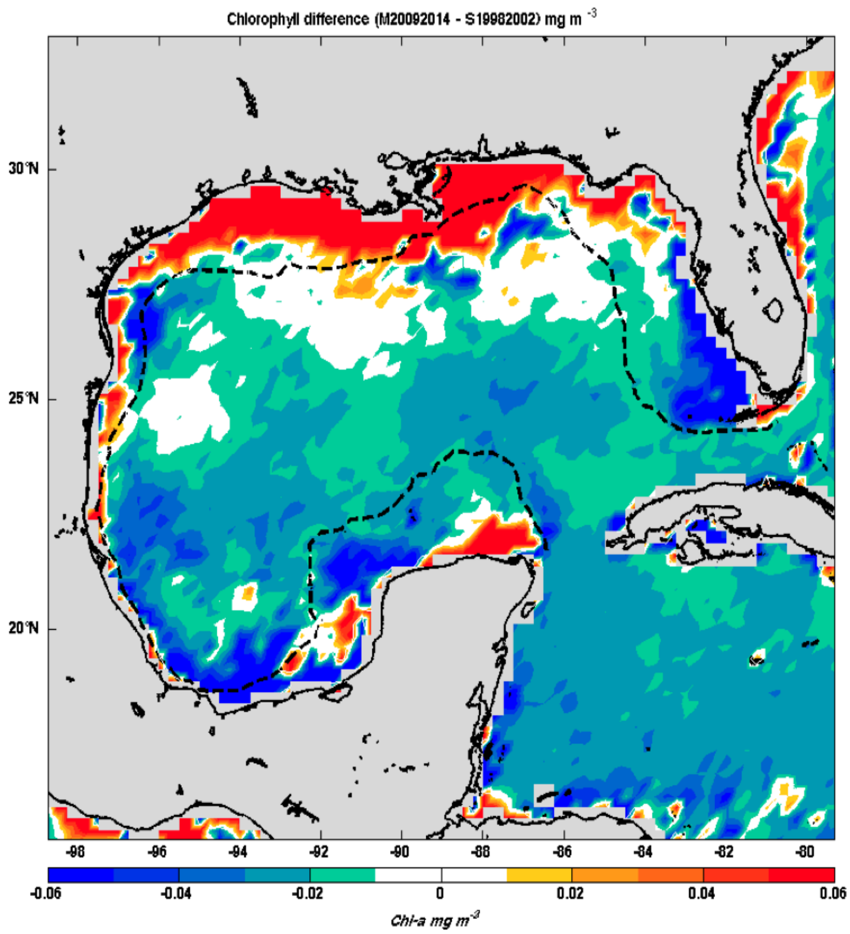
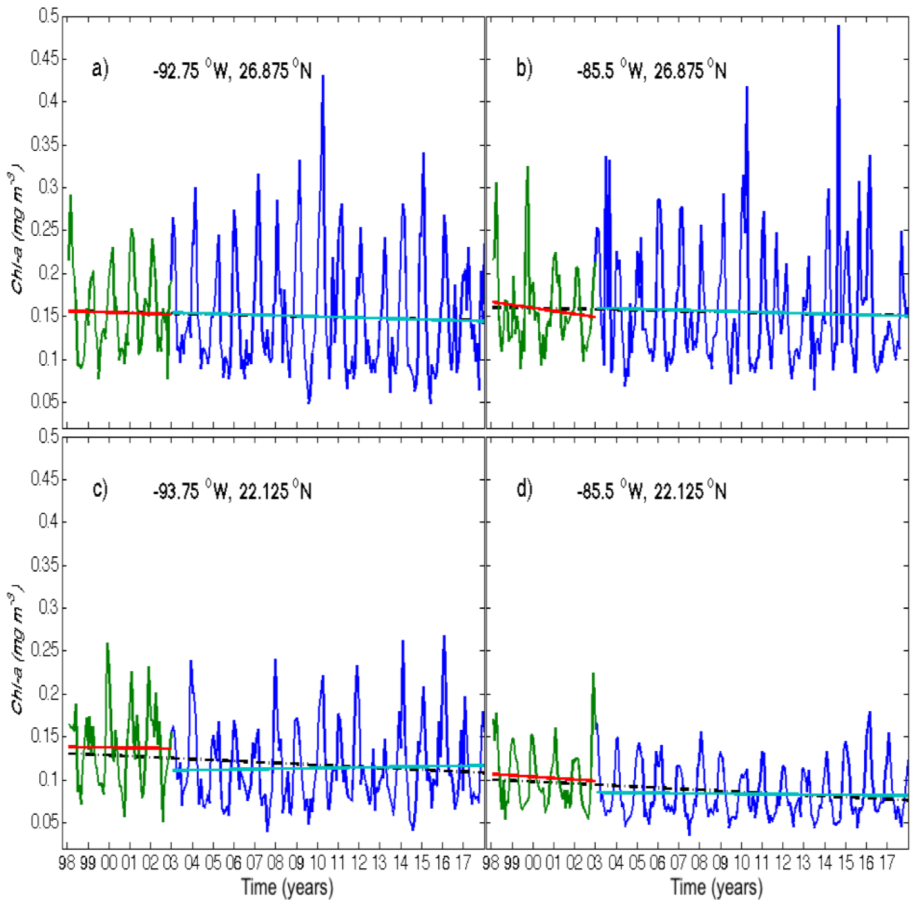

30°N
25°N
20°N
Winter
Winter
Winter
Spring
Spring
Spring
Summer
Summer
Summer
Autumn
Autumn
Autumn
95°W 90°W 85°W 80°W
0.04 0.05 0.1 0.2 0.3 0.4 0.5 0.6 0.8 1
Chlorophyll-a (mg m-3)

FIGURE 10



Chlorophyll difference (M20092014 - S19982002) mg m -3
30°N
25°N
20°N
-98
-96
-94
-92
-90
-88
-86
-84
-82
-80
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
Chl-a mg m-3


FIGURE 11



a) -92.75 °W, 26.875 °N
b) -85.5 °W, 26.875 °N
c) -93.75 °W, 22.125 °N
d) -85.5 °W, 22.125 °N
Chl-a (mg m^-3)
Time (years)